Role of nanostructuring of sensing materials in performance of electrical gas sensors by combining with extra strategies

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Abstract

1. Introduction

Rapid industrialization, informatization, intelligentization, and population expansion put forward higher and more stringent requirements for gas sensing technology which undoubtedly helps to address environment-related issues [1–5]. The emergence of novel nanomaterials/ nanostructures fabrication and integration technologies and the design of novel gas sensing chips and sensors with great functionalities are necessary to rapidly push gas sensing technology forward. As a result, more intelligent, miniaturized, compatible and flexible, and low-power gas sensors are more popular than those sophisticated instruments like mass spectroscopy, gas chromatography, and ion mobility spectroscopy [6]. Particularly, electrical gas sensors based on chemiresistors and Field Effect-Transistors (FET) are receiving increasing attention due to their relatively simple working procedures, miniaturizable size, low cost, low power consumption, portability, and integrability with fifth-generation (5G) smart devices for effective real-time data transmission through the Internet of Things (IoT) [7–14]. Miniaturized electrical gas sensors can be easily integrated into the platform of an electronic device/ system, which would further stimulate their applications, including electronic nose [15, 16], outdoor/indoor air quality assessments [17–22], exhaled breath analysis for early disease diagnosis (asthma, kidney, halitosis [23], diabetes, lung cancer, cystic fibrosis, tuberculosis [24]) [25, 26], chemical process control, pharmaceuticals, food grading [27], safety [28], etc.

An ideal electrical gas sensor is required to have excellent ‘4S’ including selectivity, sensitivity, stability, and speed (response and recovery time) which is determined by gas trap, identification and transport kinetics at sensing surface, interactions between gas and sensing materials, and signal transduction, as shown in figure 1 [29–32]. Among these, the speed, strength, and repeatability of interactions between gas molecules and sensing materials may have a more critical role to play in influencing the electrical properties of sensing materials by gas to be detected [33–36]. Therefore, it is reasonable to conclude that structures, dimensions, and sizes of sensing units and their constituent materials are crucial for the performance of electrical gas sensors. Great effort in gas sensing technology is made to explore sensing materials including metals [37], metal oxides [38], metal chalcogenides [39], graphene derivatives [40, 41], carbon nanotubes [42], black phosphorous [43], polymers [44], and their combinations [45–50]. A consensus for these materials is that a strategy of nanostructuring was employed to improve their sensing performance [51, 52]. Nanostructuring shows not only its great strengths but also some weaknesses. The advantages include modulation of the energy band alignment capable of creating an additional depletion layer, changing the electronic states of materials (p- or n-type), tuning of surface/interface properties, creation of additional reactive sites, and geometrical changes of materials with particular crystal facets. In contrast, the weaknesses are the possible smearing of selectivity as a result of cross-sensitivity to various gases by hybridization through doping, heterojunction, and mixing of nanostructuring sensing units on
occasions, induction of unknown harmful effects, unpredictability of miniaturization especially down to atomic size, and complication of correlating various properties.

Among ‘4S’ above, selectivity is most challenging for electrical gas sensing nanostructures which are usually considered to be inherent. However, this could be ameliorated by the possible prediction of physical and chemical properties of nanostructured sensing blocks with specific dimensionality, size, and morphology in terms of DFT and first-principle studies [53–55]. It is highly anticipated that the better selectivity enhancement could be unveiled by the combination of two or more nanostructured sensing materials to benefit from their synergistic effects (such as electronic reactivity, electronics and chemical sensitization) of multicomponent composites [56, 57]. For example, by tailoring the element constituents of sensing blocks (e.g. Cu and Mo), the semiconductor junctions (between CuO and Cu₃Mo₂O₉) could be formed to create a more reasonable depletion layer, which improved both selectivity and sensitivity of NO₂ gas [58, 59]. This is related to the structure of Cu₃Mo₂O₉ composed of two polyhedral Cu-O₅, one octahedral Cu-O₆, and two tetrahedral, which makes it possible to act as a catalyst just like MoO₃ because of their similar Mo-O bond lengths and synergistic effects of Cu and Mo ions in the lattice [58, 60]. However, the catalytic effects and synergistic effects from multi-ions could be further enhanced in terms of nanostructuring of sensing materials and modifications such as decoration [34], mixing [61], doping [62] and/or functionalization [63], which can reasonably improve gas sensing performance remarkably [64–68]. Diversified morphologies and dimensionalities with miniaturized sizes were successfully tuned to realize superior gas sensing performances [69–71], such as zero-dimensional (0D, nanoparticles [72]), one-dimensional (1D, nanocolumns [63], nanowires [73], and nanorods [74]), two-dimensional (2D, nanosheets [75], nanoribbons [76], and 2D materials and their derivatives), three-dimensional (3D, nano...
parameters to improve their sensing performances significantly. FET sensors possess an additional gate terminal that provides extra freedom for tuning the switch of conduction mode, etc, which may not ensure effective control over gas sensing performance. In comparison, chemiresistive sensors with a simple configuration of electrodes and sensing blocks detects gases through the change of the resistance (current) of the blocks before and after gas exposure. However, chemiresistors lack the tunability of multi-parameters such as carrier concentration, mobility, charge transfer barrier, or desired switch of conduction mode, etc, which may not ensure effective control over gas sensing performance. In contrast, FET sensors possess an additional gate terminal that provides extra freedom for tuning the field-effect parameters to improve their sensing performances significantly. For instance, the gate bias-dependent carrier concentration (holes or electrons) would change the work function and binding affinities that modulate the adsorption/desorption barrier to facilitate the charge transfer between sensing surface and gas molecules. Generally speaking, chemiresistive sensors are cheaper and more facile to fabricate and easier to operate compared to FET type sensors, as shown in Table 1. In the following sections, both chemiresistors and FETs will be reviewed separately according to the nanostructuring of sensing blocks in 0D, 1D, 2D, and 3D, respectively, with working principles described in (85–87). Their performances such as response and recovery behaviors, the limit of detection (LOD), sensitivity, and stability will be concentrated to be associated with nanostructuring.

2. Device configuration

Electrically-transduced gas sensors configured predominantly in chemiresistors (85), and FETs (86) show numerous advantages like a simple operation, low power consumption, low cost, and easy fabrication. Generally, sensors normally operate either in p- or n- mode, which is determined by the interplay of the sensing materials, the types (donor or acceptor) of gases to be detected. The efficacies can be further enhanced externally by the extra heating, light illumination, or electrical field, etc, as presented in Figure 1. A double terminal chemiresistive sensor with a simple configuration of electrodes and sensing blocks detects gases through the change of the resistance (current) of the blocks before and after gas exposure. However, chemiresistors lack the tunability of multi-parameters such as carrier concentration, mobility, charge transfer barrier, or/and desired switch of conduction mode, etc, which may not ensure effective control over gas sensing performance. In contrast, FET sensors possess an additional gate terminal that provides extra freedom for tuning the field-effect parameters to improve their sensing performances significantly (Figure 1). For instance, the gate bias-dependent carrier concentration (holes or electrons) would change the work function and binding affinities that modulate the adsorption/desorption barrier to facilitate the charge transfer between sensing surface and gas molecules. Generally speaking, chemiresistive sensors are cheaper and more facile to fabricate and easier to operate compared to FET type sensors, as shown in Table 1. In the following sections, both chemiresistors and FETs will be reviewed separately according to the nanostructuring of sensing blocks in 0D, 1D, 2D, and 3D, respectively, with working principles described in (85–87). Their performances such as response and recovery behaviors, the limit of detection (LOD), sensitivity, and stability will be concentrated to be associated with nanostructuring.

2.1. Chemiresistor

As one main type of electrical sensor, chemiresistors are explored extensively due to their simplicity, cost-effectiveness, ease of high precision measurements, and predictable electrical properties (57). These features of chemiresistive devices make them attractive starting platforms for investigating gas sensing performance of new sensing materials and their applications in the era of IoT and the industrial internet of Things (IIoT) (119). Moreover, the superior compatibility of the chemiresistor configuration with various techniques for incorporating novel sensing materials such as wet-chemical techniques (self-assembly (91), hydrothermal (93, 94), sol-gel (96), precipitate (97), templated assisted (98), solvothermal synthesis (95), auto-combustion (99)), flame spray pyrolysis (72), chemical vapour deposition (100), film techniques (mechanical exfoliation (101), sputtering (102), spray coating (103), atomic layer deposition (104), and E-beam evaporation (105)), printing and patterning (inkjet-printing (107), micropatterning (108), near field electrospinning (85), nanografting (109), and nanolithography (106)) and their combinations (120), allows for a preliminary performance test of new types of sensing materials and structures and thus their immediate discovery. Amongst these techniques, wet chemistry is the most explored method for chemiresistive gas sensors, which has advantages of simple fabrication, facile measurements, low cost, mass production and even low power consumption. However, this simplicity may also bring about its disadvantages such as uncontrollable miniaturization and difficulty of integration with modern electronics and other platforms, as shown in Table 1. Chemiresistive gas sensors play an indispensable role in performance improvement through nanostructuring of novel sensing materials and search of performance enhancement strategies and exploration of underlying sensing mechanisms (85). This section
Table 1. Advantages and disadvantages of different synthesis methods of sensing materials for chemiresistor and FET gas sensors.

| Sensor     | Method                        | Advantage                                      | Disadvantage                                      |
|------------|-------------------------------|------------------------------------------------|---------------------------------------------------|
| Chemiresistor | Wet-chemistry                 | low cost [90]                                  | post-treatment is required to develop the sensing film |
|            |                               | simple [92]                                     | poor rigidity                                      |
|            |                               | easy modification [28]                          | poor mechanical properties                        |
|            |                               | abundant morphologies with high area/volume ratio and porosity [23] | enable large production                           |
|            | self-assembly [91]            |                                                |                                                   |
|            | hydrothermal [93, 94]         |                                                |                                                   |
|            | sol-gel [96]                  | flexible                                        | difficulties in materials growth                  |
|            | precipitation [97]            |                                                | limited quantity and materials modification       |
|            | template-assisted [98]        |                                                |                                                   |
|            | auto-combustion [99]          |                                                |                                                   |
| Thin films | chemical vapour deposition [100] | good rigidity                                |                                                   |
|            | flame spray pyrolysis [72]   | good mechanical properties                     |                                                   |
|            | mechanical exfoliation [101] | controllable thickness                         |                                                   |
|            | sputtering [102]              |                                                |                                                   |
|            | spray coating [103]           |                                                |                                                   |
|            | atomic-layer deposition [104] |                                                |                                                   |
|            | E-beam evaporation [105]     |                                                |                                                   |
| Printing and patterning | Nanolithography [106]     | good quality and scalability                   | high cost                                          |
|            | inkjet-printing [107]        | portable and compatible                        | relatively large miniaturized size, tedious        |
|            | micropatterning [108]        |                                                |                                                   |
|            | electrospinning [85]         |                                                |                                                   |
|            | nanograting [109]            |                                                |                                                   |
| FET        | Thin films                    | flexible                                        | limited materials and nanostructures               |
|            | mechanical exfoliation [111] | one time making                                 |                                                   |
|            | chemical vapour deposition [111] | good rigidity                              |                                                   |
|            | sputtering [114]             | good mechanical properties                     |                                                   |
|            | atomic-layer deposition [115] | controllable thickness                        |                                                   |
|            | E-beam evaporation [116]     |                                                |                                                   |
| Printing and patterning | nanolithography          | excellent quality and scalability              | limited nanostructures                              |
|            | inkjet-printing [117]        |                                                | expensive                                          |
|            | electrospinning [118]        |                                                |                                                   |
| Nanofabrication | focused ion beam (FIB)       | scalable fabrication                           | limited nanostructures                              |
|            | electron beam lithography (EBL) | miniaturized size                        | high cost                                          |
|            | photolithography [37]        | with modern electronics                        | high energy consumption                             |

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will discuss the performance and possible mechanisms of chemiresistive gas sensors with 0D, 1D, 2D, and 3D nanostructured sensing blocks.

2.1.1. Zero-dimensional nanostructures

0D nanostructures such as graphene quantum dots [119], nanoporous noble metals [121], carbon dots [47, 94], ZnO [99], α-Fe₂O₃ [122], SnO₂ nanoparticles [123], etc., are widely used as chemiresistive sensing blocks in the form of their films or their combination with other 1D or 2D nanostructures [94, 124]. Specific surface areas, catalyzing effects, spillover effects of carriers, and their combinations are normally taken as the dominant sensing mechanisms for gas detection [121, 125]. The particular architectures of 0D nanostructures, such as the closed-packed morphology, could assist the charge carrier transport between the grains, which may facilitate the performance [126]. In a closed-packed structure, the electrons could easily jump through potential barriers between the grains and possibly benefit from the grain size effects [18, 123]. Since the overall current between the two terminal electrodes depends on the electronic charge mobility between the individual grains, the closed-packed structures may suggest good electronic transportation [99, 126]. Consequently, an improvement in sensing performance is possible when the gas sensing performance depends on a potential barrier between the grains [99]. However, the easy agglomeration of 0D nanostructures due to the size and surface effects during fabrication and synthesis may decrease the porosity and even active sites as sensing chips [82, 127]. Benamara et al [99] revealed that the 0D ZnO non-uniform spheres with an average size of about 62 nm exhibit the highest response of ΔR/R = 208 with the response and recovery times of 5 and 2.5 min, respectively, upon exposure to 1 ppm NO₂ at 150 °C, as shown in figures 2(a), (b). This could be due to the easy jump of electrons through the potential barrier between nanosized grains. Hussaini et al [82] found that 0D ZnS nanospheres with sizes of about 18 nm could exhibit the highest response (Rᵣ/ Rₒ) of 94.4 to 50 ppm formaldehyde, as shown in figure 2(c), attributed to the large exposed surface areas, small enough nanospheres and good chemical/thermal stability. Relatively uniform In₂O₃ nanoparticles with sizes of 20–30 nm were revealed to show superior NO₂ gas sensing performance at 60 °C [127]. Again, Liang et al demonstrated that ultrafine α-Fe₂O₃ nanoparticles with an average size of about 3 nm exhibited excellent gas-sensing performance towards acetone vapour, as shown in figure 2(d), which could be ascribed to their very small sizes with a narrow distribution and catalyzing effects [122]. Therefore, for 0D nanostructures, their distribution, size, and surface properties are critical parameters in determining the underlying sensing mechanisms [99]. As a matter of fact, there are fundamental requirements for the size of 0D nanostructures: When the crystallites size (D) is not more than twice the depth of space charge region (L), i.e., D ≤ 2L, the electrical resistance of nanostructures would be governed predominantly by the size effects, and thus the better response performance may result [123]. The resultant performance could be further optimized for a certain size of 0D nanoparticles by surface modifications and control of arrangement periodicity and agglomeration degree [82, 127].

For chemiresistive gas sensors with sensing blocks composed of 0D nanostructures, their sensing mechanisms depend on catalyzing effects, surface and size effects, and spillover effects which are overseen by their sizes, surface properties, arrangement manners, and agglomeration degrees. Therefore, sensing
performances such as response, response/recovery kinetics, LOD, selectivity, and stability can also be re-designed and optimized by carefully considering these aspects. However, in most cases, 0D nanostructures are employed as sensing chips by combining with other nanostructures.

2.1.2. One-dimensional nanostructures

1D nanostructures with a high aspect ratio (length/width) are extensively explored in which semiconducting ones in single or ensemble can be widely adopted as the functional sensing units for gas sensors [131, 132]. The strong anisotropy in morphology allows one to investigate 1D electrical transport behaviors of individual objects conveniently because of the easier fabrication of single-object gas sensors compared to 0D nanostructures [87, 133, 134]. This would assist in better understanding the interactions between gas target and 1D nanostructures, the transport characteristics and mechanisms of carriers, and further the processes and principles of gas sensing [135, 136]. Individual 1D semiconductor nanostructures such as nanowires [137], micro/nanofibers [128], nanorods [138], and 2D and 3D architectures composed of 1D nanostructures demonstrate superior gas sensing performances, even at low temperatures (table 2) [139]. Zuo et al [128] reported the response (R_s/R_a) of 49.5 to 100 ppm triethanolamine (TEA) and the LOD of 2 ppm for 1D SnO_2 hollow fibers with the diameter of 8 μm and the shell thickness of 500 nm, which is attributed to the efficient gas diffusion enhanced by sufficient channels of this unique 1D hollow structures, as shown in figures 2(e) and (f). Pradhan et al [129] investigated the nanostructuring effects of CoP as branched nanowires, nanospheres, and nanorods for the VOCs sensing, as seen in figure 2(g). The CoP branched nanowires show a better frequency change (Δf) of 920 Hz to benzene gas compared to both the sensors composed of CoP nanospheres and nanorods due to the greater surface area. 1D 10 μm-long and 100 nm-wide single-crystalline black phosphorous (BP) nanowires were found to show the response four times that for bulk BP within the NO_2 concentration range from 10 to 400 ppm (figure 2(h)), which arises from their larger ratio of surface to volume [130]. Complete response and recovery with durations of 40 s and 160 s at 25 °C, respectively, were achieved for 1D WO_3 nanorods [140].

Size effects, surface effects, and planar and spatial arrangements of 1D nanostructures may significantly influence the performance of chemiresistors gas sensing with sensing blocks composed of 1D nanostructures. The unidirectional transport of charge carriers may endow the sensors with unique features and performances, which is different than 0D nanostructures. For example, the strong anisotropy of 1D nanostructures may favour the flow of gas targets along their longitudinal direction, especially in the case of unidirectional arrangements, which may lead to sufficient contact between gas molecules and sensing chips and thus possibly the improvement of performance. However, the catalyzing effect may not be as pronounced as that for 0D nanostructures in some cases due to the large size along the longitudinal direction. To think along this line, combining 1D and 0D nanostructures may result in synergistic effects such as catalyzing and spillover effects, which would improve the performance significantly.

2.1.3. Two-dimensional nanostructures

2D nanostructures such as nanofilms [49], nanoflakes [100], nanoplates [177], and nanosheets [75] were usually utilized as sensing units for chemiresistive sensors on account of their strong planar anisotropic morphologies, high surface-to-volume ratios [150], and abundant active sites [151, 178]. Recently, various researches are focusing on the emerging 2D materials, including metal oxides, metal chalcogenides, graphene, black phosphorous, boron nitrides, MXenes, etc. These materials are made of few (or non) layers and even a single layer composed with (or without) Van der Waals forces involved in their bulk structures, which can lead to more exposed surface atoms and stronger charge confinement in the 2D plane [4, 39, 85, 179]. This renders it possible to achieve far better sensing performances and even realize the highly effective detection of trace gas molecules. Yuan et al [75] proposed the chip-level pyrolysis of zeolitic imidazolate framework (ZIF-1) as the precursors of 1.45 μm thick ZnO nanosheets to substantially improve the oxygen vacancies, surface homogeneity, and thus gas sensing (figure 3(a)). The bandgap narrowing influenced by the modulation of oxygen vacancies, induced along with the high specific surface area of 53.4 m^2 g^-1 and larger average pore size of 14.4 nm, led to about two times enhanced response and shortened response and recovery times to 447 ppb CO at 300 °C (figure 3(b)). Co_3O_4 nanosheets network sensors with an average thickness of about 39.5 nm showed the outstanding performance to NH_3, with the LOD of 0.2 ppb at RT, and fast response (9 s) and recovery (134 s), as shown in figure 3(c), ascribed to the porous 2D network structures [151]. The 2D WO_3 nanoplates were found capable of detecting 1 ppm NO_2 with the optimal response (R_s/R_a) of 131.75 to 100 ppm at 100 °C, accompanied by weak recovery, as seen in figure 3(d) and table 2 [153]. The weak recovery of the 2D WO_3 nanoplates at low temperatures may be related to the strong binding of NO_2 molecules on their surfaces, unfavourable for their gas sensing applications at low temperatures [36, 153].

As an important type of 2D layered semiconductors, MX_2 (M = Mo, Sn, Mn, or W and X = S, Se, Te, etc) and MXene-(Ti_3AlC_2) [185] are quite intriguing and promising as sensing chips for gas sensors because of their
Table 2. Summary of gas sensing performance parameters for selected chemiresistor and FET sensors published in the literatures.

| Materials | Morphology | Test gas | Concentration | Temp.(°C) | Response | Detection limit | Res/rec time (s) | References |
|-----------|------------|----------|---------------|-----------|----------|----------------|-----------------|------------|
| **1D chemiresistor sensors** | | | | | | | | |
| CuO | nanowires | NO₂ | 100 ppm | RT | 13% | 100 ppm | 60/270 | [83] |
| CuO/CuO | nanorods | NO₂ | 5 ppm | RT | 93.5% | 400 ppb | 85/511.2 | [58] |
| CuO | nanowires | CO | 30 ppm | 325 | 27.6% | 1 ppm | — | [141] |
| CuO | nanowires | H₂S | 100 ppm | 160 | — | 500 ppb | — | [135] |
| h-MoO₃ | nanorods | NH₃ | 10 ppm | 200 | 41% | 5 ppm | 202/241 | [138] |
| NiO | nanotubes | Tulene | 5 ppm | 275 | 10% | 5 ppm | 10/24 | [139] |
| ZnO | nanowires | Acetone | 100 ppm | 375 | 150% | 250 ppb | 64/349 | [142] |
| h-ZnO | nanotubes | Ethanol | 700 ppm | RT | 64% | 10 ppm | 274/92 | [143] |
| W₁₆O₁₉ | nanowires | NH₃ | 200 ppm | RT | — | 100 ppb | — | [144] |
| Te | nanotubes | NO₂ | 1 ppb | RT | 5000 | 0.5 ppb | 300/300 | [145] |
| SnO₂ | nanotubes | NO₂ | 9.7 ppm | RT | 89.2% | 9.7 ppm | 6/218 | [136] |
| SnO₂ | nanorods | NO₂ | 5 ppm | 150 | 5310 | 125 ppb | 150/— | [146] |
| Au-ZnO | nanowires | H₂S | 10 ppb | RT | 80% | 1 ppm | — | [147] |
| Pd-ZnO/ZnS | nanowires | H₂S | 10 ppm | 200 | 4491% | 2 ppm | 61/62 | [148] |
| **2D chemiresistor sensors** | | | | | | | | |
| ZnO | nanoplates | ethanol | 100 ppm | 380 | 790% | 100 ppm | 32/17 | [149] |
| ZnO | nanosheets | CO | 447 ppb | 300 | 2490% | 20 ppb | — | [73] |
| SnO₂ | nanosheets | Acetone | 1 ppm | 280 | 740% | 200 ppb | — | [4] |
| Co₉O₄ | nanotubes | Acetone | 100 ppm | 150 | 1040% | 1 ppm | — | [150] |
| Co₉O₄ | nanosheets | NH₃ | 20 ppm | RT | 130% | 200 ppb | 204/835 | [151] |
| CuO | nanosheets | H₂S | 200 ppm | RT | 401% | 10 ppb | 336/543 | [152] |
| WO₃ | nanotubes | Acetone | 20 ppm | 300 | 1310% | 1 ppm | 4/8 | [36] |
| WO₃ | nanotubes | NO₂ | 5 ppm | 100 | 900% | 1 ppm | — | [153] |
| α-MoO₃ | nanotubes | Xylene | 100 ppm | 370 | 1820% | 10 ppm | 1/15 | [154] |
| In₂O₃ | nanosheets | NO₂ | 10 ppm | 120 | 21 200% | 10 ppb | 4/— | [155] |
| MoS₂ | nanoflakes | NO₂ | 0.5 ppm | RT | 20.1% | 500 ppb | — | [100] |
| WS₂ | nanosheets | NO₂ | 6 ppm | RT | 361% | 200 ppb | — | [156] |
| WS₂ | nanosheets | NO₂ | 50 ppb | RT | 406% | 50 ppb | 50/1050 | [157] |
| MoS₂ | nanosheets | NO₂ | 500 ppm | RT | 213% | 100 ppm | — | [158] |
| MoS₂ | layered | NO₂ | 10 ppm | RT | 80% | — | — | [159] |
| MoS₂ | layered | NO₂ | 200 ppb | 100 | 54% | 200 ppb | 400/303 | [160] |
| MnPS₃ | few-layered | NO₂ | 2 ppm | RT | — | 50 ppb | 96/220 | [161] |
| CNTs/MoS₂ | nanosheets | NO₂ | 50 ppm | 75 | 17.53% | 3 ppm | 365/1950 | [162] |
| Graphene | nanomesh | NO₂ | 1 ppm | RT | 6% | 1 ppm | 420 s/— | [40] |
| Graphene | nanoribbons | ethanol | 500 ppm | 100 | 1200% | 50 ppm | — | [163] |
| Graphene | NO₂ | 5 ppm | RT | 12% | 1 ppm | 328/1941 | [164] |
| **2D FET sensors** | | | | | | | | |
| Re₀.₃Nb₀.₇S₂ | layered | NO₂ | 5 ppm | RT | 401.86% | 50 ppb | 245/504 | [165] |
| MoS₂/Al₂O₃ | layered | NO₂ | 2 ppm | RT | 62% | 500 ppb | — | [111] |
| Phosphorene | nanosheet | NO₂ | 20 ppb | RT | 190% | 20 ppb | — | [166] |
| MoS₂/SnO₂ | nanosheets | NO₂ | 500 ppb | RT | 0.6% | 500 ppb | — | [167] |
| Pt-BP | layered | H₂ | RT | 50% | 2000 ppm | — | — | [43] |
| rGO | Methanol | 150 ppm | 100 | 127.93% | 50 ppm | — | — | [168] |
| MoS₂ | layered | H₂ | 200 | >800% | — | — | — | [169] |
| Pd-graphene | H₂ | 5 ppm | — | — | — | — | — | [170] |
| MoTe₂ | layered | NH₃ | 70 ppb | RT | 101% | 70 ppb | 1s/— | [171] |
| BP/BN/MoS₂ | layered | NO₂ | 100 ppm | RT | >100% | 10 ppb | — | [172] |
| Graphene | NH₃ | 100 ppb | RT | 12% | 85 ppb | — | — | [66] |
| ZnPc | nanobelts | NO₂ | 10 ppm | RT | 220% | 50 ppb | — | [173] |
| SnO₂/Gr | H₂ | 100 ppm | 50 | 500% | 1 ppm | 1.1/1.1 | [174] |
| MoS₂ | layered | NO₂ | 2 ppm | RT | 25% | 25 ppb | 10/— | [175] |
| TiO₂/GR | NH₃ | 25 ppm | RT | 16.4% | 25 ppm | — | — | [176] |

Response (%) = (ΔS/S) × 100; S = Current, resistance or conductance.
Figure 3. Structures, morphologies, and performances of 2D (a)–(h) and 3D (i)–(l) based chemiresistors. (a) SEM image, (b) density of states (DOS), and the response of ZnO nanosheets to CO (300 °C), adapted with permission from [73]. Copyright 2019 Wiley–VCH Verlag GmbH & Co. KGaA, Weinheim. (c) RT dynamic response–recovery curve of Co3O4 nanosheets sensors exposed to NH3, adapted with permission from [151]. Copyright 2016 Elsevier B.V. (d) Response of WO3 nanoplates sensors to NO2 at 100 °C, adapted with permission from [153]. Copyright 2016 Elsevier B.V. (e) HRTEM image, photograph, and configuration design, (f) assembly of flexible wearable NO2-detection wristband system composed of microcontroller board, breadboard, LEDs, and resistors with the circuit design of NO2 detection in the inset, (g) dynamic gas sensing profile of WSe2(0.96)Se(1.04) layered sensors upon exposure to different NO2 concentrations, adapted with permission from [180]. Copyright 2018 American Chemical Society (h) Response performance of layered SnSe2 upon exposure to 1 ppm NO2 and 40 ppm NH3, adapted with permission from [181]. Copyright 2019 American Chemical Society. (i) SEM image, (j) transient response of 3D In2O3 sensors to NO2 at 150 °C, adapted with permission from [182]. Copyright 2021 American Chemical Society. (k) Transient response of 3D nanoflowers SnO2 sensors to ethanol, adapted with permission from [183]. Copyright 2014 American Chemical Society. (l) The 1 ppm H2S selectivity of 3D porous CuO sensors against the 100 ppm others at 190 °C, adapted with permission from [184]. Copyright 2012 American Chemical Society.

high susceptibility, strong chemical surface activity and relatively easy preparation [156]. Recently, Moumen et al reported the response of 361% for 6 ppm NO2 at RT and good stability within nine months for 2D bilayer 2H-WS2 prepared using liquid exfoliation technique, which has great potentials as breath biomarker analyzers for early diagnosis of asthma and other related diseases [156]. Furthermore, the incorporation of sulfur with W and Se via CVD to form the sulfurized WS0.96Se1.04 alloys, which is flexible, low-power, and wearable, shows over 2.4 times enhanced response (2621%) to 500 ppm NO2 at RT compared to the WSe2 sensor, as shown in figures 3(e)–(g) [180]. First principle calculations revealed the transfer of electrons from SnSe2 to NO2, but the reversed transfer for NH3 [181]. This reveals the lower adsorption energy of NO2 (−293 and −296 eV for monolayer and bilayer SnSe2, respectively) relative to NH3 (−181 and −176 eV for monolayer and bilayer SnSe2, respectively), which agrees very well with the experimental results, as shown in figure 3(h) [181]. The vertically oriented trilayer MoS2 nanoflakes prepared using a catalyst-free CVD approach showed the response of 20.1% at RT and the response of 1.73% at 150 °C to 0.5 ppm NO2 and the LOD as low as 42 ppb with excellent selectivity, which is attributed to the vertically oriented 10 nm-thick 2D networks morphology composed of about three layers and 150 nm in size [100]. Unfortunately, full recovery was never appreciated at RT unless extra heating is applied (say, 150 °C). In fact, additional energy supplies such as thermal or light sources are normally required to improve the recovery behaviors, which will be discussed later. Kumar et al showed a very high response of 9530% to 35 ppm NO2 and a theoretical LOD of 9.5 ppb with high selectivity and full reversibility at RT for exfoliated few-layered MnPS3 sensors [161]. The excellent performances can be attributed to the synergetic effects of phosphorous and sulfides, which deserve further study as gas sensors.

Another important 2D material, graphene and its derivatives as gas sensors, was revealed to have exceptional sensitivity to toxic gaseous molecules with ppb detection levels [186–188]. A self-activated and flexible graphene-based chemiresistor is highly sensitive and selective to NO2 with reversibility at RT [164]. The common major challenge for graphene and its derivatives-based gas sensors is long response and recovery durations such as 328 and 1941 s, respectively [164]. However, the slow recovery and response could be alleviated greatly by functionalizing the freestanding graphene sensor surface with hydrophilic oxygen group
and the hydrophobic benzene ring, leading to ultrafast response and recovery times of even down to 50 ms for humidity detection [189]. Some selected sensing materials are given in table 2 for comparison.

2D nanostructures were utilized as sensing units for chemiresistors with high performance due to their structural uniqueness, high surface area, and layer-dependent electronic properties. The strong interactions between gas and 2D nanostructures, especially with atom-layer thicknesses due to adequate and fast contact, may cause the sensors to recover sluggishly, which is unfavorable for practical applications. Therefore, the introduction of alien nanostructures, extra energy supplies, and functionalization may be necessary for performance improvement in terms of catalyzing effects and the formation of heterojunctions, which may need to be considered upon the design.

2.1.4. Three-dimensional nanostructures

3D nanostructures, including nanoflowers [69], microcubes [77], microspheres [78], and hierarchical nanostructures ensembles [80] assembled from 0D, 1D and 2D nanostructures are characterized by high specific surface areas [33] and rich micro/mesopores [190] which show the potential of improving the response performance and response/recovery kinetics as chemiresistive sensors [69, 96, 182, 191]. 3D porous In2O3 microcubes were reported to exhibit an outstanding NO2 gas sensing performance with fast equilibrium surface reactions at 150 °C, as shown in figures 3(i), (j), which can be ascribed to the unique 3D porous morphology, the high surface area of 25.48 m² g⁻¹, suitable pore radius of 6.2 nm, rich oxygen vacancies, and high conductivity [182]. 3D-rGO showed a response of 65% to 20 ppm NO2, roughly three times that of 2D-rGO [192]. Liu et al [183] reported response and recovery times of about 1 and 2 s, respectively, for 3D SnO2 nanoflowers made of intermingled ultrathin nanosheets as smart ethanol sensors (figure 3(k)), much shorter than the corresponding ones of bulk structures, which arises from the special hierarchical 3D nanostructures [183]. Again, 3D porous CuO hollow spheres exhibited excellent H2S sensing performances, such as short response/recovery time of 3/9 s, high sensitivity at the ppb level, excellent selectivity, and LOD of 2 ppb, being ascribed to their unique 3D porous morphology composed of nanosheets assembled by primary CuO nanograins and quasi-single crystals (figure 3(l)) [184]. This kind of porous structure could significantly improve the sensing performance by facilitating gas penetration due to gas diffusion length reduction through adequate particle-to-particle contacts [184]. Therefore, 3D porous hierarchical structures are promising for high-performance chemiresistive gas sensing units by optimizing porosity and agglomeration [69, 193, 194].

2.2. Field effect-transistor (FET)

FET gas sensors, including gate, source, drain, and channel (sensing unit), may have better performance compared to chemiresistive sensors since multiple parameters are tunable such as gate bias voltage (Vbias), field-effect mobility (μFET), and certainly, drain current (Ids) upon detection of gas molecules [195]. Three-terminal FET gas sensors can detect trace gas molecules even at RT by applying gate bias voltages to reasonably modulate the carrier concentration in the sensing units even by orders of magnitude. In contrast with chemiresistors, FET gas sensors are more difficult to be fabricated, which may need to employ focused ion beam (FIB), electron beam lithography (EBL), photolithography, and other structuring techniques (shadow mask and etching etc). These may require to design of sensing blocks, FET configuration, fabrication processes and even integration techniques beforehand, which makes it less realistic for FET sensors as a preliminary test platform for novel sensing materials, as shown in table 1. However, FET-based sensors show their strengths such as precise miniaturization and cross-reactive sensor arrays, which thus allows for the development of more powerful functions of sensors and better integration with wearable electronics for IoT and IoT and other platforms [37, 114]. To date, FET-based sensors with various nanostructured sensing units are receiving considerable attention for detection of toxic gases [51, 196–198]. This section will be focused on the discussion of FET type sensors based on 0D, 1D, 2D, and 3D sensing blocks.

2.2.1. Zero-dimensional nanostructures

0D nanostructures were used in FET sensors focusing on metallic nanoparticles or clusters (such as silver, gold, copper, zinc, iron, titanium, and silicon), which aims to promote electronic mobility, catalytic effects, chemical sensitization and electronic sensitization [199]. When their sizes get close to the Debye length, 0D nanostructures would fully contribute to sensing performance by being completely depleted [200]. Jeong et al [114] reported 12 nm thick SnO2 thin-film transistor (TFT) and chemiresistors sensors for NOx at RT, as shown in figures 4(a), (b) [114]. When operated in the subthreshold region, the TFT SnO2 sensors showed a response (ΔR/R) of 19.4 at RT with superior selectivity, far higher than that of two-terminal chemiresistive sensors, 2.8 (figure 5(c)), which evidences the strength of TFT sensors by applying a gate voltage. Yun et al [201] successfully fabricated ZnO nanoparticles FETs for NH3 gas sensors by controlling the atomic layer deposition (ALD) temperatures and the cycles conditions from 140 to 160 °C and 5 to 30 cycles, which showed a sufficiently good
response to NH$_3$ upon exposure for 10 min at 150 °C. This was attributed to the combination of device configuration and ZnO nanoparticles [201]. Kim et al discovered that the H$_2$ gas sensing performances of nanoporous Pd-based FET were much higher than those of the plain Pd-FET sensors due to the nano-porosity and catalytic effects as shown in figure 4(d) [202].

2.2.2. One-dimensional nanostructures

Different 1D nanostructures of nanorods [205], nanowires [206], nanotubes [207], and nanofibers [118] are commonly used as sensing units for FET gas sensors and extensively explored, particularly as a prototype device with single objects as sensing chips. There are diversified 1D nanostructured materials, including metals [208], metal oxides, sulfides and nitrides [209], carbon nanotubes, and fibers [113], conductive polymers [210], and even their combinations. Recently, In$_{Yb}$O$_2$ nanofibers FET was reported to show enhanced stability and response to ethanol from 10 ppm due to the high mobility of 6.67 cm$^2$ V$^{-1}$ s$^{-1}$, and the acceptable threshold voltage of 3.27 V, as seen in figures 4(e), (f) [203]. Also, In$_{Yb}$O$_2$ nanofibers FET exhibit a response ($\Delta I/I$) of 89 to 2000 ppb N, N-dimethylformamide (DMF), fast response (36s) and recovery (67s), and quite a low LOD of 5 ppb with a charge carrier mobility of 6.18 cm$^2$ V$^{-1}$ s$^{-1}$, a threshold voltage of 3.08 V and an on/off current ratio of 10$^4$ [118]. Song et al [204] reported a 70 nm thick back gated SnNW-FET sensor fabricated via low-cost step-guided in-plane solid-liquid-solid growth (figure 4(g)), which exhibited a high response of 75.8% for 100 ppm NH$_3$, LOD of 100 ppb, fast response, and recovery of 20 s, excellent selectivity, and outstanding stability over 180 days at RT. Yang et al demonstrated that the carboxyphenylboronic acid (CPBA) modified SnNW-FETs could detect as low as 13 ppm dimethyl-methylphosphonate (DMMP) with a fast response of 100 s and a theoretical LOD of 100 ppb, respectively [211]. Singh et al [206] fabricated a novel cylindrical gate In$_{1-x}$Ga$_x$As nanowires FETs for H$_2$ and O$_2$ sensing. They found that the sensitivity to H$_2$ and O$_2$ increases with an increase (a decrease) in the In$_{1-x}$Ga$_x$As nanowires channel length (radius) [206]. Nickel-based MOF (Ni$_3$HHTP) nanorods FET sensors with carrier mobility of 8.5 \times 10^{-2} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} and a threshold voltage of 0.6 V could respond to SO$_2$ with a concentration as low as 627 ppb within 13 s and recover within 32 s [205]. The Pd nanoparticles decoration of carbon nanotube back-gated FET sensors could lead to a vanished gate dependence and a decrease in current upon detection of H$_2$, which results from the electric field screening effects of Pd nanoparticles to preclude the effective tunning of the CNT current at the particular gate voltage responsible for on/off states of the device [42]. Meanwhile, the CNT functionalized with 1 nm Pd nanoparticles could achieve the highest response ($\Delta R/R$) of 1000 to 311 ppm H$_2$ within 7 s, and a LOD of 890 ppb at RT as shown in figure 4(h) [42]. Zhuo et al reported the enhanced H$_2$ gas sensing with a maximum response of 13000% to 100 ppm H$_2$ and a LOD of 90 ppb at RT for the Pd modified CNT FET H$_2$ sensors by optimizing the thickness of Y$_2$O$_3$ dielectric layers [207].

![Figure 4. FET sensors based on 0D (a)–(d) and 1D (e)–(h) nanostructures. (a) SEM image, (b) schematic configuration of typical FET sensors, (c) NO$_2$ responses of chemiresistor and FET SnO$_2$ sensors, adapted with permission from [114]. Copyright 2019 Elsevier B.V. (d) Response of Pd nano-porous FETs sensors to H$_2$, adapted with permission from [202]. Copyright 2015 Elsevier (e) SEM image, (f) comparison of responses of In$_{Yb}$O$_2$ nanofiber FET and chemiresistor sensors, adapted with permission from [203]. Copyright 2020 American Chemical Society. (g) Response curves to NH$_3$ for SiNW-FET sensors, adapted with permission from [204]. Copyright 2021 American Chemical Society. (h) Response to H$_2$ for CNT-FET hydrogen sensors, adapted with permission from [42]. Copyright 2018 American Chemical Society.](image-url)
Numerous 2D nanostructures [173], including metals, metal oxides [176], metal chalcogenides [175], graphene and its derivatives [187], black phosphorous (BP), phosphorene [212], boron nitrides (BN) [172], their combinations [170] and Ti$_3$C$_2$Tx—MXenes [213] are potential candidates as sensing blocks for FET gas sensors due to their intrinsic and tunable properties, designability and compatibility with traditional semiconductor processes [165, 168, 197]. The superior tunability of charge carrier concentrations and transport for 2D nanostructures, especially atom-layered ones, allows optimizing the performance of FET-based gas sensors [187]. A single/double-layered Ti$_3$C$_2$Tx—MXenes FET sensor exhibited a fast response of 1 s and realized strong selectivity to alkali in terms of a strong anti-interference to a high-ionic-strength environment [214]. Moreover, the better surface carrier mobility for Ti$_3$C$_2$Tx—MXenes FETs could be achieved through tailoring the work function by doping NH$_3$ [215].

Graphene-based FET sensors have proven highly sensitive to various gaseous species (including VOCs), while the poor identifiability of gas molecules species precludes their practical applications [216–218]. Vertically oriented graphene-based FET sensors were demonstrated to be highly sensitive to both NH$_3$ and isoprene with the minimum detectable concentrations of 86 ppb and 420 ppb, respectively. The sensitivity, LOD, and recovery kinetics could be further improved by UV light irradiation [66]. Also, hybridizing graphene with other nanostructured materials or chemicals may improve the gas molecular identification and stability of graphene FET-based sensors. The 1 nm Pd-modified graphene FETs sensors can detect 100 ppb H$_2$ and the detection sensitivity of H$_2$ is highly dependent on the Pd nanostructures involved [170]. TiO$_2$/graphene hybrid FET sensors could realize the switch between n- and p-working mode for NH$_3$ by varying the back gate voltage from $-75$ V to $100$ V, as shown in figures 5(a)–(c), making it possible to identify gas species with different natures [176]. Nozaki et al. reported ppb level detection of ethanol with an estimated LOD of 60 ppt for single-stranded-DNA-modified graphene FETs sensors via the positive and negative shift of the transfer characteristic curves upon adsorption of ethanol [219]. Gajjarushi et al. [220] reported an ultrasensitive (down to 4 ppb) and rapid (40 s) detection of TNT (2,4,6-trinitrotoluene) for the covalent (ZnTTPOH) functionalized graphene Zn-GFETs sensors through the shift of the Dirac point extremely sensitive to the number of the nitro groups of TNT. The ultrasensitive TNT detection is synergistically governed by monolayer graphene acting as an effective transducing channel and ZnTTPOH as the chemically selective receptor [220]. Graphene FET sensors showed 5.3 times enhanced response performance and a theoretical LOD of 4.8 ppb to NO$_2$, by ultrathin polymer brush modification, which leads to a 3.5 times increase in field-effect hole-mobility ($2216 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) than that (628 cm$^2$ V$^{-1}$ s$^{-1}$) of bare graphene FET [221].

2D Metal chalcogenides, black phosphorous (BP), boron nitrides, etc. are quite popular for low-cost FET gas sensors. The Schottky diodes of α-MoTe$_2$ realized the response of 101% to 70 ppb NH$_3$ within 1 s [171]. The sensitivity of MoS$_2$ sensors could be enhanced by a shift of the threshold voltage towards the negative direction by H$_2$ adsorption as a result of the monotonic increase of MoS$_2$ conductivity with H$_2$ concentration, as seen in figure 5(d) [169]. Except for heterostructures or surface modifications by alien materials, the IT/2H MoS$_2$

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Image: Figure 5. FET sensors based on 2D (a)–(d) and 3D (e)–(h) nanostructures. (a) Schematic diagram of FET sensors with different areas of sensing units, (b) transfer characteristics curves, (c) response to 25 ppm NH$_3$ for TiO$_2$/Graphene FETs sensors, adapted with permission from [176]. Copyright The Royal Society of Chemistry 2020. (d) Response plots as a function of gate voltage at 200°C for monolayer MoS$_2$ FET H$_2$ sensors, adapted with permission from [169]. Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) SEM image, (f) selectivity test to H$_2$ for GaN FET sensors, adapted with permission from [222]. Copyright 2021 Elsevier B.V. (g) Schematic configuration of 3D Ag NP/rGO FET sensors, (h) transient current to 20 ppm NO$_2$, adapted with permission from [86]. © 2020 IOP Publishing Ltd All right reserved.
heterostructuring kinetics, LOD, selectivity, repeatability, and low operating temperatures. Various strategies including Signiﬁcant performance enhancement strategies heterophase FET sensors also show excellent performance with a response of 25% to 2 ppm NO₂ at RT in a very short time of 10 s and a LOD of 25 ppb [175]. Pt-functionalized BP with a back gated FET configuration exhibited a fast response/recovery to H₂, a high sensitivity over 50%, and excellent repeatability at RT [43].

Though many strengths for 2D nanostructures as sensing units were demonstrated and applying a gate voltage for FET sensors could to some degrees ameliorate the recovery kinetics, the relatively sluggish recovery kinetics is still quite challenging. Again, as usually done to chemiresistors, extra energy supplies such as heating or light illumination may be necessary to improve the recoverability of 2D FET gas sensors, which, however, would increase the complexities of operation at RT, fabrication, and thus the cost. Therefore, new strategies are requisites to improve the recovery kinetics. For example, for graphene-based sensors, applying alternative circuit signals (AC, high-frequency input) instead of direct circuit signals (DC) was found capable of enhancing the recovery kinetics greatly [223].

2.2.4. Three-dimensional nanostructures
Sensing units comprised of 3D nanostructures are endowed with enhanced diffusivity of gas molecules, which could improve gas sensing performance. To date, several techniques have been used to fabricate the 3D nanostructures for FETs gas sensing [86, 222, 224–227]. Novel honeycomb nanonetwork GaN in FET configuration showed an ultrafast H₂ response of 3 s with superior sensitivity and a quite low LOD of 34 ppb H₂, which is attributed to the significant reduction in Schottky barriers (ﬁgures 5(e), (f)) [222]. Yin et al [86] fabricated novel 3D microtubular FET sensors based on rGO decorated with Ag nanoparticles shown in ﬁgures 5(g), (h), which exhibited a response of 4.92% to 20 ppm NO₂ within 116 s and good repeatability. Vertically grown nanoflakes networked MoS₂ FET sensors fabricated using chemical-vapor-deposition (CVD) technique showed signiﬁcant potentials sensing to both ethanol and methanol [225]. Wongrat et al [224] reported that FET sensors of networked ZnO nanostructures prepared using RF sputtering showed appreciable ethanol sensitivity at RT with a response twice that of 2D ZnO nanostructures.

3. Performance enhancement strategies
Signiﬁcant effort has been made to improve the performances of gas sensors such as response and recovery kinetics, LOD, selectivity, repeatability, and low operating temperatures. Various strategies including heterostructuring [228, 229], nanopatterning [230, 231], heating [232, 233], external photo- or electrical-ﬁeld excitation [234–236], and others (piezotronics, piezo-phototronics, catalytic combustion, conductometric Raman spectroscopy, spin-orbitronics) [237, 238], were attempted to enhance the gas sensing performance further. Heterostructuring and nanopatterning of sensing units are actually associated with tailoring or modiﬁcations of physical, chemical, and structural properties, morphology, and surfaces [57, 58]. While, extra energy supplies such as photoactivation or excitation, heating, and electrical ﬁeld loading would greatly change both the physical and chemical properties of sensing units instead of structures and morphologies [234]. This section will brieﬂy discuss the strategies of performance enhancement of 0D, 1D, 2D, and 3D nanostructured sensing units.

3.1. Heterostructures
Many approaches were proposed and implemented to prepare promising heterostructures for high-performance gas sensors resulting from their unique structures, physical and chemical properties, and morphologies [46, 228, 239, 240]. It was anticipated that sensing materials with poor gas sensing performance, inert structures, or non-reactive morphologies could be hybridized with catalytic materials to form the heterojunctions (with the desired 0D, 1D, 2D, and 3D nanostructures), which in a sense can improve/activate the gas sensing performance due to various nanostructuring effects [229, 241]. For example, Cheng et al [94] prepared 0D carbon dots hybridized with In₂O₃ for sensing NO₂ with a response of about 4 times that of pristine In₂O₃, accompanied by a reduction of working temperature, which is due to high activity of the surface edges of 0D–carbon dots and the formation of heterojunctions, as seen in ﬁgures 6(a), (b). Ultrathin 0D Au nanoparticles of ca. 6.6 nm decorated mesoporous ZnO nanospheres showed superior performance of sensing ethanol with $R_s/R_p = 159$ for 50 ppm at 200 °C (ﬁgure 6(c)), which could be attributed to the synergistic effects of classical catalytic reactions, strong chemical and electrical sensitization, and spillover effects of Au nanoparticles [242].

Vertically aligned 1D nanorods of Cu₃Mo₂O₉@CuO p–p heterojunction sensors exhibited a high response of 160% to 5 ppm NO₂, an excellent sensitivity of 50% ppm⁻¹, low LOD of 2.30 ppb, a short response time of 49 s, and a rapid recovery time of 241 s at RT (ﬁgures 6(d), (e)), evidently better than those for CuO@CuO homojunction sensors [58]. The superior NO₂ sensing performance of Cu₃Mo₂O₉@CuO sensors is attributed to the Schottky heterojunction formed between $p$–Cu₃Mo₂O₉ micro/nanorods and $p$–CuO films, the catalytic effect, and the anisotropic nature of Cu₃Mo₂O₉ micro/nanorods [58]. Suh et al reported the vertically aligned
decorated p-NiO on p-Co3O4 nanorods prepared by multiple-step glancing angle deposition with an improved response to 50 ppm ethanol, 16.7 times that of bare p-Co3O4 nanorods at 350 °C, as shown in figure 6(f) [243]. Here, the performance enhancement arises from a synergistic effect of the formation of p-p heterojunctions, increased active sites, and catalytic effects of NiO [243]. The Au functionalization of 1D ZnO nanowires led to the enhanced H2S sensing performance with the lowest detection limit of 10 ppb and theoretical LOD of 500 ppt due to the spillover effect of Au nanoparticles [147]. Pd decorated ZnO/ZnS nanowires also showed a good response of 4491% to 10 ppm H2S with fast response and recovery of 61 and 62 s, respectively, at 200 °C as a consequence of the catalytic effects of Pd nanoparticles [148]. n-n TiO2/Au0.35V2O5 based gas sensors with novel branched nanoheterostructures showed a response increment by a factor of about 9 for 100 ppm ethanol, faster response/recovery (7/8 s), and better selectivity compared to the TiO2 nanofibers-only sensors [244]. The performance enhancement arises from the n-n nanostructured heterojunctions, the unique branched structures, and the increase in the surface area [244]. Zou et al [199] found that Au, Ag, and Pt-decorated Mg-doped In2O3 nanowires FET sensors could be taken as a fast gas sensing platform with a detectable limit down to sub-ppm level by reducing the conductance and shifting the threshold voltage positively due to the spillover effects of the metallic nanoparticles [199]. Particularly, Au decorated samples exhibited more than 3 orders of magnitude increase in response for 100 ppm CO at optimized VGS = 0 V and RT relative to the other test gases, confirming the superior catalytic activity of Au nanoparticles to CO [199].

2D heterostructured MoS2/VS2 (figures 7(a), (b)) exhibited an excellent sensitivity towards NH3 with a higher adsorption uptake of 344.5 Hz upon exposure to 5 ppm NH3 compared to the pristine MoS2 or VS2, which is attributed to the heterojunction between two sensitive nanostructures [245]. Cui et al [167] reported that MoS2 decorated with SnO2 nanostructures to form the MoS2/SnO2 heterostructures could be used for practical sensing of NO2. 2D MoS2-MoO3 hybrid sensors exhibited a high response of 33.6% to 10 ppm NO2 within 19 s, full reversibility, and superior selectivity to NO2 against other selected gases, which was caused by the combined effects of highly efficient hole injection from n-MoO3 to n-MoS2 and the effective modulation of the barrier height, as displayed in figure 7(c) [246]. MoS2/ZnO hetero-nanostructures formed by surface modification of MoS2 nanosheets with ZnO nanoparticles had an excellent response of 3050% to 5 ppm NO2, 11 times that for the pristine MoS2 nanosheets, which is attributed to the nanojunctions and the unique 2D morphology [247].

A 3D Pd-loaded quintuple-shell Co3O4 heterostructures (figure 7(d)) exhibited good selectivity to toluene and xylene with Rs/Rn of 30.8 and 64.2, respectively [103]. 3D hollow nanospherical Fe-WO3 showed a quite low detectable limit of 10 ppb for NO2 (figure 7(e)) and outstanding selectivity [248]. The 3D hollow quasi-graphite capsule/polyaniline (GCs/PANI) hybrids exhibited a response of Rs/Rn = 1.3 to 10 ppm NH3 and rapid
Hierarchical core-shell heterostructures composed of NiO shell deposited onto stacked-cup carbon nanotubes (SCCT) were reported for low concentration ethanol and acetone gas sensing (figure 7(f)) at 200 °C [104]. The 200NiO-SCCT with 6.4 nm NiO shell layer shows the superior response performance due to the matching of the Debye length (\(\lambda_D\)) with a coating thickness of 6.4 nm [104]. Brush-like SnO\(_2@\)ZnO hierarchical heterostructures via the epitaxial growth of SnO\(_2\) nanowires on the non-polarized plane of ZnO nanorods with a six-fold symmetry showed much-improved performance such as ultrafast response, broad detection range, superior selectivity, and LOD of 5 ppb at 150 °C relatives to SnO\(_2\) or ZnO only, which is mainly ascribed to the presence of multi-junctions [81].

### 3.2. Nanopatterning

Structural nanopatterning is one of the dominant manners for tailoring materials geometry and dimensions to realize particular functions and performances of devices in terms of state-of-the-art fabrication technologies [7, 250]. Nanopatterning requires high precision and accuracy for well-defined structures even with atomic size levels, which is quite popular in fabricating gas sensors [120]. According to the space charge layer theory, sizes of nanostructures may need to go down to sub 10 nm for maximization of sensing performance, suggesting effective contributions from all nanostructures [251, 252]. In addition, the design and fabrication of particular 0D, 1D, 2D, and 3D nanostructures with sufficiently high resolutions may facilitate effective transport, diffusion, and adsorption of gas and further their interactions [48]. Figures 8 and 9 summarize some nanopatterning strategies in gas sensors to enhance sensitivity, response and recovery kinetics, and LOD [7, 132, 250–252].

Novel Pd nanopatterned sensors with sizes of 5 nm and gaps of 2 nm showed enhanced H\(_2\) detection performance with LOD of 2.5 ppm, which is attributed to ultrafine Pd grain sizes, unique high-aspect-ratio of 25.73, and high-resolution morphology, and the interfaces, as displayed in figures 8(a), (b) [251]. Inkjet-printed Pt-In\(_2\)O\(_3\) humidity sensors displayed a fast response of 32% within 58 s for 18% RH (figure 8(c)) [117]. Cho et al fabricated high-resolution CuO and NiO nanopatterned sensors with an ultrathin 14 nm-thick, a high aspect ratio of about 25, and structures composed of ultrafine grain sizes of about 5 nm (figures 8(d)–(f)) [132]. Relative to the films, the responses (\(\Delta R/R_0\)) to 1 ppm hexane for CuO (figure 8(e)) and NiO (figure 8(f)) sensors are 5 and 30, respectively [132].

Large area nanopatterned MoS\(_2\) nanomesh sensors exhibited an enhanced NO\(_2\) gas sensing performance at RT (figures 9(a), (b)) with high resistance to humidity [120]. Nanopatterned Pd/Co/Pd gas sensors improved the sensitivity and response kinetics for H\(_2\) even in the absence of an external magnetic field relative to the previous ones [252]. Choi et al reported a dramatic improvement in response by a factor of about 7.3 to 125 ppb
acetone for nanopatterned CuO/Cu2O/Ag sensors, which arises from a high structure resolution of 30 nm, the high aspect ratio of about 12, and narrow boundaries of about 10 nm of CuO/Cu2O nanopatterns, and spillover effects of Ag nanoparticles [106]. Also, nanopatterned 20 nm-thick WO3/CuO p-n heterojunctions with a high aspect ratio (> 10) exhibited a response of 12 times that for nanopatterned WO3 sensors only and ultralow LOD of 94 ppt for ethanol [8].

Nanopatterned sensors have been real-time applied for the long-awaited IoT. Tang et al fabricated fully integrated smartphone sensors based on the flexible nanowires for real-time NH3 detection in food grading with robust flexibility, mechanical durability, high selectivity, reproducibility, enhanced response, low power of...
about 3 μW, and LOD of 100 ppb, as illustrated in figure 9(c) [27]. Portable and integrated chemo-mechanically nanopatterned Pd sensors can detect and produce an alarm in the presence of H₂ gas (figure 9(d)). Again, nanopatterned integrated wireless smartphone transparent sensors of Au–SnO₂ nanofibers exhibited high selectivity, sensitivity, repeatability, and LOD of 6 ppb for NO₂ at RT (figures 9(e), (f)) [85]. Therefore, the strategy of nanopatterning is believed to be a critical next move in the practical application roadmap of gas sensors, especially for IoT [7, 8, 120, 251–253].

3.3. Heating

Here, heating is referred to as the elevation of the sensors working temperature [254]. The effect of temperature on gas sensing performance is primarily reflected in the diffusion of gas molecules, including adsorption and desorption, activation of charge carriers of sensing units, and their interactions. The temperature elevation could favor the reactions between gas molecules and sensing blocks and enhance the electrical conductivity of semiconducting sensing blocks to some degrees [141, 255]. As a result, optimal performance such as enhanced sensitivity and response/recovery kinetics may be achieved at an appropriate temperature which depends on the properties of sensing materials [61, 76, 256, 257]. Tamvakos et al. found that the ZnO thin-film-based gas sensors are characterized by a high response of 1850% to 0.5 ppm NO₂ with good selectivity when heated to 200 °C, accompanied by a decreased electrical conductivity [258]. First-principle calculations attributed the decrease in conductivity of ZnO to the competitive adsorption between NO₂ and the atmospheric oxygen due to their different binding energies of —0.3 and —0.57 eV, respectively. This suggested that NO₂ would bind to ZnO surfaces more strongly than the O₂ at 200 °C [258]. When heated to 450 °C, α-MoO₃ nanoribbons exhibited a fast response of 72% to 50 ppb NH₃ within 21 s, good stability, and selectivity with a theoretical LOD of 280 ppt [76].

Yuasa et al. investigated the nanostructuring effects of SnO₂ on hydrogen sensing. The size of 0D SnO₂ nanostructures significantly affects the response performance at 350 °C with the optimum response at 4 nm, as seen in figure 10(a) [259]. Also, mesoporous ZnSe/ZnO showed a temperature dependence of NO₂ sensing performance in which the optimum performance was achieved at 200 °C (figure 10(b)) [256]. The response and recovery durations were quite short, only 98 s and 141 s at 200 °C, respectively, which could be attributed to the increased activation energy triggering the exchanges between NO₂ and oxygen [256]. Cr₂O₃/ZnCr₂O₄ particulates had a response (Rₚ/R₀) of 69.2 to 5 ppm xylene with excellent stability and selectivity at 270 °C [257]. SnO₂@CuFe₂O₄ particles showed an optimum voltage change of —40 mV upon exposure to 80 ppm NH₃ at 650 °C, as illustrated in figure 10(c) [61]. Chen et al. [260] found that the temperature of 50 °C only could lead to the excellent sensing performance of Ag/Zn-LaFe₂O₃, with a response (Rₚ/R₀) of 64.2 to 100 ppm ethanol and response and recovery within 100 and 20 s, respectively (figure 10(d)). In₂O₃-FET sensors with a low-power

Figure 10. Morphologies and performances of 0D (a)–(d) and 1D (e)–(h) based sensors operated at elevated temperatures. (a) TEM of SnO₂ nanostructured H₂ sensors, adapted with permission from [259]. Copyright 2016 American Chemical Society. (b) Response of ZnSe/ZnO sensors to NO₂ at various temperatures, adapted with permission from [256]. Copyright 2019 American Chemical Society. (c) Response of SnO₂@CuFe₂O₄ sensor to NH₃ at 650 °C, adapted with permission from [61]. Copyright 2020 Elsevier B.V. (d) Response of Ag/Zn-LaFe₂O₃ to 100 ppm ethanol at 50 °C, adapted with permission from [260]. Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) TEM images of Ga₂O₃ nanorods CO sensors, adapted permission from Chen et al. [260]. Copyright 2019 American Chemical Society. (f) Response of SnO₂–ZnO/NiO nanofibers to formaldehyde at 150 °C, adapted with permission from [232]. Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (g) SEM image, demonstration of Joule heating effect and (h) response of Pd–SiNW sensors to H₂, adapted with permission from [263]. Copyright 2019 American Chemical Society.
microheater of 1.6 mW which is approximately 25.7 times lower than that of the commercial one with heating within 0.8 s and 2.2 s, respectively, as seen in self-heating sensors of 1 nm thick palladium decorated silicon nanowires enables the faster and stable response. Noticeable responses were observed at lower temperatures of 300 °C with superior selectivity, high sensitivity, and high stability at higher temperatures as high as 36 to 50 ppm, high selectivity, a LOD of 50 ppb, and rapid response and recovery within 25 and 37 s, respectively, as seen in figure 10(f) [232]. Joule heat (<1 mW) generated by applying a low bias voltage to form self-heating sensors of 1 nm thick palladium decorated silicon nanowires enables the faster and stable response to H2, even in the presence of humidity or CO (figures 10(g), (h)) [263].

For 2D nanostructures, heating is also applied quite often for the improvement of sensing performance. 2D porous Au/WO3 sensors achieved an enhanced performance for ethanol at 200 °C with a response (Rs/Ra) as high as 36 to 50 ppm, high selectivity, a LOD of 50 ppb, and rapid response and recovery within 25 and 37 s, respectively (figures 11(a), (b)) [264]. 275 nm-long and 125 nm-wide α-Fe2O3 nanorods 2D nanostructures showed an optimum sensing performance for H2S with a LOD of 100 ppb and ultrafast response and recovery within 0.8 s and 2.2 s, respectively, at 260 °C (figures 11(c), (d)) [233]. Gas sensors prepared by sequentially loading tin-oxide nanorods and platinum single atoms on silicon carbides nanosheets can realize the sensitive sensing of ethanol at 500 °C as well with a response (Rs/Ra) of 119.75 to 500 ppm and fast response and recovery within 14 s and 20 s, respectively [265].

3D Nickel–Cobalt oxides (Ni3Co2−xO4) hierarchical nanostructured sensors realized ultrafast H2 sensing with superior selectivity, high sensitivity, and high stability at higher temperatures >500 °C, whereas no noticeable responses were observed at lower temperatures of 300 °C–400 °C, which may be related to the temperature-dependent switch of working mode (n type: >500 °C and p type: <500 °C) (figures 11(e), (f)) [38]. MoO3/Bi2Mo3O12 hollow microspheres sensors showed the strong temperature dependence of performance for trimethylamine (TMA) in which the optimum response (Rs/Ra) of 25.80 to 50 ppm TMA with excellent selectivity was achieved at 170 °C, as shown in figures 11(g), (h) [59].

It is well recognized that extra heating is normally necessary for performance improvement for 0D, 1D, 2D, and 3D nanostructures-based gas sensors. This originates from not only the inherent temperature dependence of physical and chemical properties of sensing materials but also the probably more sensitive temperature dependence of performance as a result of nanostructuring.

3.4. External photo-activation or excitation and electrical field
3.4.1. Light illumination
Photo-illumination is another alternative strategy for performance enhancement normally through two mechanisms, i.e., recovery kinetics acceleration by the photo-stimulated desorption as a result of the
interactions between photogenerated electrons and adsorbed gaseous molecules [234], and improvement of charge carrier transport by energy level match and barrier height reduction between sensing units and electrodes [266]. The simultaneous realization of two mechanisms by light illumination was found for both chemiresistor [73] and FET [186] sensors with significantly enhanced performances. Response and reversibility improvement under UV, visible and red light illumination was seen for MoS2 [234], SnS2 [51], ReS2 [267], MoS2/ZnO nanohybrids [268], MoTe2 [269], mesoporous ZnO [270], GaN nanowires [73], and graphene hybrids [186]. Red light illumination with power as low as 60.9 nW led to an increase in response to NO2 by a factor of 5 for single-layer MoS2 sensors, an increase in sensitivity by 50, and a theoretical LOD of 0.2 ppb within 22 and 33 s for 80 ppb NOx [275], respectively. The macro/mesoporous ZnO sensors exhibited the responses of 1310% to 400 ppb and 0.5% to 0.2 ppb for NO2 and 19 s response and 32 s recovery under UV light illumination, in sharp contrast with 109% and 0%, and 108 s and 173 s, respectively, in the dark [270]. Zhao et al observed strongly enhanced NO2 sensing performances of GaN-nanowires and novel sensing characteristics under UV light illumination, as seen in figure 12(a) [73]. Both Ti/graphene and Cu/graphene sensors also showed enhanced performances of NH3, especially the acceleration of response and recovery at RT under visible and UV light illumination in terms of bandgap engineering, respectively (figure 12(d)) [47, 271]. Reddeppa et al [272] reported a novel ternary composite of PGO/InGaN nanorods for CO detection with better response performance under UV light illumination.

Recently, the concept of light-dependent self-powered gas sensing has been proposed to be one of the future directions in the development of low-cost and low-power gas sensors [9–11, 273]. To date, several nanostructures have been shown to have promising light dependences of performances for self-powered gas sensors capable of detecting various toxic gaseous species with zero applied bias [10, 12–14]. Liu et al reported that novel self-powered sulfur- and nitrogen-hyperdoped Si sensors under the asymmetrical light illumination of a portion of sensing units showed an increase in response for 50 ppm NH3 by 18.5 compared to the dark conditions (figures 12(e), (f)) [273], a detectable NO2 concentration of 11 ppb, and rapid response and recovery within 22 and 33 s for 80 ppb NO2 [275], respectively. Self-powered nanostructured p-Si/n-ZnO diodes were
found capable of detecting 250 ppb NO2 concentrations with excellent selectivity [11]. Kim et al [274] reported photovoltaic self-powered WSe2/WS2 (MoSe2/WS2) heterojunctions sensors with the LOD of 10 ppm NH3 for a 10 min exposure (figures 12(g), (h)). Niu et al [12] fabricated photovoltaic self-powered vertical n-MoS2/p-GaSe2 heterojunctions sensors with a response of 346% (12 mW cm−2) to 500 ppb NO2, rapid response and recovery within 23 s and 173 s, respectively, LOD of 20 ppb and high selectivity under 405 nm visible light illumination. Interestingly, wireless self-powered integrated Pd/SnO2@ (Au, Cu, Ni, and Ag) nanostructured sensors realized the selective detection of H2, formaldehyde, toluene, and acetone with LOD of 10, 2, 1, and 1 ppb, respectively, under the mild illumination of indoor light with Si solar cells (figure 12(i)) [9]. These sensors could precisely track gas leakage locations, which may have potential applications to buildings, smart homes, and cities (figures 12(j)–(l)) [9].

3.4.2. Applied electrical field

Ever since the gas sensing capability of conventional FET gas sensors mentioned above is limited by insufficient transduction [168, 276, 277], several alternative designs, including chemical-sensitive field-effect transistors (CS-FET) [37] and floating gate FET (FGFET) [255] gas sensors have been proposed to enhance and optimize the sensing performance. The conventional electrical active gate is replaced by a floating chemical-sensitive layer for CS-FET sensors, as shown in figure 13(a). Thus, exposure to target gas molecules could trigger the electrostatic effects leading to changes in channel threshold voltage ($V_t$) and effective work function ($\phi$) for highly sensitive detection [278]. Therefore, the gas sensing of CS-FET sensors is highly dependent on the electrostatic effects between the sensing layer and the charge carriers introduced by the target gas molecules (figure 13(b)) [37].

Figure 13. Applied electrical-field-enhancement: chemical-sensitive FET (CS-FET) sensors (a)–(c), floating gate FET (FGFET) sensors (d)–(f), and others (g)–(i). (a) Schematic representation and TEM images of response of Pd0.3nmAu1nm CS-FET sensors to H2S at RT, adapted with permission from [278]. Copyright 2017 Science/AAAS. (b), (c) Schematic illustration of electrostatic confinement effect of the charge inversion and its effects on response performance of Ni0.3nmPd1nm floating CS-FET sensors to H2, adapted with permission from [37]. Copyright 2018 American Chemical Society. (d), (e) SEM and response of WO3 FET sensors to SO2, adapted with permission from [279]. Copyright 2019 Elsevier B.V. (f) The current changes of ZnO CFET sensors to 0.5 ppm NO2 at 0 gate voltage, adapted with permission from [115]. Copyright 2019 Elsevier B.V. Illustration and functionality (g) the tip induced charge in NW-based sensors using AFM, adapted with permission from [236]. Copyright 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (h) Multifunctional, adapted with permission from [280]. Copyright 2020 American Chemical Society. (i) External electric field manipulation, adapted with permission from [237]. Copyright 2019 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.
H$_2$S interaction with ultrathin Pd$_{0.3nm}$Au$_{1nm}$ chemical-sensitive layer can lead to changes in the work function and charge carrier density [278]. Such net changes increase the electrostatic potential favor 1 ppb H$_2$S detection with the maximum achieved a response of 280%, response (144 s), and recovery (800 s) times at RT [278]. Also, electrostatic effects between H$_2$ gas molecules and Ni$_{0.3nm}$Pd$_{1nm}$ floating sensing layer (made of thin inversion layer) resulted in strong charge confinement, which increased the response up to over 100% to 0.5% H$_2$ with rapid response and recovery within 60 s and 120 s, respectively and low power consumption of less than 50 μW at RT (figures 13(b), (c)).

Moreover, FGFET sensors have their control gate and a floating gate facing each other, with their sensing layer formed between the two gates [255]. For FGFET sensors, various sensing materials can be adopted without contamination since the sensing layer is usually formed at the final stage (figure 13(d)). Here, the reaction between the gas molecules and the sensing layers will create a potential difference in the floating gate leading to a high coupling ratio (between the control and the floating gates) [281]. Also, FGFET enables the applicability of pre-bias pulse ($V_{pre}$) to enhance the electric-field-induced chemisorption [235] of various gas molecules [115]. The electric-field–enhanced effect was observed for porous 18 nm thick WO$_3$ nanoparticles FET sensors for SO$_2$ detection by varying pre-bias voltages ($V_{pre}$) (figure 13(e)) in which a pre-bias of $V_{pre} = -2$ V could increase the response to 10 ppm SO$_2$ by a factor of 3.7 compared to that at $V_{pre} = 0$ V [279]. Jeon et al fabricated graphene quantum dots decorated Si-MOSFET sensors with a horizontal floating gate interdigitated with the control gate (CG) for humidity sensing in which the response and recovery improved by 30% and 40%, respectively, by applying a pre-bias of 2 V and -1 V to the CG [281]. For ZnO nanoparticles capacitive type FET (CFET) sensors for NO$_2$ detection at 180°C, the response is negligible when the pre-bias voltage and the read gate voltages are equal, whereas the lowest (highest) pre-bias of −2 V (2 V) could lead to an increase (decrease) of 46.6% (43.2%) in current change upon exposure to 0.5 ppm NO$_2$ without the gate voltage applied (figure 13(f)) [115]. Even a tip of atomic force microscopy (AFM) could be used as a local top gate to induce an electric field effect (figure 13(g)) on the ethanol sensing performance of NWs sensors with sensitivity to even an elementary charge [236].

3.5. Others

Except for those above, newly emerging strategies and principles were also introduced for performance improvement of electrical gas sensors, such as the use of passivation layers [282], multiple gating [283], piezotronics [284], piezo–phototronics [285], catalytic combustion [280], conductometric Raman spectroscopy for accurate molecular gas recognition [238, 286] and/or multi-functionality, spin–orbitronics (external electric field control) [237]. Basically, these principles/techniques aim to discover the novel phenomena and functionalities that may serve as the solution to the inherent challenges of the electrical gas sensors. For instance, high-affinity gas molecules like NO$_2$ were found to initiate sub-gap states at the sensing surfaces, increasing the leakage current and thus negatively influencing the gas sensing performance [287, 288]. Im et al reported that the MoS$_2$ FET sensors covered by an Al$_2$O$_3$ passivated layer exhibited a negative shift of the threshold voltage from −0.83 V to −1.05 V as a result of the introduction of the Al$_2$O$_3$ passivation layer, which resulted in a remarkable increase in sensitivity to NO$_2$ [282]. According to the pseudo–double gate structure, this enhanced performance arises from the induction of the positive charge states by the capping layer as a secondary gate [282]. In addition, the combination of applied mechanical strain and piezo–phototronics could synergistically modify the barrier height at the interfaces between MoS$_2$ and metal to significantly enhance the performance with a response of 671% to 20 ppb NO$_2$ under the red light illumination of 625 nm (4 mW cm$^{-2}$) and fast response and recovery within 16 and 65 s, respectively [285]. Also, a simple and cheap catalytic combustion technique was employed for selective NH$_3$ detection in complex environments like agriculture and harsh weather (figure 13(h)) [280]. The very short screening length of layered Pd/ Ni$_{30}$Fe$_{20}$ allows the spin–orbital torques to be reversibly manipulated externally by the adsorption/desorption processes of H$_2$ gas molecules, which appears comcomitantly with the variations of the electrical resistance (figure 13(i)) [237]. Hence, a novel spin–orbitronics strategy is believed to be potential for developing high-performance gas sensors by externally manipulating the spin–orbit torques with the simultaneous reflection of electromagnetic properties.

Nanostructuring effects along with extra strategies on the sensing performances and mechanisms were discussed in detail above. The detailed effects of nanostructuring, possible challenges and opportunities, and future technology roadmaps were summarized in figure 14. Nanostructuring brings about not only particular structures and morphologies but also novel properties and/or enhanced performance. This, along with extra strategies, may more readily lead to the emergence of novel materials or structures as sensing units for gas sensors, which furthermore makes it possible for electrical gas sensors to be directed in a different way from the conventional ones. For instance, electrical gas sensors with multifunctionalities and multimodalities which operate with novel sensing mechanisms may also emerge as ‘intelligent or smart’ detection, monitoring or diagnosis platform, as illustrated in figure 14.
4. Conclusion and future perspectives

This review highlights the effects of 0D, 1D, 2D, and 3D nanostructuring of sensing units on the performance of chemiresistive and FET-based gas sensors with the particular underlying sensing mechanisms involved. Nanostructuring, including tailoring of dimensionality, size, morphology, and even nanopatterning, can not only endow sensing materials with new and unique physical, chemical and surface properties and functionalities but also change the transport characteristics of gas molecules at the surface of sensing units and their interactions, which allows to develop novel gas sensors with high performance. However, nanostructuring of sensing materials in 0D, 1D, 2D, and 3D also shows their respective strengths and weaknesses, which may require special nanostructuring for certain sensing materials and gases. The combination of nanostructuring with heterojunctioning and heterostructuring via state-of-the-art fabrication technologies can undoubtedly escalate further the capacity of designing novel sensing units with desired properties and performances, which was also demonstrated. Except for tailoring and modifying sensing units themselves, the incorporation of extra heat, light, electrical, and mechanical forces and even their combinations can provide extra freedom for further performance optimization and improvement of gas sensors. In reality, the superior performance of a sensing sensor normally results from the synergistic effects from the structural, catalytic and size effects, and other physical and chemical effects in which one or two effects may dominate. However, the adoption of diversified strategies still cannot guarantee the achievement of excellent ‘4S’ such as superior response, recovery, sensitivity, selectivity, low LOD, long-term stability and repeatability at RT, and even low-cost, as seen in table 2 and figure 14. Novel strategies, ideas, and solutions need to be proposed to promote the emergence of novel high-performance gas sensors for extensive practical applications, which are given as follows.

Low-cost nanostructuring/nanofabrication technologies of devices and preparation approaches of new sensing materials and nanostructures would be more effectively and compatibly combined. This makes it possible to bring novel emerging sensing nanomaterials with special properties and high performances into prompt use for gas sensors, which is favourable for rapid performance escalation. Normally, the breakthrough in the performance of gas sensors is closely related to the discovery of new sensing materials, accompanied by proper nanostructuring. Nanostructuring and nanopatterning would be extensively used for tailoring sensing units with more precise control, accompanied by continuous miniaturization and increased integration level for smart sensing applications (figure 14). High precision nanostructuring and nanopatterning with size reduction can better ensure high performance based on the design of gas sensors desired. The design of gas sensors with novel configurations, principles, low-power consumption, and even self-power is indispensable for the technology roadmap of gas sensors. 3D architectures with special configuration design and reduced dimensions are probably needed for easy operation at RT with low power in new working principles, which are not necessarily configured merely in chemiresistors and FETs. The use of horizontal and multiple gates in FET-
based sensors is, in a sense, a modification of configurations as well, which aims to improve the performance with more effective manipulation. Furthermore, optical and/or magnetic other than electrical signals only can also be introduced as complementary signals for performance enhancement and breakthrough. Even micro/nanoscale solar cells and thermoelectric nanodevices can be integrated to form self-powered gas sensors. Extra heat and light sources, electrical and magnetic fields, and mechanical forces supplied for the purpose of performance enhancement would probably be realized by direct integration into gas sensors. This can not only enhance the specific performances but also may bring novel functionalities to gas sensors. Gas sensors would be more flexible and highly compatible with human beings and surroundings, which tend to be a comprehensive platform with greater functionalities than ever before. Also, advanced integration technologies bring great promises for professional people to work with flexible gas sensors on the body as a functionalized platform.

In summary, as predominant and fundamental configurations, chemiresistor- and FET-based gas sensors are currently the most important targets for people to work on and utilize in practice. As fundamental infrastructures and starting points, the rapid development of nanomaterials, nanostructuring/nanofabrication and integration technologies, and design concepts will accelerate the emergence of novel gas sensors with high performance and ever greater and novel functionalities which can thus meet the requirements of rapid industrialization, informatization, intelligentization, and population expansion.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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