Wearable Nano-Based Gas Sensors for Environmental Monitoring

Subjects: Nanoscience & Nanotechnology

Contributor: Sara Hooshmand, Panagiotis Kassanos, Meysam Keshavarz, Pelin Duru, Cemre Irmak Kayalan, İzzet Kale, Mustafa Kemal Bayazit

With a rising emphasis on public safety and quality of life, there is an urgent need to ensure optimal air quality, both indoors and outdoors. Detecting toxic gaseous compounds plays a pivotal role in shaping our sustainable future.

Keywords: wearable nanosensors ; gaseous pollutants ; gas-sensing nanomaterials ; environmental detection ; sensor

1. Introduction

Due to rapid industrialization and urbanization, the world is facing the problem of severe air pollution. This is witnessed by the increasingly large amounts of toxic and pollutant gases released into the environment, one of the negative aspects of the industrial revolution. The demand to improve public safety and quality of life due to the development of different industry sectors and the issues related to air pollution are significantly growing. These pollutants usually contain toxic gases such as CO, SO_2, NO_2, and H_2S that can harm humans, their surrounding atmosphere, and the environment through ozone depletion, acid rain, and the greenhouse effect [1]. The harmful effects of such gases on human health are so severe that industrial workers exposed to such gases need a safety gas alert system capable of detecting and quantifying harmful chemicals and gases. Detecting dangerous gases is becoming increasingly important for indoor and outdoor air quality monitoring in houses, office buildings and factories, public safety, and mining and energy industries [2].

Gas sensors are also widely used to measure greenhouse gases. Furthermore, studies are being undertaken to detect some of these gases in breath, including nitric oxide (NO), ethane, and NH_3, for diagnostic applications. They also act as biomarkers for different pathologies [3][4]. The detection of volatile organic compounds (VOCs) is thus of significant importance [5]. There is a tremendous need for simple and portable sensors that can measure gases sensitively, selectively, and easily in real time to analyze gases efficiently. As a result, simple, on-site, real-time monitoring of air quality and pollutant content is vital for protecting human health from poisonous and dangerous gases. Meanwhile, there is also a need for such devices to safeguard human health in various situations, including food protection and public security. As a result, the demand for developing small-sized, lightweight, and portable sensing devices has drastically increased. The global gas sensors market is projected to reach USD 2.1 billion by 2027, growing at a compound annual growth rate (CAGR) of 8.9% [6]. For this purpose, numerous sensing techniques, such as calorimetric, thermoelectric, optical, and chromatographic methods, have been applied [7]. However, most of these techniques have disadvantages, such as relatively high cost, low sensitivity and selectivity, poor design, and a need for additional equipment; some even lack portability [7].

2. Sensing Materials

2.1. 2D Nanostructures

These 2D nanostructures have gained broad interest owing to their superior electronic and material properties and high photo-response. Numerous studies have shown the exceptional physical/chemical properties of 2D nanostructures and their wide range of applications in healthcare, defence, environmental monitoring, and food safety. These 2D nanostructures, such as graphene, graphitic carbon nitride (g-C_3N_4), poly-types of transition-metal dichalcogenides (TMDC or TMD) materials (for example, MoS_2 and WS_2), and oxides of group B elements such as MoO_3, WO_3, and MnO_2, can have exceptional electrical, chemical, physical, and optical properties, with high electrical conductivity, electron mobility, and a large surface area. These are attributes that are highly beneficial in sensing applications [8], allowing the use of these materials in photoelectrochemical, field-effect transistor (FET), fluorescence, surface-enhanced Raman scattering (SERS), and colorimetric biosensors [9].

Graphene, hexagonal boron nitride (h-BN), and metal dichalcogenides, MX_2 (M, transition metal; X, chalcogen atom), have dominated the spotlight. For instance, the application of 2D titanium carbide MXenes for detecting various gases pollutants is proposed by Simonenko et al. to take advantage of lowering response and recovery times, increasing sensitivity and stability, and improving sensitive functionality in humid atmospheres [10]. The latest advancements in device integration, microfabrication, and material and device processing make it possible to integrate materials such as $Ti_3C_2T_x$ MXene-loaded 3D-substrates into lab-on-a-chip systems, which can analyze multiple analytes in the gas form [11].

2.2. Carbon Nanomaterials

Developing sensitive nanomaterials with a rapid response to detect and quantify low concentrations of gaseous pollutants is a big challenge. Carbon nanomaterials have shown great potential to be efficient sensing materials due to their exceptional characteristics like great sensitivity, high solid–gas interactions, and a superior surface-to-volume ratio [12]. Optimizing key factors such as the physical structure and surface architecture of the deposited carbon nanomaterials on the electrodes/substrates (e.g., porosity, thickness, and interface properties) should be deeply considered to achieve the best device performance [13]. On the other hand, two other key factors affect the sensitivity of carbon nanomaterial-based gas sensors: surface area and electrical conductivity. These factors can be improved through the chemical modification of the surface (e.g., surface functionalization with other nanoparticles, metal atoms, polymers, ionic liquids, enzymes, etc.) [12]. Carbon-based nanomaterials are generally classified based on their geometric structures into three types of fullerenes (spheres as in C_{60} (soccer ball) or ellipsoids as in C_{70} (rugby ball)), carbon nanotubes (CNTs, tube-shaped), and graphene (single sheets of carbon atoms) [14]. Gas sensors using such materials and their derivatives have been widely demonstrated [15].

2.3. Conductive Polymers

Polymers are macromolecules with repeating structural units united by covalent connections. Although traditional aliphatic polymers are usually insulators, polymers can also be electrically conducting. The conjugated backbones of CPs are their primary building blocks. Due to the delocalization of electrons in a continuously π-overlapped orbital along the polymer backbone, CPs, which are also referred to as conjugated polymers, possess some of the most interesting electrical and optical properties. These properties are a result of the polymer backbone [16]. As a result of their outstanding chemical and environmental stability, biocompatibility, and unique optical and electrical properties, CPs have attracted considerable attention in a wide range of scientific domains, such as chemistry, biology, electronics, and materials science [17].

The attractive and distinctive optoelectronic features of CPs allow them to be exploited for numerous applications, including gas detection. Flexible gas sensors that are constructed out of CP-sensing materials have drawn a lot of attention due to their many advantageous properties. These properties include RT operation, tunable conductivity, flexibility, environmental stability, low cost, and various functionalization options [18]. A conjugated arrangement with alternating single and double bonds, or a conjugated system linked with atoms which generate orbitals for a continuing orbital overlap, appears to be an essential requirement for a polymer to conduct inherently. For polymers to be electronically conducting, charge carriers and the orbital system that enables these carriers to move freely are necessary, similar to the free electron movement associated with high conductivity in metals [19]. Since the 1980s, CPs that are solution-processable aromatic polymers such as poly(p-phenylene) (PPP), polypyrrole (Ppy), polyaniline (PANI), polythiophene (PT), poly(3,4-ethyelenedioxythiophene) (PEDOT), and their derivatives have been utilized as active layers [20]. There are several ways to modify CP conductivity to achieve desired results. Doping modifies a polymer's structure chemically. Alternatively, CPs can be mixed with additives, including metals, semiconductors, acids, or surfactants. In a study, an NH_3-sensing composite was prepared by coating polymer sulfonic-acid-doped PANI with bacterial cellulose (BC) nanofibers and co-doped with dodecylbenzene sulfonic acid (DBSA) and poly (2-acrylamido-2-methyl-1-propane sulfonic acid) (PAMPS) [21]. BC/PANI-DBSA/PAMPS was successfully synthesized using an in situ chemical oxidation polymerization technique. This synthesis method produced a profound structure of a nanoscale PANI layer connected to the BC backbone. The homogenously coated three-dimensional network structure enabled faster gas adsorption/desorption and electrical signaling.

Furthermore, a macromolecular sulfonic acid, PAMPS, made closer connections between the crystal islands because of various interactions. Additionally, more sensing sites were created on the surface of the PANI, which enhanced the structural stability of the DBSA doping and strengthened the conduction signaling of the material. The produced chemiresistive sensor based on this macroscopic film had a simple device configuration. It displayed a sensing response (defined as the ratio of the device's intrinsic resistance to that in the presence of the target gas) of 6.1 up to 100 ppm, high selectivity, and rapid response/recovery time of 10.2 s/8.6 s for 100 ppm with a LOD of 200 ppb to NH_3 at RT. This easy and versatile method for building sensing materials on nanofiber templates has potential in NH_3-exposed areas.

The effectiveness of a nanohybrid sensor based on PANI, silver oxide (Ag_2O), and GO (PANI-Ag_2O-GO) was evaluated for NO_2 sensing [22]. The dispersed graphene and PANI/Ag_2O solutions in deionized water were combined to make the composite sensor. The resulting solution was then dropped and dried over platinum microelectrodes attached to alumina ceramic chips.

2.4. Nanohybrids

Detection of low traces of harmful toxic gases using nanohybrid sensors is increasing due to their low cost, feasibility, low maintenance, simple structures, and capability to sense various types of gases [23]. The conjugation of organic and inorganic nanomaterials has introduced a new class of hybrid nanomaterials [24]. In contrast to single-component nanomaterials, nanohybrids offer versatile chemical and physical functionalities that are advantageous in various fields [25]. Nanohybrid sensors benefit from increased conductivity, porosity, catalytic activity, and optical and electrical potential, with a low LOD for gases even at ppm concentrations [24][25][26].

Semiconductor-based gas sensors such as ZnO, SnO_2, NiO, and CuO have attracted significant attention owing to their good sensitivity, cost-effectiveness, and capability to detect a wide range of toxic gases. However, semiconductor-based gas sensors suffer from low selectivity, surface defects, weak adsorption potential, and low anti-corrosive properties [27]. Nanohybrid-based sensors offer a new paradigm to attain selectivity with enhanced sensitivity. Polymers such as PT, polyacetylene (PA), PEDOT, poly (phenylene vinylene) (PPV), PANI, and Ppy are among the CPs with potential use in gas sensing as their conductivity changes upon exposure to gas molecules [28]. Utilizing such polymers has the benefits of high functionality, low cost, excellent stability, rapid response time, remarkable recovery, facile synthesis, and high surface area. However, poor sensitivity, selectivity, response, and recovery restrict their gas-sensing capabilities. Incorporating semiconductors and inorganic nanomaterials in polymer-based nanohybrid sensors, such as metal oxides and metal oxide semiconductors, enhances their sensitivity, stability, and response by increasing the surface area and allowing the detection of a wide range of gases [29][30].

2.5. Metal Oxide Semiconductors

MOS materials have been extensively used in gas sensing due to their simple structure, simple and established manufacturing process, compatibility with microelectronics manufacturing, low-cost, excellent response, and long-term stability [31]. As a result, MOS materials and their use in gas sensing have been extensively studied over several decades. The use of metal oxide gas sensors goes back to 1962, and it was realised that the resistance of such films changes in the presence of CO_2, toluene, and propane gases at a specific temperature [32]. This chemiresistive characteristic of semiconductor materials has made them ideal candidates for gas sensing. Initially, MOS gas sensors suffered from high power consumption and complicated fabrication processes, which hindered their application. However, in 1986, gas sensors based on SnO_2 were commercialized [33][34].

The adsorption/desorption of gas molecules onto the surface of semiconductor-based sensors leads to changes in electrical parameters, which determine the presence of analyte molecules in the environment. Subsequently, the analyte's composition and chemical structure and the semiconductor materials' morphology significantly impact the operation of chemical gas sensors. Therefore, the right sensing material choice is critical in detecting gaseous compounds in the environment [35][36][37][38]. The use of MOSs to detect SO_2 gas in wearable sensors is increasing. MOSs such as ZnO, SnO_2, and In_2O_3 are relatively inexpensive, highly sensitive, and easy to fabricate [39]. Nanostructured ZnO-based MOS gas sensors, representative of n-type semiconductors, offer certain advantages including non-toxicity, cost-efficiency, rapid response, and stability. These attributes make them notable candidates in the realm of gas sensing, especially for wearable devices. The 1D ZnO nanostructure-based sensors have demonstrated the ability to detect gases like NO_2, NH_3, CH_4, H_2, and C_3H_8, though the sensitivity largely depends on specific operating temperatures [40][41]. However, it is crucial to highlight that the choice of the best material is influenced by application-specific requirements. Comparing the performance of ZnO with other metal oxide materials under standardized conditions would be imperative for a comprehensive analysis. In addition to ZnO-based 1D nanomaterials, advancements in gas sensing also focus on other one-dimensional semiconductors, such as Pd-doped 1D tungsten oxide nanowires [42].

3. Wearable Substrates and Conducting Electrodes

3.1. Paper-Based (PB)

A PB substrate can also be employed as a starting substrate for manufacturing flexible and wearable gas sensors. Paper is becoming more popular in electronic devices as a flexible, low-cost, lightweight, tailorable, environmentally friendly, degradable, and renewable material. Since they degrade quickly, they can reduce the quantity of electronic garbage

created for future generations. In recent years, numerous PB sensors have been described for wearable applications. PB gas, humidity, and strain sensors are among the most widely researched PB sensors. In general, electrodes are required for PB sensors. When compared to other substrates, PB substrates have an increased surface roughness and the existence of holes, both of which prevent them from being compatible with high-quality thin film deposition and transfer. Compared to other substrates, PB electrodes may be made using several processes, including printing, magnetron sputtering, conductive tape pasting, and pencil drawing [43]. Electrode production techniques such as printing, and magnetron sputtering can be applied on various substrates. Simple, low-cost, solvent-free processing methods such as pencil drawing and conductive tape pasting, which take advantage of the rough surface of the paper, can be used to make the electrodes of PB sensors. The sensing materials employed to construct PB gas sensors include carbon compounds and derivatives, MOS, and organic materials. Among these sensing materials, carbon compounds and their derivatives are particularly helpful. Because paper is not resistant to heat, traditional MOS gas-sensing materials that perform well at high temperatures are challenging. Furthermore, PB substrates are unsuitable for detecting VOCs due to their high hygroscopicity. This is because absorbed humidity affects conductivity more than the presence of the target VOCs [44]. PB moisture sensors have been demonstrated for tracking respiration rates and patterns [45]. These sensors are based on the propensity of paper to absorb moisture from its surroundings. Gas sensing has a wide range of applications, and it would be simple to print and attach a sensor like this to a human body.

Write printing is a method of printing that involves applying a solution of functional components to a surface with pens or other writing implements. When expelled from the nozzle tip, functional ink for write printing must harden fast. Printed ink should meet electrical, mechanical, and thermal standards to produce high-performance wearable sensors. For example, write printing technology has created PB wearable gas sensors of nearly “zero cost” [43]. These PB wearable gas sensors can achieve sufficient precision, ecological sustainability, and durable operation under high relative humidity (RH) settings due to appropriate printing materials and structural design.

3.2. Polymer-Based Sensors

Polymeric materials have gained popularity in sensing applications due to their processibility, durability, and low cost [24]. A recent study on polymeric sensors focuses on a nanocomposite of polypyrrole and TiO_2 to detect volatile gas analytes such as ammonia, acetone, and ethanol. The distinguishing characteristic of this nanocomposite is that it is wrapped in poly-methyl methacrylate. Synthesis of polypyrrole was achieved through chemical oxidative polymerization of the pyrrole monomer. Gaseous analytes were detected with TiO_2 nanoparticles in the composite structure. TiO_2 is advantageous as it can endure temperatures as high as 600 °C, is abundant, has good stability, and is easy to process [46]. After the individual components of the composite material were prepared, the ternary nanocomposite was designed through physical methods such as grinding and mixing. The stoichiometric ratio of TiO_2 to polypyrrole was taken as [1:1]. This ratio is critical as it helps obtain a composite of strong adsorption after 30 min of manual grinding. The gas-sensing performance of the nanocomposite was assessed with three different gases, as mentioned previously. The composite material was subjected to an air atmosphere to simulate real application conditions. The resulting composite material shows the highest sensitivity to NH_3. Although this study does not propose a wearable solution for gas-monitoring technologies as it is a fiber-optic sensor, it is nevertheless easy and fast to fabricate, and it is a promising technology and approach for future wearable sensor technologies [46].

A wearable chemiresistive CP-based NH_3 sensor was developed by constructing porous and neural-network-like electrospun films [47]. The intriguing characteristic of this sensor is that Au/Ppy was employed. The structure of the developed material (3D interconnections), the porous structure, and the synergistic effects between Au and Ppy nanoparticles make a sensitive sensor for NH_3 detection and monitoring. The neural-network-like structure of the composite provides a practical pathway for signal transferring throughout the film, resulting in the effective transfer of electric signals from NH_3-Ppy active sites to the working electrodes. The porous and hollow capsule-like structure is the key to fast and responsive detection of NH_3. This structure allows for fast doping and re-doping between NH_3 and Ppy capsules. This is especially important for detecting NH_3 in the atmosphere quickly and effectively.

Another area of polymeric material research focused on fabricating cellulose acetate (CA)-based nanofibers and nanofilms [48]. The study aimed to detect H_2S, which is crucial as it leads to respiratory problems [49]. The study’s novelty was using an environmentally friendly CA and an ionic liquid (glycerol) to facilitate charge transfer within the composite matrix. Ppy, a CP, and tungsten oxide (WO_3) doping achieved the sensor’s conducting properties. Chemiresistive sensing nanofilms were prepared by solution casting, whereas nanofibers were prepared by electrospinning. The final sensor was fabricated and assembled by placing films/fibers between two plates of copper (bottom) and stainless steel (top). Stainless steel was chosen as the top contact as it is resistant to the corrosive effect of H_2S. Heatproofing of the sensor was accomplished by using a conductive silver paste covering all the layers. Assessment of the H_2S sensing capabilities

of the sensor was carried out with a mass flowmeter, subjecting the sensor to H_2S flows at a fixed rate and different concentrations (1–50 ppm). In addition, the sensor's performance was tested under varying temperature conditions. This allows the testing of the sensor under different weather conditions. Test results revealed that nanofilm and nanofiber sensors could operate above 20 °C and have a minimum LOD of 1 ppm. In addition, the sensors showed a fast response time, nearly half a minute, with a quicker response time of 22.8 s. The sensors' distinctive reproducibility properties, long-term stability, and low humidity dependence make them great candidates for application in outdoor and indoor atmospheres [48].

3.3. Textiles

Textiles are a suitable substrate for the realization of wearable gaseous pollutant sensors, as such an approach would render the integration of such sensors with clothing trivial. Several characteristics make textiles attractive. These include their durability, breathability, and washability. Due to their availability, silk and cotton are the most commonly preferred textile fabrics [50][51]. Cotton fabrics have gathered significant attention due to their high flexibility, low cost, high moisture absorption, strong mechanical strength, good biocompatibility, and biodegradability. They can also be integrated into smart clothing [52]. Furthermore, encapsulation is essential in wearable sensor technologies regarding atmospheric conditions. Encapsulation of electronic sensors ensures a waterproof coating and acts as a shielding layer for human skin [53].

Graphene shows excellent performance in gas sensing; however, it also displays poor adhesion when used on textile materials. Research addressing this gap used amyloid nanofibrils to fabricate graphene-based electronic textiles (e-textile) [54]. Amyloid nanofibrils were used as a bio-inspired adhesive, promoting adhesion between the graphene flakes and the cotton yarn. Graphene flakes provide active sites for NO_2 molecules to absorb, enabling the detection of pollutant gas in the environment. These interactions induce an increase in the electrical conductance of graphene.

Response characteristics of the e-textile yarns were measured through exposure to a constant concentration of NO_2 (100 ppm) over 15 min, and electrical current differences were plotted ($\Delta I = I - I_0$). Among all textile composites examined, RGO/FBLG/CY had the best monitoring performance regarding NO_2. In addition, the sensitivity of all materials was investigated by exposing them to NO_2 between the concentration range of 0–100 ppm. The results show that, similarly to the results in monitoring performance, RGO/FBLG/CY achieved the highest sensitivity of 1 ppm, whereas the following best composite showed sensitivity between 3–5 ppm. RGO/FBLG/CY has the best performance among all five examined materials because amyloid nanofibrils retained the best affinity for GO flakes, as the GO flakes provided large binding sites for NO_2 molecules. The selectivity tests were performed, and RGO/FBLG/CY showed a high response to NO_2 and no reaction for N_2, acetone, CO, CO_2, NH_3, and NO. The negative response to NH_3 exposure can be attributed to the electron donor characteristics of NH_3 on the rGO flakes, which results in decreased electrical conductivity. Finally, the humidity test revealed that RGO/FBLG/CY does not exhibit any change in electrical conductivity under humidity.

3.4. Stretchable Electronics

Standard electronics and microelectronics are primarily based on thick, rigid, and fragile substrates. For example, traditional printed circuit boards (PCBs) typically use flame retardant (e.g., FR4) or other substrate materials. At the same time, bipolar junction transistor (BJT), bipolar complementary metal-oxide-semiconductor (BiCMOS), and CMOS technologies are traditionally based on silicon wafers. Wearable applications necessitate a move away from these technologies and into devices and systems that are flexible and ideally stretchable. The human body and skin are not flat, rigid surfaces; they are in constant motion and soft, flexible, and stretchable. The inconsistency between the mechanical properties of skin and electronic devices can lead to many issues; for example, the wearable device might get damaged due to the continuous motions and can fail or become detached from the skin or the wearer can also become injured from prolonged device use. Depending on the sensing modality, it can also lead to recording noise signals and motion artefacts. Other issues are related to the wearability and intrusiveness of the devices, which can create emotional stress for the wearer or a feeling of intrusiveness.

In contrast, recorded data may be biased by the wearability factor, as the device itself may prohibit the wearer from performing daily tasks [55]. First-generation wearable devices have become widely available over the last ten years. However, these are rigid devices that are limited in functionality. It has, thus, become obvious, driven by current market and societal needs, that advanced next-generation technologies are needed to improve wearable devices' wearability, form factor, un-intrusiveness, and ubiquity. Flexibility and stretchability are key factors in this direction. Technologies and devices can be divided into techniques and devices realized through standard clean-room-based microfabrication and additive manufacturing approaches. Microfabrication techniques (thin-film deposition methods, photolithography, etc.) can lead to high-quality and performance devices with high resolution. However, they require high-cost, complex fabrication

tools and facilities. Additive fabrication techniques (stencil screen, inkjet, extrusion-based printing, laser carbonization, etc.) are lower-cost simpler technologies, which, however, are limited in resolution [55][56][57][58]. Many devices have been demonstrated using such techniques, including strain/pressure sensors, interconnects, and electrodes. Hybrid technologies exploiting the advantages of each of these families of technologies but also in combination with standard rigid technologies have emerged to address the challenges of wearable applications, particularly since the performance and level of integration of traditional microelectronics technologies cannot yet be rivalled. For example, the island-bridge approach can be used to allow some components and the electrical interconnects to be highly flexible and stretchable and rigid components to sit on islands, thus allowing a hybrid implementation [58].

As the substrates of on-body types of wearable gas sensors are in direct contact with the skin surface, they must be light, thin, flexible, and, most importantly, breathable to avoid airflow blockage and inflammation resulting from sweating. A sufficient stretchability provides appropriate stability to the sensor during movements. However, conventional flexible substrates such as polyethylene terephthalate and polyimide have low stretchability in the flat film form, so their suitability for epidermal electronics is low. Similarly, PB and textile substrates are unsuitable for manufacturing high-density circuits. They also cannot be used for the deposition of high-quality sensing materials. Therefore, designing advanced stretchable substrates with proper stability and durability becomes crucial in fabricating wearable sensing devices [59].

4. Sensor Types

4.1. Colorimetric

Colorimetric-based gas sensors can detect the presence of gaseous analytes and the concentration of the analytes through chemical reactions, resulting in color changes in the sensor [60]. The use of colorimetric gas sensors, such as thread-based washable textile gas sensors, is increasing due to their low power consumption and low LOD, low cost, selectivity, and multiplexity [61]. Additionally, the color changing of these sensors is easy to visualize and, hence, is intuitive, attributions that make them ideal for application in monitoring of air quality, personal exposure tracking, assessment of food quality, detection of hazardous chemicals, and breath analysis. In addition, using a smartphone camera to analyze their response quantitatively is another attractive characteristic. Colorimetric sensors typically employ various organic compounds for capturing target molecules, such as dyes, fetal organic complexes, and polymers [60]. Colorimetric sensors operate based on various mechanisms. One is based on the ring opening and closing reactions [62]. Various dyes and organic compounds of aromatic structures with several conjugated π-systems can be used as colorimetric sensors based on the ring opening and closing reactions. This leads to a change in the number of conjugated π-bindings.

4.2. Optical

Optical-based gas sensors have the advantages of fast response (allowing rapid real-time detection) with minimum drift (owing to absorption of gas molecules at a specific wavelength) and extreme gas specificity and sensitivity without disturbing the gas sample. If they are appropriately designed, cross-response to other gases can be eliminated, which makes optical gas sensors inherently reliable [63][64]. Furthermore, optical gas sensors can distinguish various gas species by comparing their unique gas optical fingerprints. Optical gas sensors, thus, exhibit remarkably high selectivity, with exceptional physical and chemical stability compared to chemiresistive metal oxide sensors. There are several different optical techniques available that are suitable for gas sensing. These include non-dispersive infrared (NDIR) sensing, photoacoustic spectroscopy (PAS), tunable diode laser absorption spectroscopy (TDLAS), and spectrophotometry.

4.3. Electrochemical

Compared to traditional instrumentation approaches, which require specialized apparatus and complicated protocols, electrochemical sensors have several distinct advantages when it comes to detecting environmental contaminants. As a result, they have been applied in various applications, including clinical diagnostics, food safety and quality, biological analysis, and environmental monitoring. These advantages include ease of use, low cost and power consumption, high miniaturization, and relatively simple instrumentation [65]. When it comes to wearable sensors, biocompatibility is an additional consideration. Electrochemical gas sensors are relatively more specific than other methods to detect individual gases and have ppm- or ppb-level sensitivity. However, similarly to semiconductor-based sensors, they suffer from cross-response issues and have a limited lifetime [66][67][68]. In addition, they are susceptible to temperature fluctuations; thus, the temperature should be kept constant and ideally known [69].

4.4. Transistors

In these types of sensors, sensing is achieved through a transistor, mainly using the MOS FET. One advantage of transistor-based sensors is that they have the potential for high miniaturization and a high level of integration with all the necessary readout electronics in the form of a standalone integrated circuit. Consequently, they are highly suited for wearable applications. Furthermore, they have the potential to overcome limitations found in other technologies concerning size, power consumption, dynamic range, and sensitivity [70]. On the other hand, although semiconductor-based gas sensors are susceptible at the low ppm level, they suffer from changing humidity levels which can cause drift and cross-response to other gases [71][72][73]. The subject and fundamental operation of the various approaches for FET-based sensing were recently reviewed [74].

4.5. Chemiresistors

Chemiresistive sensing is the most popular sensing approach. The use of chemiresistors has been accelerated in recent decades due to their relatively suitable amenability for inexpensive portable devices. Gas-sensing approaches achieving higher accuracy are typically more expensive and complicated and may even be unsuitable for wearable applications. The mechanism of gas response is based on the change in surface resistance due to gas interaction [75]. In most printed gas sensors, chemiresistive structures are employed to detect trace gas amounts due to their response principles to gas analytes through changes in channel conductance. The structure of a chemiresistor contains two pairs of electrodes linked together by a film of sensing materials, e.g., metals or semiconductors. Interdigitated electrodes (IDEs) are often employed to boost the sensing response. A known constant current or potential can be applied across electrode pairs. The resulting voltage or current is then measured upon exposure to gaseous analytes to obtain the film's resistance through Ohm's law, which is a function of a target gas's concentration [43].

The MOS family, including materials such as SnO_2, ZnO, In_2O_3, TiO_2, and WO_3, is frequently used in chemiresistive gas sensors. While CeO_2, Fe_2O_3, CdO, and CuO are also employed in various sensor applications, their primary use in chemiresistive gas sensors is often as catalytic additives rather than primary sensing materials.

4.6. Self-Powered Triboelectric Gas Sensors

Triboelectric nanogenerator-based (TENG) self-powered gas sensors have gained interest as they enable the development of portable gas sensors that do not require an external power source. These sensors require no maintenance and are able to be miniaturized and portable [76][77]. Self-powered active gas sensors function simultaneously as an energy source and sensor. The TENG-based self-powered wearable gas sensors response is due to changing the TENG output as the triboelectric charge density varies upon gas exposure [78]. Since triboelectricity involves temporary electrostatic charge, which is a common phenomenon in most materials, the use of various material options is possible. Triboelectricity is simply a friction-generated static electrical charge [79]. Metal oxide semiconductors and conducting polymers are commonly used as sensing materials in the fabrication of TENGs [80].

Self-powered high-performance MXene-based flexible wearable sensors driven by triboelectric–electromagnetic nanogenerators are developed as multifunctional detection systems for gas and movement monitoring [81]. The $Ti_3C_2T_x$ MXene/Ag-based TENGs fabricated by microelectronic printer and electrospinning devices performed successfully on the finger and knee with high selectivity to ethanol with a long-term stability up to 30 days. The sensor response to ethanol was also ~25 higher than that of chemiresistors [81].

5. Environmental Gaseous Pollutants Monitoring

5.1. Ammonia (NH_3)

NH_3 is a dangerous gaseous chemical with serious health consequences. Exposure to excessive amounts of NH_3 can result in life-threatening effects. It is an odorless, water-soluble, and poisonous gas that can pollute the environment and cause severe lung conditions [82]. It has a high solubility in water-rich environments and contact with its vapors causes acute irritation of the eyes, mucous membranes, and respiratory system. Despite the essential industrial role of NH_3 in petrochemical, plastics, textiles, explosives, and nitric acid manufacture, it is one of the most hazardous gaseous pollutants. The USA National Institute for Occupational Safety and Health has defined legal safety limits for NH_3 exposure, with a concentration limit of 25 ppm for long-term exposure of 8 h and 35 ppm for short-term exposure of 15 min. However, prolonged exposure to higher concentrations of NH_3 gas can cause significant injuries or even death [83]. Thus, it is vital to identify low levels of this gas by providing sensors with superior precision and performance, specifically in small dimensions for environmental purposes. Furthermore, NH_3 is reported as a general marker in many illnesses (e.g.,

kidney failure), as well as an index for food quality monitoring (e.g., fish) since some bacteria produce it as part of their metabolic processes [84].

Three-dimensional maze-like graphene nano-sheets with improved structure and thickness were prepared from two-dimensional graphene nanosheets by plasma-enhanced CVD and applied for the chemiresistive RT detection of NH_3 gas. Due to H_2 plasma etching, the surface area and the number of defect sites were enhanced, which led to an excellent performance of this platform with small-sized crystalline sensing nanomaterials [85]. Trace amounts of NH_3 gas (10 ppm) were also measured at 40 °C on a polyaniline nanofiber/SWCNT composite. Compared to pristine SWCNT-based sensors, higher repeatability and long-term stability were observed for the chemiresistive sensor [86]. The importance of the functionalization of GO sheets in the sensing performance of NH_3 sensors has also been investigated. Meta-toluic acid was modified on GO thin films via esterification, leading to a lower sensor resistance from RT to 600 °C than bare GO sheets. Sufficient sensor response of 32.7% and a response time of 10 s were obtained for 100 ppm NH_3 gas [87]. The application of non-covalent functionalized pyrrole/phthalocyanine with MWCNTs has also been verified in ultrafast detection (11.7 s) of NH_3 gas with a recovery time of 91.8 s. The improved chemiresistive sensing performance of the platform to 50 ppm NH_3 gas at RT was ascribed to the synergistic optimization and recombination of pyrrole, phthalocyanine, and MWCNT [88]. The performance of ZnO-based chemiresistive sensors towards NH_3 has been efficiently improved by MWCNT decoration compared to bare ZnO sensors.

5.2. Nitric Oxide (NO)

One of the most hazardous gaseous pollutants is nitric oxide (NO). It contributes to acid rain deposition and participates in ozone layer depletion. It is formed by lightning in thunderstorms and combustion systems, such as car engines and various industrial processes. Exposure to even infinitesimal concentrations (ppb-ppm) of NO can significantly impact the environment and human health. NO is a colorless gas, and, along with CO, it is known as a silent killer and irritates the skin, eyes, and mucous membranes. At the same time, it also increases the risks of respiratory and cardiopulmonary diseases [89][90]. The USA Occupational Safety and Health Administration (OSHA) has defined a safety limit at the workplace of 25 ppm over an eight-hour workday; above this limit, it reduces the oxygen-carrying capacity of hemoglobin. Above 100 ppm, it becomes immediately dangerous. NO is a signaling molecule in several physiological and pathological processes in humans and other mammals. It can diffuse freely across cell membranes; it is, for example, a cardiovascular signaling molecule. It increases vasodilation and blood flow while playing a strong role in angiogenesis. In almost all types of organisms, it is a byproduct. As a diagnostic biomarker, its measurement in exhaled breath can be exploited for diagnosing digestive diseases and inflammation in the stomach (gastritis, hepatitis, and colitis), liver transplant rejection, cystic fibrosis, encephalopathy, helicobacter pylon digestive cancer, and respiratory diseases, such as chronic obstructive pulmonary disease (COPD) and asthma [91]. Hence, converting NO into harmless nitrogen species through catalytic reactions has gained attention [92][93]. Therefore, the production and development of gas sensors has become a significant concern for researchers and scientists. Carbon structures such as fullerene (C_{60}), graphene, graphene nanoribbons, graphene quantum dots, and CNTs have been proposed for sensing CO, NO, and NH_3 gases [94].

5.3. Nitrous Oxide (N_2O)

N_2O is a toxic gas that finds widespread use in medicine, specifically in surgery and dentistry, due to its anesthetic and analgesic properties. It is commonly known as ‘laughing gas’ due to its euphoric effects upon inhaling it, which can cause slight hallucinations. As a result, it is also used as a recreational substance. Nevertheless, it is neurotoxic and can cause irreversible neurological damage, while it has also been associated with DNA damage. It is a non-flammable and colorless gas with a sweet smell and taste; it is stable at RT and easy to store. At elevated temperatures, it is a powerful oxidizer, and it is thus used in motor racing and rockets as a propellant. It is also extensively used as a food additive as an aerosol spray propellant for cooking sprays and aerosol whipped cream. N_2O is known to be a primary ozone scavenger in the stratosphere, contributing significantly to global warming, especially since it is the third most important long-lived greenhouse gas. CO and N_2O are critical greenhouse gases that play a crucial role in air pollution, with N_2O being ~300 times more damaging and having a longer lifetime in the atmosphere than CO_2 [95].

N_2O is primarily generated in industrialized agriculture, animal farms, and through excessive use of synthetic fertilizers [96]. Its concentration in the atmosphere increases annually by approximately 1 ppb, and, in 2020, it reached a value of 333 ppb. About 40% of emissions between 2006 and 2016 are estimated to be due to human activity, primarily from emerging economies’ industrial and agricultural sectors. The above highlight the necessity for developing reliable methods to monitor N_2O. Currently, N_2O is analyzed using several methods, such as infrared laser spectroscopy using QCL, gas chromatography, (MEMS)-based approaches, NDIR adsorption, and chemiresistive and electrochemical methods (e.g., amperometry) [95]. Gas chromatography, however, requires the removal of moisture and particles and dilution steps that increase measurement uncertainty, making this approach unsuitable for real-time measurements of N_2O [97].

5.4. Nitrogen Dioxide (NO_2)

NO_2 is a highly reactive gas and one of the most prevalent atmospheric gaseous pollutants, ranking second among the hazardous pollutants produced by automobiles. It is mainly produced by fossil fuel combustion, automobile exhaust, power plant emissions, and industrial activities. It is considered one of the most hazardous environmental and biological pollutants. It can cause severe respiratory problems, such as asthma, lung inflammation, and increased susceptibility to respiratory infections, even at short-term exposures and low (ppm) concentration levels. Some non-respiratory system problems caused by NO_2 exposure are diabetes, hypertension, and heart and cardiovascular diseases [98]. It is also a threat towards animals, plants, and the environment, and also one of the primary factors producing photochemical pollution and acid rain [4]. Therefore, it is of utmost importance to develop high-performance gas sensors that can precisely monitor concentrations of NO_2 at the parts per billion (ppb) level. MOS gas sensors, such as those based on ZnO, SnO_2, TiO_2, In_2O_3, MoO_3, and WO_3, have garnered significant attention for their low cost, high sensitivity, and abundance [99][100][101][102]. MOSs commonly requires elevated temperatures, which enable them to achieve considerable sensing performance. However, this also results in higher power consumption, making their use impractical for portable applications like wearable devices.

On the other hand, two-dimensional (2D) metal sulfides have emerged as high-performance and power-saving materials for gas sensing but have received relatively little attention. However, doping of 2D metal sulfides has been shown to enhance gas interaction properties, particularly at RT. For example, Cheng et al. synthesized three-dimensional (3D) micro-combs from 2D N-doped In_2S_3 via hydrothermal synthesis, resulting in an RT reversible NO_2 gas sensor [103]. They have shown that N-doping significantly enhances the electronic band structure of In_2S_3, which enables hybridization with NO_2 molecular orbitals.

5.5. Carbon Monoxide (CO)

CO is one of six primary air pollutants the World Health Organization (WHO) identified. CO is a colorless and odorless gas that is less dense than air. It is produced by the incomplete combustion of fossil fuels, gas from automobiles, aeroplanes, natural gas emissions, coal mines, fires, industrial waste, sewage leaks, solid fuel appliances, water heaters, open flames, and other biological activities [104]. This pollutant harms all natural resources, including the air, water, earth, and all living organisms. Therefore, several attempts have been made to reduce and prevent exposure to harmful pollutants. As CO is an industrial-based chemical gas that is widely used in fuel production and other applications, the WHO has set an exposure limit of 9 ppm for CO for 8 h. Mild exposure to CO can cause breathing problems, headaches, nausea, dizziness, and fatigue [105][106]. However, more deadly symptoms are triggered when a person is exposed to a greater CO concentration [107]. When exposed to CO gas, CO molecules displace the oxygen in the body, leading to poisoning. CO rise in blood carboxyhemoglobin (CO-Hb) is the best biomarker to characterize CO poisoning [108].

On the other hand, the most probable direct cause of mortality is the buildup of CO in tissues. Apart from gas chromatography, there is no dependable technology that can accurately assess the amount of CO present in tissues. A synthetic supramolecular molecule called hemoCD1, consisting of an iron(II) porphyrin and a cyclodextrin dimer, was utilized as a reagent in a simple colorimetric test to measure the concentration of CO in biological samples [108]. The test was validated in various organ tissues obtained from rats under standard settings and after exposure to CO. The kinetic profile of CO in blood and tissues after CO treatment revealed that CO buildup in tissues was avoided by circulating Hb, suggesting a protective function of Hb in CO intoxication. This finding was based on the kinetic profile of CO in blood and tissues after CO treatment. According to the findings, the buildup of CO-Hb and CO in tissues in vivo is accelerated when CO gas is inhaled. Even while air or O_2 ventilation can return CO-Hb levels to baseline levels, it is challenging to eliminate CO from tissues, particularly in the brain. This is especially the case for accumulation.

5.6. Carbon Dioxide (CO_2)

All aerobic organisms release CO_2 as a waste product when they metabolize organic compounds to produce energy by respiration. CO_2 is also released from organic materials when they decay or combust (e.g., forest fires or by humans for heating and other purposes). On the other hand, CO_2 is utilized by plants as part of their metabolism for photosynthesis, releasing O_2. Consequently, CO_2 is necessary for the survival of life on earth. CO_2 is also released into the environment from the extraction and burning of fossil fuels (such as coal, oil, and natural gas) and natural processes like volcanic eruptions. Other significant anthropogenic sources include biomass burning, deforestation, and cement production. Transportation, industry, and agriculture are the primary sources of air pollution in cities. As of May 2022, the global average concentration of CO_2 in the atmosphere is 421 ppm. Compared to 280 ppm before the mid-18th century, this is an increase of 50% since the start of the Industrial Revolution [15]. This is well above the threshold of 350 ppm required to prevent irreversible climate change. This increase is due to human activity, mainly due to the burning of fossil fuels. In

addition, CO_2 absorbs and emits infrared radiation. As a result, it plays a significant role in influencing Earth's surface temperature through the greenhouse effect, making CO_2 a major contributor to global climate change. This phenomenon has been linked to an increase in severe weather conditions, such as storms, droughts, and wildfires worldwide [109].

CO_2 is a colorless, odourless greenhouse gas [110]. It is an asphyxiant gas and not classified as toxic or harmful. Nevertheless, high levels of CO_2 can have a significant impact on human health, causing everything from tiredness and loss of concentration (100–2000 ppm), drowsiness and a stuffy lung feeling (10,000 ppm), to death (>40,000 ppm), with concentrations of 70,000 to 100,000 ppm causing suffocation, even in the presence of sufficient oxygen. This initially manifests as dizziness, headache, visual and hearing dysfunction, and unconsciousness within a few minutes to an hour. As a result, detecting CO_2 gas is crucial. More efficient building insulation can minimize the consequences of climate change, but over-insulated buildings may not be healthy. Poor ventilation can lead to low oxygen levels and a build-up of CO_2. Even low levels of CO_2 can severely impact health and productivity. There is, thus, an increasing demand for miniaturized and precise gas sensors that can be effectively employed in large-scale sensor networks to monitor greenhouse gas concentration patterns. These sensors must be capable of monitoring fluctuations in greenhouse gas concentrations [111]. As a result, manufacturers of CO_2 sensor modules are seeing a rise in demand for smart indoor air quality monitors that can detect rising CO_2 levels and inform the user or trigger a system reaction. Wearable CO_2 sensors in smart homes and workplaces enable precise measurement of CO_2 levels. A recent study took advantage of the widespread use of facemasks for combating the spread of the severe acute respiratory syndrome coronavirus (SARS-CoV-2) virus that caused the COVID-19 disease.

5.7. Hydrogen Sulfide (H_2S)

H_2S is a colorless, poisonous, highly flammable, corrosive, and toxic gas that is produced during the processing and breakdown of organic materials, e.g., from bacteria and industrial production activities related to fossil fuels, natural gas and petroleum production, and refineries. It inhibits cellular respiration and can rapidly damage the organs, and cause convolutions, breathing difficulties, and even death, affecting the nervous system. At low levels (~10 ppm), it causes eye irritation, nausea, cough, shortness of breath, fatigue, dizziness, and headache over time; 50–100 ppm can lead to eye damage. Consequently, it is classified as a hazardous air pollutant as it causes adverse health effects, making it a dangerous gas.

Moreover, the odor of H_2S diminishes beyond 100 ppm, which is considered a potentially fatal concentration, due to damage in the olfactory nerve [49][112][113]. An amount above 320 ppm leads to pulmonary oedema, and 530 ppm leads to strong nervous system stimulation and potential loss of breathing. In contrast, 5 min exposure to 800 ppm is lethal for half the population. At the same time, H_2S is a signaling molecule and a mediator for several disease states and healthy physiological processes. For example, overproduction of H_2S is related to cancer and Down syndrome, while underproduction is associated with vascular disease. Thus, a sensing solution for rapidly detecting low H_2S concentrations is required. Commercially available solutions typically provide an alarm to the user at 5–10 ppm and a second alarm at 15 ppm.

5.8. Sulfur Dioxide (SO_2)

SO_2 is a dangerous toxic pollutant produced by burning fossil fuels in places such as oil refineries, power stations, and industrial plants. It is also generated from volcanic eruptions and forest fires. It is a widely used food preservative, particularly with dried fruit, due to its antimicrobial properties and aptitude to prevent oxidation. It is extensively used in winemaking as an antibiotic and antioxidant since it protects wine from bacteria, and oxidation can spoil it. It is widely used for chlorinated wastewater treatment. It can be found in small concentrations in the atmosphere, in the region of 15 ppb. It is one of the six air pollutants monitored in the US, with a limit of 75 ppb for one hour of exposure. Endogenous SO_2 is essential in regulating cardiac and blood vessel function, and its deficient metabolism can lead to cardiovascular problems. Overexposure to SO_2 can cause severe health problems in the eyes, lungs, and throat. This pollutant harms human health, due to its high solubility in water.

SO_2 molecules can accumulate in rivers, soil, and clouds, resulting in acid rain. Acid rain disrupts the natural balance of wildlife and can damage building materials, such as limestone, ecosystem stability, and agricultural production [114]. These adverse effects of SO_2 have stimulated research in developing sensitive, low-cost, and wearable sensors.

5.9. Ozone (O_3)

Ozone formation in the troposphere occurs through a reaction between nitrogen oxides and volatile organic compounds released into the atmosphere by solar radiation. Ozone has a negative impact on human health, as it can cause

respiratory and cardiovascular diseases and can affect the central nervous system. Ozone pollution in urban areas is related to heat-related mortality during heat waves. Moreover, exposure to even low ozone levels, below those currently regulated, can have chemical and toxicological effects due to its potent oxidative properties, leading to cellular-level oxidative damage. Above 0.1 ppm, it causes damage to mucous and respiratory tissues in animals and in plant tissue. As specified by the WHO, 50 ppb is the O_3 exposure threshold for 8 h [115]. At the same time, it also interferes with photosynthesis, affecting the growth of certain plant species. These detrimental effects of ozone have prompted research into its rapid and accurate detection, even at very low concentrations. In 2020, the USA Environmental Protection Agency (EPA) established the safe limit for ozone exposure at 0.09 ppm/h. In addition to its harmful impacts, ozone is also utilized for disinfecting medical environments owing to its oxidative properties. At high altitudes and in the so-called ozone layer, its high concentrations in the range of 2–8 ppm protect life on Earth by preventing dangerous and damaging UV irradiation from reaching the planet's surface. It is important to note that catalytic decomposition with solid catalysts can be achieved with noble metals, such as Pt, Rh, or Pd and transition metals, including Mn, Co, Cu, Fe, Ni, or Ag. Alternatively, it can be decomposed with heat (a prolonged process below 250 °C) or under UV irradiation. However, given the potential toxicity of ozone in public spaces, there is a need for portable sensors to detect its presence [116][117].

5.10. Hydrogen Fluoride (HF)

Hydrogen fluoride (HF) is widely utilized in various industries, such as electronics manufacturing and metal cleaning, as well as in the production of various pharmaceuticals and other chemicals, such as fluoropolymers, chlorofluorocarbons, aluminum fluorides, and petrochemicals. Additionally, it is employed as a rust removal and car washing agent for domestic use. With a pH level of approximately 5.5, HF is classified as a weak acid that can dissolve lipids. Its significant solubility in lipids enables it to swiftly penetrate tissues when contacted or inhaled, resulting in poisoning upon ingestion, skin burns, and blindness by rapid destruction of the cornea. Exposure to it necessitates immediate medical attention. In severe cases, prolonged exposure to HF can cause hypocalcemia and hypomagnesemia due to its affinity for calcium and magnesium in the body.

In contrast, it can cause death due to irregular heart rates or pulmonary oedema [118]. Due to the toxic properties of HF mentioned above, regulating, and detecting its presence is crucial. OSHA has set the permissible exposure limit for HF at 3 ppm, with a short-term exposure limit of 6 ppm. However, exposure to HF would quickly exceed these established limits in case of a leak or spill. For example, the thermal decomposition of hydrofluorocarbon (HFC)-based fire extinguishers and lithium-ion battery fires can result in high levels of HF exposure. In such cases, the rapid production of HF from HFC-based fire extinguisher decomposition can exceed the limits set by OSHA by a significant amount [118].

5.11. Volatile Organic Compounds (VOCs)

VOCs are chemicals with a relatively high vapor pressure at RT and atmospheric pressure. VOCs are a complex and difficult-to-detect group of substances. This category encompasses alcohols, aldehydes, aromatic hydrocarbons, non-methane hydrocarbons (NMHCs), oxygenated organic compounds, halogenated hydrocarbons, and organic compounds that contain sulfur and nitrogen. Most VOCs are hazardous, possess strong odors, and can harm human health and the environment. They can cause a wide range of versatile respiratory, immune, and allergic effects, among other issues, such as liver, central nervous system and kidney damage, loss of co-ordination, nausea, headaches, irritation to the throat, eyes and nose, allergic skin reaction, dyspnea, fatigue, vomiting, visual disorders, memory impairment, and nose bleeds. In addition, their presence can affect the air quality inside and outside buildings; their indoor concentration can be two to five times greater than outdoors, or even thousands of times more when specific activities occur indoors [119]. These compounds can originate from various sources, including natural processes and human activities. However, they are mainly generated through manufacturing processes in the energy industries, fossil fuel production and use (through their incomplete combustion or evaporation), and the use of solvents in paints, inks, and coatings, which are crucial components in the production of ash and photochemical haze [120].

Nevertheless, they play an essential role in communicating with animals and plants. Consequently, VOC sensors are crucial in the oil industry, food and agriculture, healthcare, safety, environmental monitoring, and other fields [121]. Therefore, wearable VOC electrical, optical, and gravimetric sensors are gaining increasing scientific and technological attention. Recently, $Ti_3C_2T_x$ nanosheets and 2D TMDCs (such as WSe_2) were combined to create a chemiresistive sensor that selectively detects oxygen-based VOCs. The $Ti_3C_2T_x/WSe_2$ hybrid sensor was found to have a reduced noise level, quick response and recovery times, and high adaptability for a wide range of VOCs. In addition, the sensitivity of the hybrid sensor to ethanol was increased by over 12 times, which is a significant improvement compared to unmodified $Ti_3C_2T_x$. Inkjet printing was used to deposit the hybrid gas-sensing membrane on a polyimide substrate with an Au-interdigitated electrode structure composed of six pairs of fingers with an active electrode area of 8 mm × 8 mm, allowing measurements to determine the concentration of ethanol gas between 1 to 40 ppm [122].

A prototype for a wearable VOC sensor was designed and demonstrated based on the synergistic effect of mechanochromic–vapochromic luminescence [123]. The synthesis pathway was developed based on crystal analysis and emissions from molecules in crystalline states. These molecules adopt a planar conformation and avoid π–π stacking through side-inserted molecules. Additionally, the mechanical structure of these crystals forces the molecules into coupled π-dimers to quench the light emission. However, upon detection of VOC, intermolecular interactions are rebuilt, and π-dimers are isolated, giving light emission an advantage. Such a molecular-level design allows for VOC detection at the ppm level.

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