Gas sensing technologies – status, trends, perspectives and novel applications

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Abstract

The strong, continuous progresses in gas sensors and electronic noses resulted in improved performance and enabled an increasing range of applications with large impact on modern societies, such as environmental monitoring, food quality control and diagnostics by breath analysis. Here we review this field with special attention to established and emerging approaches as well as the most recent breakthroughs, challenges and perspectives. In particular, we focus on (1) the transduction principles employed in different architectures of gas sensors, analysing their advantages and limitations; (2) the sensing layers including recent trends toward nanostructured, low-dimensional and composite materials; (3) advances in signal processing methodologies, including the recent advent of artificial neural networks. Finally, we conclude with a summary on the latest achievements and trends in terms of applications.

Keywords: electronic nose; gas sensors; signal processing; food monitoring; environmental monitoring; breath analysis.

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1. INTRODUCTION

Gas sensing has been object of intense study in the past years because of its extremely wide range of applications, such as detection of toxic or explosive gases in safety/security field, monitoring of industrial processes, environmental pollution and air quality [1-3], food aroma identification and food quality control [4], breath analysis and diseases diagnosis [5]. The first commercial gas-sensor device dates back to 1960s and employed metal oxides as sensing layer [6, 7]. Another milestone was the patent of the first chemiresistive gas sensor at the beginning of the 1970s. In this early development stage, one of the main purposes related fire prevention [2]. Then, the field attracted increasing attention while broadening the range of applications with efforts dedicated to enhance the sensors’ performances in terms of “3s” improvement: sensitivity, selectivity and stability.

Another major goal was to implement an "electronic nose" able to mimic the ability of human olfactory system to detect a complex pattern of gases by comparing the signal of millions of nose receptors [7-9] with brain supporting for odours recognition (Figure 1). Thus, such devices will permit to recognize the unique fingerprint associated to a substance/environment/condition. Emulating olfaction means reaching both high sensitivity for odours and high discrimination between them. According to Garden and Bartlett, an electronic nose can be defined as "an instrument which comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern recognition system, capable of recognizing simple or complex odours ” [10].

Among the pioneering works, it is worth mentioning the first olfaction device proposal by Moncrieff in 1961 and the first electronic nose developed by Wilkens, Hatman and Buck in 1964 [11]. However, making an electronic nose is a challenging task, often demanding compromises during design. For example, the high specificity of the human receptors is based on irreversible interactions with analytes, which is possible since natural receptors have a lifetime of few weeks [8]. On the other hand, general lifetime of artificial sensors
must be much longer for practical applications. However, using an array of sensors responding in a different manner to a fixed stimulus, it is possible to cross data and obtain information on the environmental composition [8] with recognition achieved thanks to data analysis [5].

A crucial aspect investigated in the last years concerns finding novel classes of materials to improve the sensors characteristics. After metal oxides and conductive polymers, nanoscience and nanotechnologies brought a wide range of novel active, nanostructured, low dimensional and nanocomposite materials for gas sensors. In this respect, the main challenges regard improved selectivity and tunability, high sensitivity and short response time, long-time stability, room-temperature operation, easy device fabrication, scalability [12]. Another key element in determining the sensor performance is the transducer.

Due to the strong, continuous progress in the field of gas sensors and electronic noses, the available active materials and transducers, the always increasing range of applications and the huge impact of these technologies on modern societies, it is then worth reviewing the field with special attention to established and emerging approaches as well as the most recent breakthroughs and perspectives. This is the aim of the present review, which is organized in different sections focusing on advances in (i) sensing principles and transducers, (ii) active material design, (iii) signal processing such as by Principal Component Analysis (PCA) and (iv) specific applications. In particular, without the ambition to be exhaustive, but having the goal to give useful insights to researchers either approaching or working on this topic, we will discuss both seminal works and recent literature, dedicating special attention to Volatile Organic Compounds (VOCs) and hazardous gases detection analysing.
2. STATUS AND PROGRESSES IN GAS SENSORS TRANSDUCERS

Two key elements for all chemical/gas sensors are the transducer and the active layer material which together allow to transform analytes concentration in a measurable physical signal, then available to be processed and analysed (Figure 2). In this section, we will focus on status and innovation in terms of transducers, while active materials and processing are described successively. Detection can be carried out exploiting a wide range of approaches, including (i) benchtop methodologies such as mass spectrometry, ion mobility spectrometry, gas chromatography, infrared spectroscopy [13-15] or (ii) miniaturized devices such as optical sensors, chemiresistors and impedance sensors, transistor/diode (electronic) sensors, amperometric sensors, piezoelectric crystal sensors (e.g. SAW devices, QCMB), calorimetric/thermometric sensors [8, 12, 16, 17]. Remarkably, the second approach is more suitable for portable tools and parallel monitoring of various compounds. It is worth analysing transduction strategies and the involved concepts in more detail before performing a comparative discussion.

*Figure 1: Analogies and parallelism between the human olfactory system and the electronic nose.*
2.1 Optical sensors

Different optical parameters can be monitored for realizing sensors based on absorption (UV-VIS, IR), colorimetric changes, reflectometry, ellipsometry, refractive index sensing, surface plasmon resonances. Absorbance measurements in a particular frequency range are one of the most direct methods to quantify an analyte concentration based on the Beer-Lambert Law [15] and a simple approach consists of using colour-changing indicators [8]. Figure 3 shows an example of a commercial non-dispersive infra-red optical sensor, including a first filter for broadband measurements and a second filter to measure a neighbour band which is not absorbed from the gas and is then used for calibration purposes in order to compensate for changes in the emission of the source [15]. Another example concerns polyaniline-based optical sensors which detect a gas analyte (e.g. ammonia) through refractive index sensing based on changes in surface plasmon resonance typically via reflectance measurements [18]. This group of sensors generally presents high gas specificity and sensitivity, in comparison with other transducing principles such as chemiresistors and impedance devices. On the other hand, among the main disadvantages
there are cost and a larger complexity of detecting systems. These systems are daily adopted in environmental quality control such as in cities, but today research focuses strong attention on other, simpler, transduction principles such as chemiresistors (discussed below).

![Figure 3: Non-dispersive infrared optical device: a) device architecture and b) typical response for CO₂; reproduced from ref. [15].](image)

### 2.2 Chemiresistors and impedance devices

Another class of devices exploit transduction based on resistance or impedance variations (chemiresistors and impedance devices, respectively) as a consequence of analyte-induced changes in the electrical properties of the active layer. A typical implementation consists of one (Figure 4 a) or several pairs (Figure 4 b) of electrodes and an active layer contacting them following a layout introduced for the first time in the 1960s [2]. Regarding impedance sensors, the typical response curve has the form of a Nyquist plot, as reported in Figure 4 c), containing information on resistance variations (x-axis intercept at low frequency), capacitance changes, peak frequency variations (frequency of highest value of $-\text{Im}Z$). In general, the electrical parameters can be extrapolated by fitting with an equivalent circuit. Among the major strong points of this kind of devices, there are the easiness in miniaturization and their stability, especially considering metal-oxides (MOX) based sensors. Different commercial (and experimental) e-noses (see Section 2.6) are today available using this technology, especially for air quality control. The research
trend in this field mainly focuses now on addressing some drawbacks of these devices, such as power consumption for MOX-based sensors or instability for polymers-based devices. Hybrid materials showed great improvement in the operating temperature (which often became room temperature, while traditional metal oxide-based sensors work in the range 100–400 °C) and in the sensitivity/selectivity of the detectors. The topic of materials for sensing layers is discussed in Section 3.

Figure 4: a) Chemiresistor response to NH₃, [reproduced from [19]] and architecture of a typical device; b) response of a solid-state electrochemical NOₓ gas sensor upon NO exposure, [reproduced from [20]] and layout of a typical EIS device presenting an active layer on interdigitated electrodes.

2.3 Electronic devices

A Thin Film Transistor (TFT) consists of a semiconductor as active layer in contact with two electrodes (source and drain) and a third electrode (gate) which is separated from the active layer by an insulating film. In this device, when a voltage is applied between source
and drain and to the gate, the exposure to gas analytes modulates the current flow in the dielectric (Figure 5 a). An example of a typical response curve is reported in Figure 5 b), in which the current between source and drain changes based on the gas exposure [21]. Another example of employed electronic device is the diode: upon the gas analyte exposure, the electrical properties of one or more active materials vary, and the saturation current changes [12]. Given an applied voltage, the current changes can be measured and hence the concentration of the gas analyte can be estimated. Comparing diode and transistors devices with chemiresistors, it can be shown that their preparation can be more complicate [12].

These devices can be suitable in e-noses and can be considered a great supplement of the previous technologies. Differently from the chemiresistors, the active material conductivity is controlled by a gating effect which can result from variations induced in other physical properties such as polarizability. One application of interest is reported in ref. [22], in which an electronic nose made of OFETs is used to monitor chicken meat spoilage.

Figure 5: a) Design of a Field Effect Transistor in bottom-gate top-contact (BGTC) configuration and b) typical response curves of an Organic Field Effect Transistor with a p-type organic semiconductor (CuPc) toward MeOH in air and N₂ [adapted from ref. [7] and [21]].
2.4 Piezoelectric crystal sensors

Quartz Crystal Microbalance (QCMB) sensors and Surface Acoustic Wave (SAW) sensors are also employed within the class of piezoelectric crystal sensors.

QCMB exploits quartz piezoelectricity: if an alternate voltage is applied to the electrodes (Figure 6 a), periodic oscillations can be induced in the piezoelectric crystal which exhibits a resonance frequency dependent on the mass load, according to the equation [12, 23]:

\[
\Delta f = -\frac{\Delta m f^2}{A \sqrt{\mu \rho}}
\]

where \( \Delta f \) is the resonance frequency shift, \( f \) the resonance frequency, \( \Delta m \) the mass change on the surface of the device, \( \mu \) the shear modulus, \( \rho \) the density of the quartz crystal, and \( A \) is its surface area. Once the active layer is placed on the piezoelectric crystal, the analyte-induced changes in adsorbed mass can be measured via \( \Delta f \).

It must be underlined that piezoelectric sensing principles do not measure electrical or optical variations in the active material, making this transduction principle complementary to the ones discussed above.

Surface Acoustic Waves (SAW) are mechanical oscillations traveling on the surface of an elastic material, whose amplitude decreases exponentially with depth [24, 25]. Among the simplest setup, there are interdigitate structures (spaced few microns) on piezoelectric substrates (e.g. quartz) made via photolithography techniques. By providing a sinusoidal voltage (input) to one couple of interdigits (emitter), a wave propagating on the surface of the piezoelectric material can be generated: an electric sinusoidal input modifies periodically the distance between the electrodes, generating the surface wave. Measuring the output signal with additional interdigits, employed as receiver, it is possible to measure changes in the propagating wave (e.g. resonance frequency and phase shift) which are correlated with surface modifications on the piezoelectric material due to mass or morphology changes (Figure 6 b). An example of signal variations upon the gas exposure
in SAW devices is shown in Figure 6 c) and d) [26]. The transmitted signal is measured while providing as input an alternate voltage, swiping in a range of frequency and considering that the resonance peak is of the order of 100-300 MHz and that the resonance peak shifts upon the gas exposure (Figure 6 c). This information can be calibrated to extrapolate the gas analyte concentration in the environment Figure 6 d). SAW sensors have important advantages, including low cost, ultra-high sensitivity, superior response time, small size, wireless mode, planar structure, excellent selectivity, fast response, linearity [27].

Figure 6: a) Configuration of a quartz crystal microbalance sensor device, adapted from ref. [12]; b) SAW emitted by an interdigit transducer in opposite directions; c) transmitted signal in a SAW device with different relative humidity (RG); d) frequency shift of the resonance as a function of RH in the SAW device [reproduced from [26]].
2.5 Calorimetric/thermometric sensors

In this kind of sensors, the temperature of the active layer varies upon the gas exposure because of catalytic combustion. More in detail, on the catalyst (e.g. TiO$_2$), which is the active layer, the gas analyte burns, generating a measurable change in temperature. This allows the detection of low concentrations of gas in a short response time. These sensors are generally employed in online pipeline inspection [28] and are also used in high-temperature harsh environment. In ref. [18], an example of catalytic sensor is reported. The sensor works at 100-500°C and comprises alumina beads embedded with a dispersed catalyst such as Pt or Pd; in this case, when combustion of the gas analyte on the catalyst occurs, the generated heat causes measurable resistance variations.

2.6 Commercial sensors and research trend

In the previous sections, several transduction principles have been discussed. Among today most precise and reliable devices, we reported optical sensors, while we emphasized on the possibility to scale down devices made of chemiresistors and electronic sensors in general. Piezoelectric crystal sensors show very good sensing characteristics but, if compared with this last group of sensors, they are more complex and difficult to implement into commercial all-purpose devices. To date, one of the main research trends consists of using different chemiresistors whose active layer is made of hybrid organic-inorganic materials with special topologies, and analyse the data array through artificial intelligence to further improve sensitivity and selectivity.

Among the available commercial sensors, chemiresistors based on metal-oxides active layer are one of the most used technology. This is due to characteristics such as long life, small size, simple electrical circuits, high sensitivity. As an example, we report the TGS 2602 Figaro USA Inc. gas sensor for the detection of Air Contaminants (Figure 7).
Figure 7: sensitivity characteristics of TG 2602 Figaro USA Inc. gas sensor. As reported in the datasheet, the circuit needs a long conditioning period before test (7 days) and the conversion table to calculate the gas concentration is provided through a graph in logarithmic scale.

Nowadays, a number of e-noses are available in the market, promoted as generic devices suitable for a specific range of applications; as previously mentioned, they generally comprise a multi sensor array, an information-processing unit, a software with digital pattern-recognition algorithms and a reference-library database to provide the composition of an analyte mixture, also referred as electronic analyte fingerprint. In Figure 8, some examples are reported [29], including Figaro Engineering Inc., Japan, e-noses which were employed for example for tea or coffee classification.
Figure 8: Applications of e-nose in different food matrices, adapted from ref. [29].

Table 1: Transduction methods summarizing table.

| Transducer                  | Working principle                                      | Advantages                                                                 | Limiting factors                                                                 |
|-----------------------------|--------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Optical sensors             | changes in optical absorption, emission or refractive index | fast response time (below 1s), minimal drift and high gas specificity and sensitivity | need of excitation sources and detection devices, lower portability, expensive   |
| Chemiresistors (metal oxides) | changes in impedance                                  | stable reactions, can be miniaturized, high sensitivity                      | high working temperature (~300 °C), high power consumption, sensitive to humidity |
| Chemiresistors (polymers)   | changes in impedance                                  | easy tuning, can be miniaturized, low power consuming, room temperature operation | generally unstable in the atmosphere, sensitive to humidity, long recovery time  |
| Transistors (electronic devices) | changes in the flowing current under a fixed applied voltage | mechanical flexibility, low operating voltages, low temperature, large-scale manufacturing [7] | absence of unified working mechanism model; need of improvements for OFET sensors; more complex with respect to other devices |
| Diodes (electronic devices)  | changes in the flowing current under a fixed applied voltage | presence of additional parameters for measurements if compared to chemiresistors | generally, more difficult to realize and characterize if compared to chemiresistor devices |
| Piezoelectric sensors       | changes in acoustic waves signal amplitude / resonant frequency | high sensitivity, superior response time, good response time, small size | sensitive to external interferences (e.g. temperature) as well as to internal defects |
| Catalytic sensors           | temperature variations due to gas analyte combustion   | low sensitivity to humidity, low cost, fast response and recovery time       | low sensitivity, low selectivity                                                 |
3. ADVANCES IN ACTIVE LAYER MATERIALS

The active layer is the second key element in gas sensors and different kinds of materials have been used or proposed so far, including metal oxides, organic compounds and conductive polymers, mesoporous materials, nanomaterials, 2D materials, nanocomposites and hybrid combinations of them. A summary is reported in Table 2. For a further insight in the process of designing and optimizing modern gas sensors and electronic noses, it is then useful to discuss them in some detail.

3.1 Metal oxides

Metal oxides were among the first materials to be employed for gas sensing purposes. In this case, the sensing mechanism depends on active surface charge variations [17] and thus these materials are very suitable for resistive or impedance-based read out. Various metal oxides were investigated, such as SnO$_2$, TiO$_2$, WO$_3$, ZnO, Fe$_2$O$_3$ and In$_2$O$_3$ (Figure 9). Among them, ZnO attracted large interest as a multifunctional n-type semiconductor material [30]. One of the major drawbacks of metal oxides-based sensors consists in the poor selectivity: this comes from the fact that, in most of the cases, a similar local surface modification is induced by different analytes. Another drawback resides in the high working temperatures (100 – 400 °C) which are typically required; this leads to baseline drift, oxidation of analytes [17] and high power consumption. The sensitivity and the specificity of the devices depend also on the operating temperature [14]. Metal oxide sensors generally need a pre-heating in which oxygen on the surface adsorbs and ionizes and the material becomes sensitive to the gas analyte; as a consequence, the resulting O ions at the surface become reactive with activated hydrogen or dehydrogenate hydrides and hydrocarbons [2, 3, 14, 30]. In the case of ZnO, for example, if the sensor is exposed to air, oxygen molecules adsorb on the surface and collect electrons from conduction band of ZnO. Chemisorbed reactive oxygen species (O$_2^-$, O$^{2-}$, O$^{-}$) are formed in this process [30] and these
species can react with gas analytes, i.e. O\textsuperscript{-} reacts stably with acetone: when the vapour is introduced, a chemical reaction occurs between the adsorbed oxygen and acetone vapours, releasing electrons back into the conducting band of the material, causing a drop in the measured resistance of the active layer. It must be underlined that, in the case of oxidizing gases, the analytes also react directly with the bulk material instead of the formed O ions, modifying the material’s conductivity [31]. The grain size effect is another relevant aspect in determining the response (Figure 10). In general, the resistance variation depends on the sensing material (n-type or p-type metal oxide) and the gas analyte (oxidizing or reducing) [2, 31, 32]; both n-type and p-type oxide semiconductors adsorb oxygen, exhibiting different conduction trends in their response. From a general point of view, most of the oxides used in these applications are n-type materials [32] (Figure 9). An interesting application for metal oxide gas sensors is food aroma identification: considering that the human nose is less responsive to higher oxidized volatiles [14], artificial sensors could be helpful in this field.

*Figure 9: Pie chart illustrating the use of n-type and p-type materials in gas sensing research [reproduced from ref. [32]].*
3.2 Organic compounds and conductive polymers

The use of organic compounds, such as conducting polymers, in gas sensing started in the early 1980s [34]. In general, they are useful for realizing room-temperature gas sensors with high sensitivities and short response times (generally tens of seconds) and provide a huge variety of possible candidate materials as a result of possible functionalizations and tunings. Conductive organic materials are based on conjugated molecules presenting $\pi$ and $\pi^*$ bonds with delocalized electrons enabling conduction along the polymer backbone chain mainly via hopping mechanism. In this case, sensitivity comes from changes in electrical conductivity due to doping-dedoping processes, variations in optical absorption and polymer weight modifications. Notably, conducting polymers can be significantly tuned: to increase their conductivity, carrier density can be modified via doping; moreover, by adjusting their chemical properties, it is possible to change the affinity to different gases. Additionally, these materials generally present good mechanical properties and can be
made soluble, allowing the use of inexpensive techniques (such as drop casting, spin coating or blade deposition) and permitting a facile fabrication of sensors, even on flexible substrates. Another point of interest resides in the fact that chemical reactions occurring between polymers and gas analytes are generally reversible. On the other hand, the main drawbacks comprise: the possible influence of many ambient factors (such as the presence of other gases) to their response, long-time instability (e.g. due to de-doping of conducting polymers due to environment interaction, i.e. moisture), low selectivity (although this is a general limit in the overall sector of gas sensing). In particular, the humidity in a real environment strongly affects the electrical properties and responses [17], although competitive adsorption occurs between water and the analyte was also observed to increase sensitivity in some reports [12]. Some of the main used polymers in gas sensing based on chemiresistors are polyacetylene (PA), polyaniline (PAni), polypirrole (PPy), polythiophene (PTh) and their derivatives (Figure 11). PAni (polyaniline) often appears as the best solution in polymeric gas sensing because it reacts with a wide range of analytes and is very suitable for ammonia detection [35]. In fact, significant interest in using PAni in gas sensing goes back to 1987 [36]. PAni presents outstanding properties, including simple, reversible and unique doping-dedoping chemistry, stable electrical conduction mechanisms, high environmental stability and ease of synthesis [34, 37].

Figure 11: Main conducting polymers adopted in gas sensing [adapted from ref. [12]] and layout of a gas sensor with conducting PAni nanofibers as active material [adapted from ref. [38] and [39]].
3.3 Mesoporous materials

Mesoporous materials are interesting active layers because generally present large surface-to-volume ratios which are useful to increase sensitivity. By definition a mesoporous material has mesopores with sizes between 2 nm and 50 nm [1]. In general, porous semiconducting metal oxides are often used in gas sensing; in fact, these structures can combine high gas accessibility with availability of larger sensing areas.

To measure a low signal, the target gas must penetrate as much as possible into the porous layer in order to induce a larger signal change. However, this could be also exploited to obtain an additional degree of freedom: supposing that an analyte penetrates more than another, this process could be used to improve selectivity in their discrimination; in fact, gas diffusivity strongly depends on pore size in this size regime (Figure 12a): in mesopores, the diffusion coefficient $D_k$ is proportional to the pore radius $r$ [1]:

$$D_k = \frac{4}{3} r \sqrt{\frac{2RT}{\pi M}}$$

where $R$ is the universal gas constant and $M$ is the molecular weight, while $T$ is the absolute temperature.

By heating a mesoporous metal oxide, as a consequence of the O ions adsorption, a depletion layer forms. The depletion layer is responsive to the gas concentrations in the environment, instead, the interior parts do not contribute to the sensing; as a consequence, best results are obtained when sizes are about few nanometres [1, 3, 32] (Figure 12b). In a nanostructured material, the most conductive part is the internal/core region, and it is necessary to limit it in comparison to the depletion layer to maximize the sensor’s sensitivity. Conventional sol-gel synthesis permits to obtain spherical shaped-particles with sizes of about few nanometers increasing the active/inactive region ratio.
Figure 12a) Illustration of gas sensing separation through different analyte percolation ability [reproduced from ref. [1]]; b) sensitivity in gas response versus crystalline size for SnO$_2$ based gas sensors [reproduced from ref. [40]].

Mesoporous materials can also be adopted as filter layers integrated on sensors. In this way, the presence of catalytically active species and the gas diffusion through porous layers can be exploited to separate certain gas molecules from others (i.e. suppression of H$_2$O or O$_2$ permeation), enhancing the sensor’s selectivity.

Mesoporous material-based sensors can exploit different sensing principles, such as capacitance variations, resistance variations, optical variations, gravimetric principle. Changes in permittivity in the porous material are measured in a capacitive sensor. In a resistive gas sensor, the sensitive layer resistance varies upon the interaction with the target gas; silica (SiO$_2$) is the simplest material used in this kind of sensors [41], but WO$_3$ was also employed to detect organic volatiles [1]. Mesoporous silica materials are also used as host matrices to create optical gas sensors [1].

Among the main disadvantages associated with metal oxides-based mesoporous materials there are the high working temperatures, which make these sensors not ideal for explosive gases detection. Moreover, on the long time period, the high temperature can also lead to the structure collapse and/or to the film crack [42].

An idea to improve the sensitivity of porous materials could be using hierarchical and hollow oxide nanostructures where the term hierarchical structure means the microscale pattern is composed of many, low dimensional, nano-building blocks. In fact, these
structures provide an effective gas diffusion path via nanoporous architectures with a high surface area [43]. In addition, other promising candidates are ZIFs structures (Zeolitic Imidazolate Frameworks), which are a subfamily of Metal-Organic Frameworks characterized by ultrahigh porosity, structural and chemical tunability and great equivalent internal surface areas [44].

3.4 Nanomaterials and Nanocomposites

The use of nanostructured materials and nanowires (Figure 13) in gas sensors can provide better performances compared to ordinary active materials [6, 45-47], because of their larger surface-to-volume ratio which results in an increased number of active sites. The advantages include ultra-sensitivity, higher selectivity, very short response time (ms), reversibility of sensing. For example, Si nanowires as well as Te nanotubes permitted to detect a concentration below 1 ppm of NO and NO₂, respectively [48, 49]. However, heterostructures were more commonly employed than single element counterparts because of their enhanced properties [50-52]. In the case of metal oxides materials, nanostructures can enable room temperature operation in contrast to their bulk form which typically requires heating elements. This property is advantageous for safety applications (i.e., explosives detection, and H₂) and makes these devices low-power consuming, at levels of 15-30 µW for the single nanowire [45]. As an example, SnO₂ nanotubes led to a NOₓ detection limit below 10 ppb [53], operating at room temperature. Different literature works report also light illuminated devices in the UV-vis range [54, 55]. Another approach is present in ref. [56], in which visible-light-modulation results in dual gas selectivity between NO₂ and NH₃ at room temperature.

Different transducers are suitable for integrating nanomaterials in the active layers, such as field-effect transistors, optical sensors, gas ionization sensors, quartz crystal microbalance-based sensors, SAW sensors, EIS sensors. In ref. [57], SAW sensors
employing palladium and copper nanowires has been reported for fast response hydrogen sensors with a LoD of 7 ppm; in this case, nanowires trap the hydrogen molecules by adsorbing them and then changing the surface acoustic wave properties (e.g. frequency shift).

In ref. [58], a tin oxide (SnO₂) nanowires forest was used to recognize the fingerprint of seven different gas analytes by measuring the dynamic resistance of a single sensor at five different temperatures. Therefore, a support vector machine (SVM) was used to classify the entire dataset leading to classification with sensitivity and precision of 94.3% with an average error of 18.4% in the concentration levels.

A new method to combine the advantages of metal oxides and polymers consists in designing organic-inorganic composite materials [2, 6] with outstanding mix of optical, electrical and morphological properties, which can be tuned varying synthetic routes or precursors [17]. The inorganic phase can be made of metal oxides, metal nanoparticles, carbon based (such as carbon nanotubes and graphene). The organic phase is typically a conductive polymer. Their mixing changes the bulk material properties, improving stability, selectivity, and sensitivity and/or leading to new functionality such as flexible-mechanical properties. Selectivity can be enhanced considering different specific functionalizations of the metal oxide, adjusting the organic material composition according to the analyte to detect. Nanocomposite properties are directly related to their composition.
and morphological/interfacial characteristics, whose control open the way to application-specific tuning and new breakthrough in this class of sensors [17]. On the other side, because of the interactions between the different materials, hybrid nanocomposites present complex sensing mechanisms, still not completely understood. In Table 3, some examples of ultra-low sensitive hybrid materials are reported. As an example, in Figure 13 e), a SEM image of gold nanoparticles functionalized PANI nanowires is reported.

3.5 2D materials

One of the first attempts of using graphene in gas sensing was reported in 2007 by Novoselov’s group [61]. In comparison to other carbon nanomaterials, graphene (Figure 14a) shows molecular reactions similar to large-diameter carbon nanotubes but exhibits significantly lower noise levels. Comparing low-quality and high-quality carbon materials, graphene and nanotubes present higher control of their surface chemistry than carbon black, carbon nanofibers, reduced graphene oxide [62]. In ref. [63], graphene-based gas and vapour sensors have been reviewed. Graphene, however, must be functionalized with polymers or metals to enhance the chemisorption, because intrinsic graphene has no dangling bonds on its surface. Reduced GO (graphene oxide) can be also used as sensing layer for NO₂; in [64] a FET sensor with repeatable 100 ppm sensitivity to NO₂ was reported; in this case, annealing is required to reduce the GO and make it more conductive, introducing reactive sites on the surface. More in detail, thermal treatments can be responsible of the oxygen functional groups removal from GO, and, as a result, the material recovers graphitic regions, making GO more conductive. These formed graphitic carbon atoms can result in active sites for the gas analytes adsorption [64].

Within 2D materials, phosphorene (a mono- or few-layer black phosphorus) is expected to exhibit excellent adsorption properties for CO, CO₂, NH₃, NO, and NO₂ according to theoretical studies [66, 67]. These studies predict superior sensing performance that could
surpass alternative 2D materials such as graphene. In ref. [68], another theoretical study reports that Si- and S- phosphorene doping can improve sensitivity in these sensors (Figure 14b). Other 2D materials have been also investigated in gas sensing, such as transition metal dichalcogenides, which are reviewed in ref. [69]. Really promising results have been reported, such as the chemically exfoliated MoS$_2$ flakes-based sensor by Donarelli et al. that have a LoD of 20 ppb for NO$_2$ gas [70].

A new class of two-dimensional transition metal carbides or carbonitrides (MXenes) recently showed exceptional and promising properties in terms of sensitivity and selectivity. In ref. [71], an acetone sensor with 0.5ppm LoD has been reported. In ref. [72], an hybrid active layer made of PAni and MXene resulted in very good selectivity and sensitivity to ammonia detection while in ref. [73] Schottky barriers formed in TiO$_2$ and Ti$_3$C$_2$ MXene films led to a sensor high responsive to NO$_2$.

![Figure 14: a) graphene layers (adapted from ref. [63]); b) Si- and S-doped phosphorene structures (adapted from ref. [68]).](image)
Table 2: Materials summarizing table.

| Active layer material | Working principle                                                                 | Advantages                                                                 | Limiting factors                                                                 |
|-----------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| metal oxides          | during a pre-heating phase, oxygen on the surface adsorbs and ionizes and the material becomes sensitive to the gas analytes, e.g. in the form of variations in electrical resistance | reliability in response, high control on the surface chemistry, the reacting species depends on the pre-heating temperature, long-term stability | high temperature operation, high power consumption, less tunable if compared to organic compounds |
| organic compounds     | changes in electrical properties and/or weight                                    | easy tuning, can be miniaturized, low power consuming                       | generally unstable in the atmosphere and very sensitive to environment-related factors, low selectivity |
| mesoporous materials  | measurable response as capacitance variations, resistance variations, optical variations, mass changes | large surface-to-volume ratios, pore dimensions can exploited for gaining further insight in gas sensing | high working temperature; long recovery time, structure collapsing and/or film cracking due to high working temperatures, resistance drift |
| nanostructured materials (nanomaterials) | the working principle depends on the material | nanostructured form increases the surface-to-volume ratio, room temperature operation, low power consumption, reversibility of sensing | poor selectivity, long recovery times, in some cases, irreversible sensor response, high fabrication costs |
| nanowires (nanomaterials) | subclass of nanostructure materials, in general, changes in electrical, weight, optical properties | large surface-to-volume ratio, room-temperature operations, reversibility of sensing, short response time (ms) | large-scale production can be challenging |
| graphene (2D materials) | functionalization with conductive polymers or metals amplifies sensitivity to target gases detection via resistance variations measurements | extremely low-noise levels, chemical tunability, wide range of electronic applications | generally, low selectivity, difficulties in large-scale production, long recovery time, absence of functional groups |
| phosphorene (2D materials) | change in electrical properties upon analyte adsorption | better performances than graphene | still under theoretical investigation |
| nanocomposites        | mainly, changes in electrical properties                                           | improved stability, selectivity and sensitivity, easy tuning, possibility to control the morphology to improve the devices characteristics, exploitable novel properties | complex sensing mechanism still not completely understood, tendency to agglomerate in solvents |
4. FROM TRADITIONAL TO NOVEL APPLICATIONS OF GAS SENSOR TECHNOLOGIES

4.1 Safety, industrial and environmental monitoring

Due to the increasing levels of pollution in different areas of the planet and the negative consequences on human health, environmental monitoring has become a primary need for the global agenda with increasing efforts towards a sustainable growth. In this framework, new user-friendly technologies are requested for the detection of Particulate Matter (PM) or hazardous gases (e.g. NO2 levels) in the air as well as pollutants in fresh waters, such as microplastics. Then, future fields of applications also include smart homes and smart mobile terminals. The market related to gas sensing is expected to grow at a rate of 6.25% per year, surpassing 1 billion dollars in 2022 [28].

From the 2000’s, semiconducting metal oxides have been widely used as sensors for hazardous gases [31], with the drawback that it is difficult to employ this kind of sensors for explosive gases, because of their high working temperature. Nowadays, also for environmental applications, hybrid materials appear among the best solutions for suitable and sensitive devices. In ref. [17], organic-inorganic hybrid nanocomposites are discussed to be among the best options to selectively discriminate the presence of hazardous pollutants in the air of residential areas, for example using PANI-MWCNT hybrid nanocomposite-based detector for hydrocarbon-vapours in the range 200-1000 ppm as reported in ref. [74]. During the years, a huge number of materials and technologies has been investigated by researchers and companies worldwide. In this field, sensors based on optical spectroscopy in absorption upon excitation with lasers or UV-VIS-NIR sources present high sensitivities [15].

However, novel technologies and systems of detection for environmentally hazardous gases and VOC concentrations in indoor domestic areas are needed. These devices must guarantee inexpensiveness, selectivity, real-time detection, large-scale fabrication, user
friendly operative systems. The current trend is towards the development of chemisensors, preferably with electrical readout, which have lower costs and are scalable with suitability for miniaturization and portable detection units. Table 3 summarizes some characteristics of most effective sensors (active layers and transducers) suitable for pollutant gases of interest.

Among the main challenges for real life applications, there is the strong dependence of the sensors’ response on the relative humidity of the environment: the device capability to detect a specific gas could even be totally screened by the presence of moisture. Furthermore, gas sensors are not specific, and response depends on the atmosphere composition. Thus, it is difficult, if not impossible, to obtain a uniform gas sensor specification for all the applications and environments. To face this issue, sensors arrays can be employed in combination with advanced signal processing and pattern recognition techniques (see Section 4.4). Moreover, large-scale open gas datasets can be built to be accessed and constantly updated thanks to the Internet of Things and the collected data can be processed by a cloud server, for example via Artificial Neural Networks nonlinear classification [28].

Table 3: Some examples of the pollutant gases and some of their most effective active layers according to the reported literature.

| Hazard. comp. | Health Effects | Guidelines | State-of-art gas sensors |
|---------------|----------------|------------|--------------------------|
| HCl           | Short-term exposure: eye, nose, and respiratory tract irritation and inflammation and pulmonary oedema in humans. Long-period exposure: gastritis, dermatitis, and photosensitization in workers. Dental discoloration and erosion. EPA has not classified hydrochloric acid for carcinogenicity [75] | 489 ppb (Hyperplasia mucosa) [75] | Nanocomposite copolymers of aniline and formaldehyde synthesized with a metal complex of Fe−Al [76] (95:05) | Variation of DC electrochemical conductivity of active layer | 0.2 ppm |
**NH₃**  
*Short-period exposure*: immediate throat irritation; cough.  
*Long-period exposure*: laryngeal and pulmonary oedema and bronchopneumonia, chronic bronchitis and bronchiectasis. [77]  
400 ppm irritation - 1700 ppm cough - 2400 ppm more severe symptoms [77]  
PAni nanograins on TiO₂ fiber surface [78]  
Variation of RF electrochemical conductivity of active layer  
50 ppt  
PANI-SWCNT [79]  
FET transfer characteristics  
50 ppb  

**H₂S**  
*Short-term exposure*: respiratory and ocular irritation, neurological effects; death may result as a consequence of respiratory failure.  
*Long-term exposure*: increased rate of spontaneous abortion. [80]  
110 ppb (1-day) [81]  
PAni-Au nanocomposite [60]  
Chemiresistance variation  
0.1 ppb  
Graphene-CuO nanosheets [82]  
Electric resistance variation  
5 ppb  

**NO₂**  
Eye, nasal, throat irritation and cough, bronchitis symptoms of asthmatic children. [83]  
100 ppb (1-hour), 20 ppb (1-day) [81]  
Au-PVC nanocomposite electrode [84]  
Cyclic voltammetry  
50 ppb  
Te nanotubes [49]  
Chemiresistance variation  
500pppt  

**NO**  
Pulmonary alterations with lesions of type I cells and cilia-bearing epithelial cells [85]  
2 ppm (8-hour) [85]  
Si nanowires [48]  
Normalized resistance variation  
500ppb  

**CO**  
Inhibits the transportation of oxygen in human blood, hypoxia. [83]  
26 ppm (1-hour), 9 ppm [81]  
PAni-Fe/Al (80/20) nanocomposite thin films [86]  
Electric conductivity variation  
0.06 ppm  

**H₂**  
Non-toxic, explosive. [87]  
10% in air [87]  
Pd/Cu NWs on SAW [57]  
Transmission parameter variation  
7 ppm  
VO₂ nanobelts [88]  
Chemiresistance variation  
0.17ppm  

**SO₂**  
*Short period exposure (up to 24-hour at conc.level<125 mg/m³)*: reduction in mean forced expiratory volume over one second (FEV₁), increase in specific airway resistance (sRAW), chronic obstructive pulmonary disease (COPD). [89]  
175 ppb over 10 minutes [89]  
Vanadium doped tin dioxide [90]  
Resistance variation  
< 5 ppm  

### 4.2 Food monitoring

Food monitoring is one of the most important fields of application related to gas sensing, especially in industrial processes. On one side, the electronic discrimination of gases produced during food fabrication could severely help in the standardization process. An example of interest can be the milk fermentation examination thanks to electronic noses [91]. In the near future, we can expect food quality to improve as the information related to
food production and packaging increases, especially with the development of Internet of Things.

On the other side, food safety and spoilage control are another promising sector for application. Indeed, there are several gases involved in the food decomposition mechanisms and food packaging techniques [4], such as: H₂, CO, NO₂, O₂, H₂S, NH₃, CO₂, CH₄, H₂O, C₂H₅OH. For example, the correlation between some VOCs and food spoilage has been widely studied in literature. Some examples are: NH₃, cadaverine, putrescine present in meat deterioration [92, 93]; H₂S and NH₃ associated to fish festering [94, 95], fruit fermentation producing ethylene [96-98]; milk fermentation bringing out gases such as 2-octanol, decane, 1-propanol, n-butanol [91]. In Figure 15 a), an example of application is shown, which consists in smart packaging systems to monitor meat spoilage within its packaging [93]. In ref. [97], instead, sol-gel sensors working at room temperature were employed for fruit monitoring via e-noses with the target to minimize the food waste and maximize the fruit quality. In general, post-harvest maturation process is very relevant for modern food industry [96]. In Figure 15 b), results are reported from a study performed on “Golden Delicious” apples ethanol emissions to monitor the decomposition process [96].

![Image](image.png)

*Figure 15: a) Wireless system based on polyaniline devices to monitor meat spoilage [reproduced from ref. [93]]; b) ethanol concentrations emitted from apples during spoilage process [reproduced from ref. [96]].*
4.3 Breath analysis and biomedical diagnostics applications

The idea of analysing breath goes back to XVIII century with the Lavoisier work about quantitative analysis of CO$_2$ in the breath of Guinea pigs. Then, in the late 1960s, novel studies led to modern breath analysis techniques [99] and large attention was gained by their application for biomedical diagnostics through association among a specific VOC pattern and a defined disease. For biomedical applications, however, gas sensors with high sensitivity are needed to detect very low (sub-ppb) concentrations of target gases associated to human pathologies [2], as shown in the examples given in Figure 16. In addition, the target gas must be analysed in a very complex mixture with a high humidity content. To avoid condensation, heating systems and breath delivery systems have been studied [99]; moreover, NiO-loaded SnO$_2$ as active material provide humidity-independent gas sensors, hence suitable to breath-based diagnosis [32].

![Figure 16: Proposed breath markers for different pathologies: diabetes, kidney disease, lung inflammation, liver disease, schizophrenia, bacterial infection, asthma [Reproduced from ref. [99]].](image)

Volatile Organic Compounds in breath can provide biomarkers for a wide range of diseases: researchers have identified more than 3000 different VOCs in human breath and some studies reported that in diseases including lung cancer and breast cancer VOC
biomarkers are present in patients’ breath [100]. A valuable table is given in Figure 17 which tries to provide a correlation among VOCs content and some relevant human diseases. In general, it is not possible to find a specific marker for the lung cancer, but a family of VOCs values are altered in the presence of the disease. In ref. [101], a list of VOCs of interest for lung cancer diagnosis is given including hexane, heptane, octane, nonane, decane, undecane, 1-methyl-2-pentylcyclopropane, isoprene2-methyl-1,3-butadiene, 2-methylpentane, methylcyclopentane, cyclohexane, 2-methylheptane, 2,2,4,6,6-pentamethylheptane, 2-methyloctane, 3-methyloctane, 3-methylnonane, 1-hexene, 1-heptene, 1-octene, benzene, trimethylbenzene, ethylbenzene, propylbenzene, toluene, o-toluidine2-amino-1-methylbenzene, m-toluidine, 3-amino-1-methylbenzene, aniline, styrene, xylenes, 2,3-dihydroxy-1-phenyl-4-(1H)-quinazoline, n-propanol, 2-propanol, formaldehyde, acetaldehyde, hexanal, heptanal, 1-phenyletanone, 2-butane, isopropyl myristate/tetradecanoic acid. Changes occurring in the transition from “healthy” to “unhealthy” status can be detected making breath analysis a powerful methodology for lung cancer prevention and many other diseases in general [99]. In healthy subjects, a concentration between 1-20 ppb is expected while in unhealthy subjects the concentrations raise to 10-100 ppb [101]. Notably, some literature reports the possibility to distinguish electronically among patients having different diseases, such as lung, breast, colon and prostate cancer via a nanoscale artificial nose [102].

To gain further insight in the involved processes, ref. [103, 104] investigated the correlation among in vitro VOC production from lung cancer cells and VOC presence in patients’ breath analysis. In ref. [103], among all the studied VOCs, eleven have been detected as markers of lung cancer in patients exhaled breath. The results of these studies support the idea that it is possible to distinguish between healthy persons and patients with lung cancer. In ref. [105], however, no reproducible correlation has been typically found between data collected by instrumental analysis and lung cancer but four VOCs of interest
for lung cancer diagnosis have been selected: n-hexanal, 1-butanol, 2-butanone and 2-pentanone with 92% accuracy in patients’ discrimination and 87% in healthy controls. In another recent work [106], the concentration of VOC biomarkers in controls and in patients with early-stage lung cancer were shown to be similar and, in addition, the VOCs concentrations are of the order of 0.1 ppb.

The discrepancy of analytical results and conclusions in the relevant literature can be ascribed to a variety of factors. First of all, breath in human being is not standardized: out of 3000+ different VOCs investigated in ref. [101], only 27 were common among all subjects. Most VOCs in the human breath are not generated in the body, but come from food ingestion or exposure to environmental pollutants and thus should be discriminated from pathologies-associated signals [101]. As a consequence, most breath markers (including VOCs) show ranges of concentrations which vary considerably from one person to another [99, 107]. Furthermore, the field still suffers for lack of standardization in breath sampling and analysis techniques, as evidenced in ref. [107]: in an overview of 10 papers, 170 distinct VOCs were found and only 10 of them appeared at least in two different experiments.

Nevertheless, for lung cancer diagnosis, by crossing the information in [101, 103-108], eighteen VOCs of interest were tentatively extracted: cyclohexane, xylene, ethanol, 2-butanone, isoprene, isopropanol, acetone toluene, decane, nonane, decanal, n-hexanal, n-nonanal, 1-butanol, butane, butanoic acid, butanal 2-pentanone.

In conclusion, it seems possible that early diagnosis from breath analysis could be achieved in future in reproducible way, but well-defined standardization procedures will be required to discern disease pattern indicators from signals influenced by individuals’ lifestyle, gender, diet. In this scenario, it is possible that relevant progresses could be achieved by analysing time-dependent data and performing differential person-specific measurements [109].
Another field of application is active ageing and real time monitoring of elderly / sport / vital parameters. The strength of this technology could result in portable and user-friendly diagnostic instruments (i.e., hardware + smartphone app) to make early and continuous physical check available to most of the population [110].

![Figure 17: Correlation reported between certain VOCs and human diseases [reproduced from ref. [111]].](image)

### 4.4 Current approaches for signal processing

In gas sensing applications, different statistical methods are used to analyse the raw data and determine the atmosphere composition through a matrix of different transducers and pattern identification strategies. The different techniques for data post-processing include Principal Component Analysis, Linear Discriminate Analysis, Partial Least Squares, Functional Discriminate Analysis, Cluster Analysis, Artificial Neural Network, Probabilistic Neural Network [29].

Among them, Principal Component Analysis (PCA) represents a useful method to
extrapolate information from a specific dataset reducing the dimensionality while preserving most of the statistics. More in detail, PCA transformation projects the multidimensional data into a coordinate system in order to maximize the variance and minimize the correlation between data [112]. As an example, four different simulants of chemical warfare agents [113] were analysed using an array of four SAW sensors with different active layers (ZnO, TeO₂, SnO₂ and TiO₂) resulting in different responses to distinct simulants and concentrations. The idea consists in transforming mathematically the n-dimensional data array in a lower dimension dataset. In this case, two principal components are calculated (PCA1 and PCA2). Most of the information is preserved (97%) because the variance of PCA1 and PCA2 are 82% and 15%, respectively. In Figure 18 a) these components are plotted and the differentiation among simulants is clear: all the analytes data are well separated from each other. In addition, further measurements have been collected and incorporated in the PCA plot (data in circles), confirming that the new data fit in the ellipses of the related gases. This demonstrates that the sensor array could be used to discriminate among analytes. Further information about the Principal Component analysis and the related mathematical transformations can be found in I.T. Jolliffe, Principal Component Analysis, 2nd ed., Springer, 2002.

Figure 18: a) Example of PCA application using an array of SAW sensors for vapours discrimination [reproduced from [113]]; b) Example of LDA application for some VOCs recognition [reproduced from [114]].
Another technique used to lower the dimensional space and then recognize the pattern corresponding to a specific mixture is Linear Discriminate Analysis (LDA). This technique uses linear combinations of the measured variables features to separate different classes of objects [115]. Discriminant functions are used to reveal the data clustering: the idea consists of maximizing the classes distance associated to the within-classes variance [114]. An example of discriminant analysis used for VOCs detection is reported in Figure 18. In this work, it is shown that LDA better identifies variance organic gases if compared with PCA. Another comparison between PCA and LDA is reported in [116], in which, once interfering samples in CO and CH$_4$ data analysis are introduced, PCA became ineffective and severely overlapped, while LDA continued showing a certain distance among classes (or levels). In general, PCA can be labelled as an “unsupervised” algorithm while LDA is “supervised” [116]. In ref. [22], LDA has been used to lower a four-dimensional matrix of data coming from four OFET transistors groups to detect meat spoilage. In ref. [117], both PCA and LDA are reported and decision tree (DT) and k-nearest neighbours (KNN) techniques are used for analytes classification.

In recent years, methods based on Artificial Neural Networks are gaining interest. These complex systems are inspired by the biological neurons, and they are generally used in gas sensing to classify an unknown data set starting from well-defined clusters of data. An example of an embedded system schematizing the treated topics is reported in Figure 19.
Figure 19: Building blocks illustrating an electronic nose embedded system [reproduced from ref. [117]].

Conclusions

In this review, transduction principles and active materials for gas sensing have been discussed in detail. A great number of different materials has been investigated since the e-nose idea was born. Nowadays, the research trend focuses on the realization and the characterization of novel classes of materials, that can be validated in specific applications and can improve some existing devices, widening the possibilities in some fields, such as in environmental monitoring, food monitoring, breath analysis.

In general, electronic noses are very complex devices and their working principle can vary from one specific technology to another. Necessary components in a commercial e-nose are:

1. a chamber with the sensor arrays whose elements are studied to make data-crossing possible since high specificity to a single gas cannot be achieved within separated sensors;
2. an aroma delivery system to transfer the gas analyte from the source to the sensor array system; several sampling techniques are reported in literature: Static headspace technique, Purge and Trap and Dynamic Headspace technique, Solid Phase Micro
Extraction, Inside-Needle Dynamic Extraction, Membrane Introduction Mass Spectrometry [118];

3 an electronic system to convert and amplify electronic outputs, comprising an analog-to-digital converter;

4 a computer processor to allow statistical analysis, sample classification and recognition. Analysis techniques can be categorized in three main groups [9]: Graphical analysis, Multivariate Data Analyses and Network Analyses. Some techniques used in data post processing of pattern-recognition routines include [29]: Principal Component Analysis, Linear Discriminate Analysis, Partial Least Squares, Functional Discriminate Analysis, Cluster Analysis, Artificial Neural Network.

There are still issues in these kinds of commercial sensors, such as sensor drift and sensitivity. In fact, because of limitations in selectivity and sensitivity, an e-nose capable of identifying any gas sample type has not been realized yet. The great part of commercially available e-noses cannot work automatically: gas sensing still involves statistical analysis and expertise of scientists, making these electronics still not scalable and fully applicable. In addition, these machines are very expensive and not portable: the goals for the next few years are miniaturization and reduction of costs, while increasing the applicability of these technologies. Recently a major interest appears to be direct on organic-inorganic nanocomposite materials, which could overcome the limiting factors associated to metal oxides and conductive polymers.

Smart gas sensing is a novel area which can be expected to enter in everybody’s daily life and there is the need to make novel classes of sensors that can be easily commercialized and employed in domestic and industrial demands, such as food monitoring applications, jointly working with the spreading technology of the Internet of Things. Miniaturized sensors for real-time environment pollution check are also necessary, according to the new lifestyles and the continuous urbanizations and industrialization of different areas of the world.
Future breakthroughs can then lead to early, non-invasive diagnostic tools to face severe pathologies, such as lung cancer, at their early stadium. Efforts are however required to overcome issues such as low sensitivity and, especially, low selectivity of present gas sensors.
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