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REVIEW ARTICLE

Application of gas sensor technology to locate victims in mass disasters – a review

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Abstract
The occurrence of mass disasters are increasing as a result of changing climates and the growing threat of terrorist activities/conflicts. When these tragedies strike, it is critical to locate victims. While search and rescue dogs are trained to locate the living, cadaver detection dogs are trained to locate the deceased. These dogs rely on the volatile organic compounds (VOCs) emitted from the victims to do so. Knowing which dog unit to deploy can be challenging, and the victims' makeup is likely to change following disasters in densely inhabited places, where commingling is likely to occur. The use of electronic nose technologies in forensic science is a recent breakthrough. Due to their ability to detect differing VOCs, this technology can be used to assist in the recovery of victims in disaster events. The most popular types of accessible gas sensor technologies are briefly introduced and compared in this article for their potential use to locate missing persons, both living and deceased. The current and future market needs are articulated, and the lack of enrichment of these needs is examined in relation to the capabilities of existing gas sensors. This will inform further research areas of preference to increase victim detection capabilities.

Keywords Artificial Plow · MOS · E-Nose · DVI · Scent detection

1 Introduction

Natural and anthropogenic disasters can strike without warning, resulting in catastrophic occurrences that are frequently connected with infrastructure devastation and high fatality rates (Ueland et al. 2021; Murphy et al. 2000; Steadman et al. 2014). Natural calamities comprise seismic events, conflagrations, tidal waves, and tempests, whereas catastrophes of human origin predominantly entail acts of terrorism or self-inflicted harm (such as detonations, blazes, and premeditated aerial collisions). Locating victims (both alive and dead) is one of the most difficult tasks in mass disasters, as they are frequently hidden under rubble (Mundorff 2014), deceased victims can be fragmented due to high-impact incidents (Biesecker et al. 2005; Anyfantis et al. 2021; Hoffman et al. 2009), or their remains of said indi-

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viduals are dispersed over extensive regions, contingent upon the scale of the catastrophic event site (Anyfantis et al. 2021). Multiple victims are more likely to be stuck in close proximity and/or intermingled when disasters strike in densely populated urban areas (Anyfantis et al. 2021; Hoffman et al. 2009; Tran et al. 2010).

There exists a range of available tools to search for and locate trapped or missing human victims. Manual searches and imaging techniques (such as visual, infrared, and thermal) are examples of this. In the cases where the victims are buried, ground penetrating radar (GPR) is another commonly used search method. Scent detection canines, specifically those utilized for search and rescue or cadaver detection purposes, currently represent the most advantageous and efficient search modality across all scenarios. This is attributed to their exceptional ability to thoroughly investigate wide-ranging areas and precisely trace odors back to their origin (Van et al. 2019; Korkalainen et al. 2012). It is not well understood what specific chemicals scent detection dogs use to locate victims, however, the great success rate of these dogs has indicate their effective utilization of human scent for the location of victims (Wilson 2014).

Despite their successes, these detection canines have a number of limitations; they are expensive to train and maintain, and tire quickly. Additionally, these scent canines cannot be used in hazardous environments, which many disaster events are. There is therefore the need for an improved approach.

The search canines rely on the detection of airborne stimuli like volatile organic compounds (VOCs) or scent compounds emitted from these humans. There have been numerous studies attempting to elucidate the VOCs associated with decomposing humans for forensic purposes (Deo et al. 2020; Knobel et al. 2019; Ueland et al. 2021; Vass et al. 2004, 2008). During the decomposition process, a wide spectrum of VOCs are emitted into the environment, resulting in what is commonly known as ‘the smell of death’(Stefanuto et al. 2017). These VOCS results from the degradation of proteins, carbohydrates and fats in the human body. These post-mortem dynamic VOC profiles consist of compounds belonging to differing chemical classes such as aromatic compounds, cyclic hydrocarbons, aldehydes, ketones, esters, acids, alcohols, alkanes, sulphur- and nitrogen-containing compounds (Stefanuto et al. 2017).

The analysis of VOCs emitted from living humans have primarily been for medical purposes rather than victim detection. Studies investigating the VOC profile of healthy humans are limited, and primarily focus on skin emissions (Bigazzi et al. 2016; Sakumura et al. 2017; Statheropoulos et al. 2005, 2006; Tsushima et al. 2018) and breath VOCs (Bernier et al. 2002; Curran et al. 2007, 2010; DeGreeff et al. 2011; Hudson et al. 2009; Mochalski et al. 2014a; Prada et al. 2011; Ruzsanyi et al. 2012). Only a few studies exist profiling whole-body emissions, as utilizing whole live humans is limited due to ethical restrictions and inconveniences surrounding the placement of humans in confining environments(Mochalski et al. 2015). Huo et al. (2011) created a chamber simulating a collapsed building environment with entrapped casualties. The study involved participants having to lie down in the chamber over a five-day period where their sweat, breath and skin VOCs were studied. Although specific VOCs were not reported, it was outlined that some VOCs had rapidly accumulated in the experiment before declining. Mochalski et al. (2014b) also used live whole volunteers to monitor 12 preselected skin-borne volatiles in an entrapment scenario, which involved the volunteers sitting in an airtight chamber for a one-hour period. This research illustrated that ketones, in particular acetone, displayed the highest VOC abundances from whole volunteers. A similar experimental set-up was conducted by He et al. (2019) who attempted to address the similarities between breath and whole body profiles.

Out of the 38 VOCs detected from the whole-body studies by He et al. (2019), 33 VOCs were also detected in the breath tests. This suggests that the VOC profiles of breath can be considered as partly representative of the whole-body emissions. In addition to skin and breath volatiles, investigations into blood and urine VOCs have been examined to detect living victims in disasters.

The use of VOCs for detection can be leveraged through the use of electronic nose (e-nose) technology (Karami et al. 2024). With the emergence of e-nose technology in the late 1980s, the importance of gas sensors and the breadth of their possible uses has increased significantly in recent years (Gardner and Bartlett 1994). The goal for this technology is to emulate the main function of mammalian olfactory systems with practical artificial mechanisms to identify the category (or quantify the intensity) of a specific odour (Èrdi et al. 1998; Pearce 1997). In mammalian olfactory systems, millions of gas sensors, often alleged as olfactory receptor neurons, are employed simultaneously for scent perception (Rasekh et al. 2023). As a result, the use of gas sensor arrays has become extensively accepted in research and even in industries concerned with gas detection and identification (Karami et al. 2020a; Karami, Rasekh and Mirzaee – Ghaleh 2020c).

The detection of VOCs or scents released by the human body has a number of potential uses that can be leveraged by e-nose technology advances. One of these application areas is in the medical industry to aid diagnosis, evaluate human health, and for other biomedical applications (Wilson and Baietto 2011). Others areas where this technology is advantageous is in forensic applications.

One of the key new areas of prospective forensic applications for e-nose technologies is the location of missing persons (both living and deceased) during disaster events. Detecting living missing victims such as those who are trapped beneath the wreckage of collapsed buildings and other structures as a result of disasters will allow life-saving aid to be provided much faster which can increase survival rates. It is equally important to locate missing and presumed dead individuals to be able to assist law enforcement solve cases and provide answers to family members.

2 E-nose technology

E-nose instruments represent novel incarnations of electronic aroma detection (EAD) technologies presently under development for a wide range of applications in forensic and criminological domains (Barshick et al. 1997; Vass et al. 2002), as well as related biomedical and pharmaceutical industries (Wilson and Baietto 2011; Wilson 2011). A variety types of gas sensors have been adopted in e-noses, such as surface acoustic wave (SAW)-based sensors, quartz crystal microbalances (QMB), metal oxide semiconductors (MOS), conductive polymers (CP), etc. (Wilson and Baietto 2009).

Most gas sensors have cross-selectivity, i.e., one type of sensor can respond to more than one chemical stimuli. Consequently, the sensor's response to a gaseous mixture is an integrated result for all components contained. In other words, e-noses are used to detect gaseous mixtures of VOCs instead of identifying individual chemical compounds present in sample mixtures (Rasekh et al. 2021b, 2022). This information differs from many standard forensic chemical analyses where individual volatiles are profiled and used as biomarkers. E-nose technology works by chemically scenting distinct organic and inorganic substances

that can be identified in pure form or in simple gaseous mixes. The e-nose discerns particular gas blends or single compounds in the specimen by comparing the e-nose sensor array's output with reference databases created by chemical standards or recognized blends. This process is based on mathematical and statistical procedures, such as pattern recognition algorithms (Wilson and Baietto 2009; Aghili et al. 2022).

E-nose devices have the capability to identify precise blends of volatile organic compounds (VOCs) through the utilization of unique "fingerprint" patterns or response profiles that originate from sensor responses to VOC gases produced by the collective output of cross-reactive sensors within the e-nose sensor array (Aghili et al. 2023). The generation of a hybrid output pattern, or aroma profile, is a direct result of distinct sensors in the sensor array absorbing and recognizing the VOCs present in the sample mixture. Different types of e-nose devices employ different detection mechanisms, although the majority of e-nose detection systems incorporate a transducer that converts the electronic detection signal from the sensors into digital output values. This is done to record the individual sensor responses that constitute the merged aroma output pattern (Wilson and Baietto 2009).

2.1 Basic concepts and definitions

The key component in e-noses is the gas sensor. In a gas sensor, the interaction of the target gas molecules with the sensing material modifies one or more of the sensor's physical properties (e.g., conductivity and capacitance). The sensor responds to the desired gas by translating these changes into an electrical signal (Albert et al. 2000). In the simplest sensor system, the density of the target gas molecules is the only input and the sensor response is the only output. However, this model is far too simplistic, in real scenarios the reaction to the target gas is constantly influenced by a number of other environmental parameters. When sampling in non-ideal more realistic conditions, these environmental parameters need to be considered to ensure optimal working of the e-nose. In some instances, it is possible to estimate and correct the effect of these variables on the sensor response which is preferred (Khorramifar et al. 2023).

When a gas sensor enters the environment containing the target gas, its response, for example in the form of sensitive electrical conduction or point potential of the circuit, increases, and becomes stable after a while (Fig. 1). As the sensor leaves that environment and returns to the reference environment, the sensor response progressively returns to the base level (Rasekh et al. 2021a).

There are a number of terms that are used to describe this sensor behavior:

Baseline The base level of the gas sensor is determined by its response after a long halt in the reference environment (for example, pure air). Conductivity, resistance, potential difference, and current can all be used to establish the base level.

Steady response The sensor reaction to the aforesaid conditions is determined after standing for a long period in an atmosphere containing a specified amount of target gas. The concentration of the target gas obviously influences the steady response. For most gas sensors, the relationship between the steady response and the gas concentration is often nonlinear.

Transient response The sensor transient response describes how to alter the sensor response from the base level to the steady response when the sensor environment quickly changes from the reference environment to the target gas medium (Fig. 1).

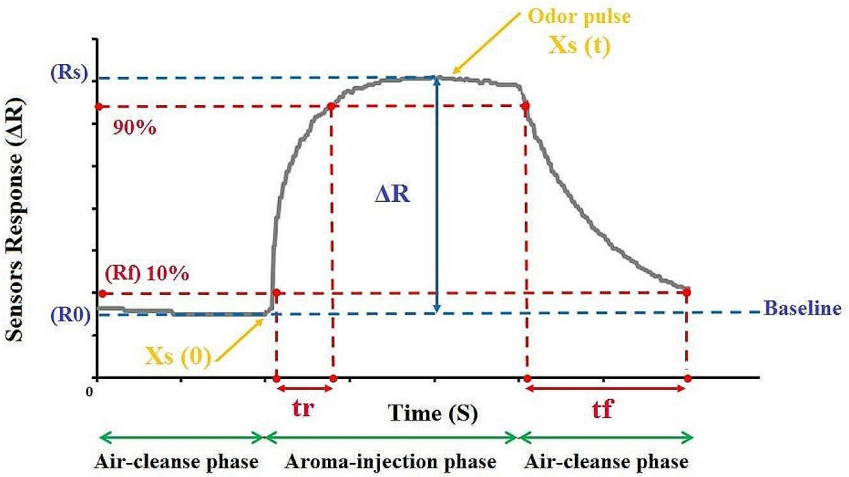

Fig. 1 Sensor response to sample VOCs during the e-nose run cycle

Sensor saturation Sensor saturation refers to the upper limit concentration of a target gas that the sensor can detect, beyond which the sensor's reading will not change.

Detection limit is the minimum level of the target gas density that can be detected by the sensor. This limit depends on the type of the target gas and a number of other factors.

Dynamic range is an interval of the target gas density in which changes of the gas density results in a considerable change in the response. The dynamic range of each gas sensor is the density range between the detection limit and saturation density.

Sensitivity is defined as the slope of the sensor response change curve in terms of gas concentrations. Because of the non-linearity of this curve, the sensitivity value is affected by the level of gas concentrations. At saturation concentrations, sensitivity is almost zero.

Response time the time it takes for the sensor response to grow from zero to 90% of the normal response provided the gas enters suddenly. A sensor's response time is also affected by the type of target gas.

Recovery time is the time it takes for the sensor response to drop from the level of the steady response to 10% above the base level after the gas is suddenly removed. The recycling time is also affected by the target gas's nature and density. The response time of most gas sensors is not equal to the recycle time.

Selectivity is a sensor's ability to detect one or more distinct gases. No single gas sensor can function as a comprehensive selection. Metal oxide sensors, for example, respond to the vast majority of reducing gases. Sensors' relative selectivity can be defined and applied in terms of differences in sensitivity to distinct gases.

Drift is the progressive change in sensor response to a specific level of target drift gas. Typically, the drift is irreversible and reduces or increases the response. The drift causes irreversible changes in not only the response but also all of the sensor's critical characteristics. Drift is caused by slow changes in the structure of the sensor's sensitive layer caused by physical and chemical causes, and it is irreversible. One of the most important of these aspects is the gradual sintering of ceramic elements in the structure of the sensitive layer.

Useful life The amount of time that the sensor's response to a specific density of target gas is lowered to an undesirable level owing to drift. It is obvious that the useful life of a sensor would vary depending on the task and working conditions. Most gas sensors have a useful life of less than a year of continuous operation. The gas sensor should have sensitivity, dynamic range, selectivity, and a long life, according to the definitions supplied. A sensor, on the other hand, must have quick response and recycle times, a low detection limit, and low drift (D' Amico and Di Natale 2001; Wang et al. 2010).

Processing The preprocessing step is often applied to select a number of parameters, which describe the response of the sensor array. The selection of this option has the potential to exert a substantial impact on the efficacy of the subsequent modules within the pattern analysis framework (Pardo and Sberveglieri 2007). Although preprocessing depends on the underlying sensor technology, there are three general steps in this step: baseline manipulation, compression (feature extraction), and normalization (Gardner et al. 1998). There are three methods used in signal preprocessing that are described below (Karami et al. 2020b; Mohammadian et al. 2023):

3 Baseline manipulation

a) Differential method: In the differential method to eliminate noise in the sensor signal, the baseline is reduced from the sensor response.

$$y_s(t) = x_s(t) - x_s(0) \tag{1}$$

b) Relative method: In the relative method, the sensor response is divided by the baseline, which results in a dimensionless response.

$$y_s(t) = \frac{x_s(t)}{x_s(0)} \tag{2}$$

c) Fraction method: In this method, the baseline is subtracted from the sensor response and then divided by the baseline. The response obtained in this method, in addition to being dimensionless, is also normalized and can be used for large or small signals.

$$y_s(t) = \frac{x_s(t) - x_s(0)}{x_s(0)} \tag{3}$$

where $y_s(t)$ is the transformed response; $x_s(0)$ is the baseline and $x_s(t)$ is the sensor response(Karami et al. 2020a, b, c). Hence, we will use the fractional change as a baseline manipulation technique to get two standard parameters:

R_f and R_s (see Fig. 1) whose expressions are given by: $\Delta R_s = \frac{R_s - R_0}{R_0}$ (4)

$$\Delta R_f = \frac{R_f - R_0}{R_0} \tag{5}$$

where, R_0: The initial resistance, calculated as the average value of the sensor's resistance during the first minute measured in the air-cleanse phase. R_s: The steady-state resistance, calculated as the average value of the sensor's resistance during the last minute measured in the aroma-injection phase. R_f: 10% of the steady-state value (Faleh et al. 2016). Time intervals τ_r and τ_f provide information about the rise time and fall time, respectively.

4 Compression (feature extraction)

The compression method constructs very few informative numerical values, known as features or fingerprints, to represent the response curves. Most widely used methods include:

a. a) Partial sampling: Extraction of dynamic information in this method is possible by sampling the transient response of sensors at different times during the phase of pulse odor or clearance.
b. b) Model Adaptation: An attempt is made to adapt a theoretical model of the response curve to the transient response obtained using automatic regression. The parameters obtained from the model are used as a feature.
c. c) Parameter extraction: This method compresses the transient response using a number of descriptors including maximum and minimum responses, curve ascent time, curve integral and sensor slopes.

5 Normalization

The last stage of preprocessing is normalization. Normalization is divided into two categories, global and local. Global methods are applied to the entire database from a single sensor and are used to compensate for differences in data scaling. The most common global normalization methods used in the olfactory machine system are given in Eqs. (6 and 7):

$$\mathbf{Y}_{ij} = \frac{\mathbf{X}_{ij} - \min\limits_{i,j}(\mathbf{X}_{ij})}{\max\limits_{i,j}(\mathbf{X}_{ij}) - \min\limits_{i,j}(\mathbf{X}_{ij})} \tag{6}$$

$$\mathbf{Y}_{ij} = 2\frac{\mathbf{X}_{ij} - \min\limits_{i,j}(\mathbf{X}_{ij})}{\max\limits_{i,j}(\mathbf{X}_{ij}) - \min\limits_{i,j}(\mathbf{X}_{ij})} - 1 \tag{7}$$

Local methods are applied to the obtained signals in order to compensate for the sample-to-sample changes, as an example shown in Eq. (8):

$$\mathbf{Y}_{ij} = \frac{\mathbf{X}_{ij} - \operatorname{mean}\limits_{j}(\mathbf{X}_{ij})}{\operatorname{std}\limits_{j}(\mathbf{X}_{ij})} \tag{8}$$

where $\mathbf{X}$ and $\mathbf{Y}$ represent feature matrix before and after normalization, repectively; index i represents the i -th sample, and index j the j -th feature. Relationships (6 and 7) place the data for all sensors in the ranges $[0,1]$ and $[-1,1]$, respectively (Pearce et al. 2003).

6 Sensor types/technologies

In this manuscript, a comprehensive examination of diverse technologies utilized for the development of gas sensors is presented. The varying categories of gas sensor technologies are discussed together with their principle of operation. The merits and drawbacks of each sensor technology are also highlighted with the focus on human detection in disaster events. For numerous decades, a multitude of technologies have been employed in the creation of gas sensors with high levels of sensitivity and responsiveness, capable of detecting various gases. Nonetheless, to achieve greater selectivity and sensitivity for these sensors, researchers propose future trends and perspectives in the conclusion of this article.

6.1 Gas Electrochemical sensors

A device that turns chemical energy into electrical energy and vice versa is known as an electrochemical cell. The Galvanic cell, depicted in Fig. 2, is the earliest and simplest variety of these devices. A Galvanic cell is made up of two heterogeneous metal electrodes that are immersed in an ion conductive fluid (electrolyte). The difference in chemical potential of two metals relative to the electrolyte is displayed as the difference in electrical potential between the two metal electrodes (Fig. 2a). Figure 2b depicts another variant of this cell in which two homogeneous electrodes are employed, but the concentration or type of electrolyte in the vicinity of the electrodes differs, and the two environments are linked by an ion conductor bridge. The latter is appropriate for comprehending the structure of gas electrochemical sensors.

An electrochemical gas sensor is frequently fabricated through the amalgamation of a solid ion-conducting electrolyte with an adjunctive sensing electrode and a reference electrode. In addition, a sensing electrode and a reference electrode can be the same metal electrodes (for example, platinum (Pt) that are installed on the surface of a ceramic disk (solid electrolyte). The determination of the electromotive force of a cell is reliant upon the establishment of chemical potentials at both the sensing and reference electrodes. These sensors are classified as potentiometric or amperometric, and are mostly employed as oxy-

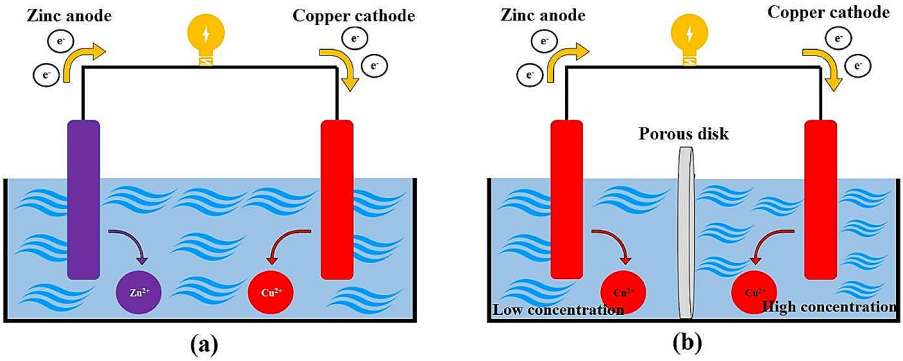

Fig. 2 Galvanic cell schema with two (**a**) heterogeneous and (**b**) homogeneous electrodes

gen sensors or λ sensors. The simplest structure used for the oxygen sensor is of the potentiometric type and is shown in Fig. 3. Zirconium oxide and its derivatives are employed as solid electrolytes in this construction, and platinum electrodes are utilized. This construction can withstand high temperatures and extreme chemical conditions. By connecting these sensors to clean air, the reference environment can be provided. Λ sensors are currently the most extensively used potentiometric sensors (Simões and Xavier 2017). These sensors are frequently employed in industry, but no application in forensic science has been discovered thus far.

In their most basic form, amperometric-type chemical sensors have a similar structure to potentiometric sensors. In this sensor, a constant external potential is supplied between two platinum electrodes, and oxygen is pushed from one side of the solid electrolyte to the other. This pumping produces an ionic current induced by oxygen ions within the zirconia electrolyte. With a fixed relative pressure of oxygen in the test medium, the intensity of oxygen pumping and hence the intensity of the current going through the circuit will be dependent on the relative pressure of oxygen in the test medium. Based on sensor calibration information, circuit current measurement yields a relative oxygen pressure in the study environment (Stetter and Li 2008). The fundamental advantage of this type of electrochemical sensor is that no reference environment is required. Electrochemical sensors have been used to detect additional gases besides oxygen, such as hydrogen, carbon monoxide, hydrogen sulfide, and ammonia (Alabdullah et al. 2021; Simões and Xavier 2017). All gases which are amongts those released by humans, showing a potential for its use in victim detection.

Electrochemical sensors possess the capability to construct a sensor that is tailor-made for a specific gas or vapor in the parts-per-million range. The degree of selectivity depends on the concentration of gas. This sensor has low power requirements, its output is linear, with good resolution. One of the most important advantages of this sensor is that after it is calibrated to a known gas concentration, the sensor will accurately read a repeatable target gas. The coexistence of additional ambient gases neither curtails the lifespan of the sensor nor impedes its functionality. This is very important in identifying the victims because in mass disasters there are a number of different emitted volatiles unrelated to the victims, depending on the disaster event, which will be present and may affect the performance of the sensor. Finally, electrochemical sensors are practical and economical and in case of failure, they can be replaced. One of the most important limiting factors for their use is the tempera-

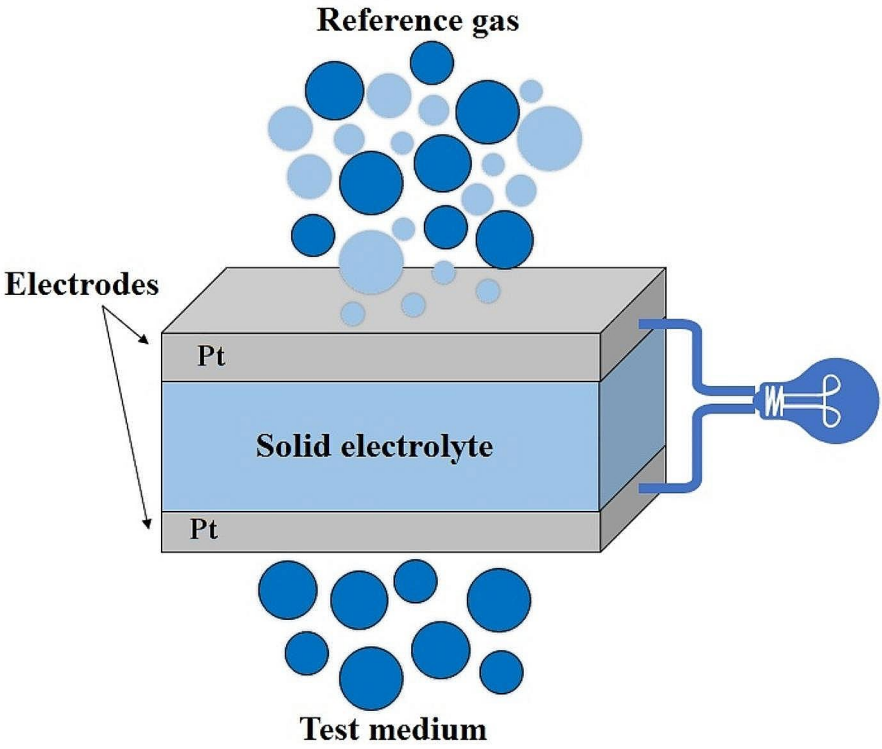

Fig. 3 Scheme of an electrochemical gas sensor of the metric potential type

ture range. This parameter limits their use in hot areas and in fires, rendering them unsuitable for disasters involving explosions or other high temperature events. Electrochemical sensors typically exhibit a lifespan ranging from one to three years. The longevity of these sensors may be compromised by various factors including low humidity, elevated temperatures, exposure to the target gas, and the presence of cross-sensitivity gases. Such environmental conditions can lead to the desiccation and depletion of the sensors' electrolytes.

6.2 Gas optical sensors

The operation of gas optical sensors is primarily dependent on changes in the optical properties of the environment caused by the presence of the target gas, or changes in the optical properties of a specific surface of the sensor caused by target gas molecule absorption. For example, the medium containing the target gas preferentially absorbs photons of a given wavelength, and the degree of absorption is proportional to the target gas concentration in the medium (James et al. 2005). Figure 4 depicts the structure of an infrared gas sensor that operates on the absorption spectrum of the atmosphere. The sensor is made up of three major components: an infrared source, a gas chamber, and a detector. The source emits a wide range of infrared light, including wavelengths that the target gas can absorb. If the target gas is present in the chamber, that wavelength is more absorbed. Using the detector to

determine the wavelength and amount of absorption leads to detecting the kind and amount of target gas in the chamber. The salient benefits of these sensors are their capacity to function at ambient temperature and the absence of direct detector interaction with gaseous molecules, rendering them feasible for extended gas monitoring. Furthermore, these sensors have a very selective sensitivity and can detect individual compounds in a complex gas mixture. Because of their fragile optical components, these sensor systems are expensive and difficult to transport (Liu et al. 2012; Wilson and Baietto 2009). The sensors under consideration exhibit superior performance in terms of measuring gas concentrations, particularly with respect to their ability to detect inert gases like CO_2. This type of sensor is capable of achieving high levels of precision irrespective of whether the gas is active or inactive, provided it has absorbance in the infrared region. Conversely, gases such as hydrogen and oxygen cannot be measured due to their symmetric molecular structure and the consequential lack of absorption in the infrared region. Additionally, these gas sensors, which incorporate a light emitter and an infrared sensor, offer a number of advantages, including ultra-low power consumption, ultra-fast response, and a high level of safety. This low energy consumption accelerates their application for long-term environmental monitoring. However, these sensors are affected by to ambient light interference. Their use for in-field detection such as that required in mass disaster events is therefore limited.

Fiber optic technology is applied in several forms of gas optical sensors (Fig. 5). Different detection architectures and methods are used by these optical sensors. In the example depicted in Fig. 5, pods of an optical fiber are removed and replaced with a type of fluorescent pigment. The interaction of target gas molecules with pigments alters the fiber conversion function in that region. The presence of a target gas in the environment can be determined by detecting these changes with an optical sensor positioned at the fiber output and utilizing appropriate software. This sensor's advantages include fast response, room temperature operation, and the ability to work in the presence of electromagnetic disturbances. Among the drawbacks of these sensors include the requirement for specialized hardware and software for gas detection, as well as the expensive cost and relatively short lifespan of gas-sensitive coatings (Yamazoe et al. 2003). Despite the benefits of this sensor type in ambient detection and rapid detection, the lack of longterm coatings and the need for a specialist operator are limiting factors for its use in real-time outdoor victim detection.

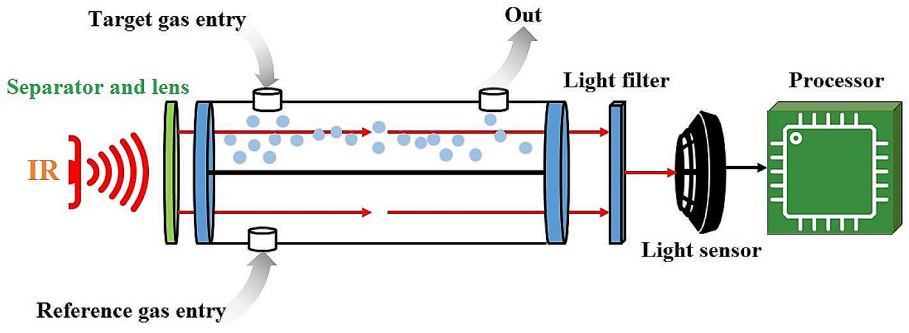

Fig. 4 Scheme of a gas optical sensor

6.3 Pellistors

Pellistors works on the assumption that as an electric resistance loses a fixed power as heat, in steady state, the whole consumed power is transferred to the surrounding environment. In this situation, the surficial temperature of the resistance depends on various parameters. One of the most important parameters is the thermal conductance of the environment. At fixed power, as the thermal conductance factor decreases, the surficial temperature of the resistance increases. This change in temperature changes the electrical resistance. Determining the magniture of this change results in detection of the compound change or pressure change of the surrounding environment. The resistance that monitors the environments based on temperature changes of the operating point is called pellistor. As gas sensors, several forms of pellistor are utilized, the most popular of which is catalytic pellistor (Krawczyk and Namieśnik 2003). Catalytic sensors primarily detect flammable gases. The change in resistance in these pellistors is caused by temperature variations, which are mostly caused by the combustion of the target gas on the pellistor's surface. The operating temperature of these pellistors is lower than the target gas's flash point, and the ignition is carried out with the assistance of catalytic particles embedded in the pellistor's surface. Gas detection is based on a comparison of the electrical resistance or temperature of two devices with and without a catalyst in the more accurate kind of these sensors. This reduces the effect of modifying other environmental parameters in response, such as humidity or ambient temperature. The flow of electric current via the sensitive layer itself provides the operating temperature in these sensors.

Figure 6 depicts a pellistor gas sensor schematic. The sensor is made up of two metal oxide resistors that are integrated with their microheaters on an aluminum foundation. One of the two resistors' surfaces is lined with platinum particles, allowing the target gas to be oxidized at operating temperature. The resistor differences are caused by the temperature difference between these two resistors. This asymmetry in a bridge is related to the target gas's density. These sensors detect the presence of almost all combustible gases without discrimination, lack a suitable detection limit, consume a significant amount of electrical power, and operate at high temperatures. The presence of these disadvantages eventually reduces pellistor consumption. However, because of established and reliable manufacturing technology, as well as user expertise, this type of gas sensors is still in use (Liu et al. 2012; Symons 1992; Overfelt et al. 2012).

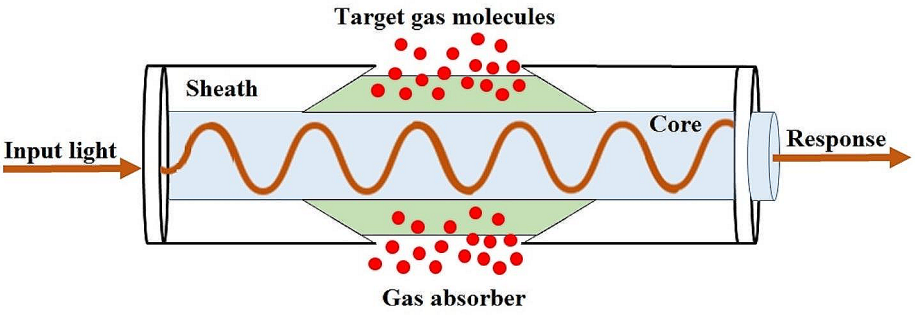

Fig. 5 Scheme of gas fiber optic sensor

6.4 Gas piezoelectric sensors

The piezoelectric effect is employed in various types of gas sensors to detect the presence of a target gas. However, in these devices, the piezoelectric material does not directly interact with the target gas molecules. Gas is usually absorbed by a separate layer that lies on the surface of the piezoelectric body and alters the device's mechanical properties. The gas adsorbent is typically a thin coating of an organic substance that is deposited in various ways on a piezoelectric foundation. Piezoelectric gas sensors are classified into three types: microbalance sensors, surface acoustic wave sensors, and gas micro electromechanical systems (Arshak et al. 2004; Tadigadapa and Mateti 2009).

The structure of microbalance-based gas sensors is straightforward. A piezoelectric disk body, often constructed of quartz (SiO_2), lithium niobate ($LiNbO_3$), lithium tantalat ($LiTaO_3$), or zinc oxide (ZnO), and two metal electrodes positioned on opposite surfaces, comprise the devices (Fu et al. 2017). The piezoelectric body is typically 0.1 mm thick and 10 mm in diameter. Figure 7 depicts the design of this device, which also shows the adsorbent layer of the target gas molecules on one of the piezoelectric body's bases. The mechanical and electrical parameters of this mechanical-electrical structure define its resonance frequency. The gadget oscillates at its resonance frequency by connecting metal electrodes to a suitable oscillator circuit. In the presence of a target gas, increasing the mass of the device reduces the oscillation frequency by absorbing gas molecules to the adsorbent surface. The change in frequency in Hertz is proportional to the change in crystal mass and, as a result, the density of the gas in the medium. This relationship is nonlinear and varies depending on the target gas and employed adsorbent. This link is determined by prior experiences and preliminary calibration. This sort of gas sensor has an operating frequency of around 10 MHz (Ferreira et al. 2009; Drafts 2001). The operation principles of piezoelectric GAS MEMS are similar to those described above, with the exception that the oscillator

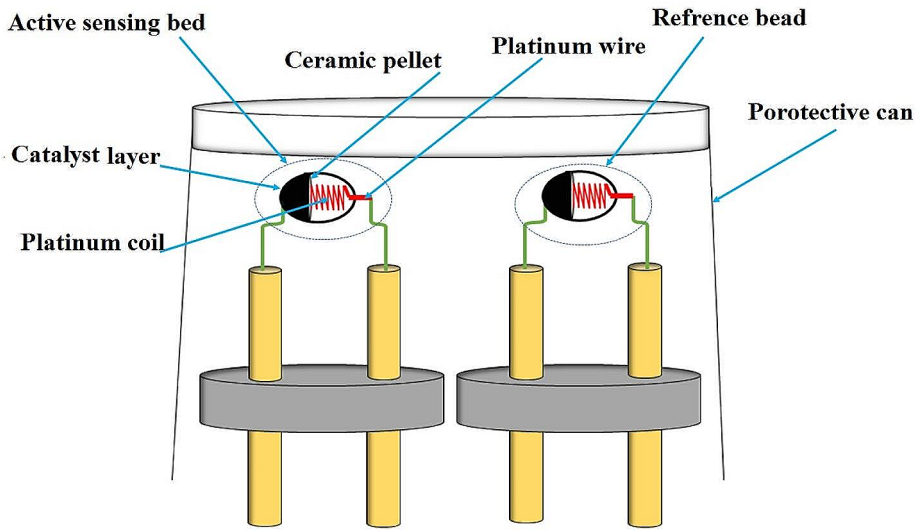

Fig. 6 Scheme of a pellistors gas sensor

structure is on the micrometer scale and has a different geometric shape. SAW metal electrodes are both positioned on one side of the piezoelectric substrate in gas sensors. An interdigital electrode pair, functions as a surface wave transmitter, transmitting acoustic waves to the substrate surface. These waves are received by another set of electrodes situated a fixed distance from the transmitter. The absorbent layer is positioned between the transmitter and the receiver on the substrate surface, allowing acoustic waves to travel through it from the transmitter to the receiver. The existence of the target gas and its absorption on the absorber layer reveals the properties of the signal received by the receiver. By absorbing the target gas, for example, the acoustic wave propagation speed at the surface varies, changing the signal phase received by the receiver. Because gas absorption in the adsorbent layer is a surface phenomenon, and wave propagation in this category of sensors occurs primarily on the surface (up to several wavelengths from the surface), the sensitivity and detection threshold of piezoelectric gas sensors of surface waves to microscales are higher. Surface wave devices operate at a higher frequency than microscales, and is about 100 MHz (Tadigadapa and Mateti 2009; Wang et al. 2009).

Piezoelectric sensors are sensitive to practically all gases because they can be covered with a variety of absorbent materials. These sensors are compact and cheap. They offer more design and material flexibility than other types of gas sensors, allowing for the creation of a sensor array for developing an e-nose based on identical microtrails by displaying different absorbent materials. Another benefit of these gas sensors is that they may operate at ambient temperature. The fundamental shortcoming of piezoelectric gas sensors is the significant interference of external elements like temperature and humidity on their response. Temperature impacts the sensor's performance through affecting the elasticity factor of the

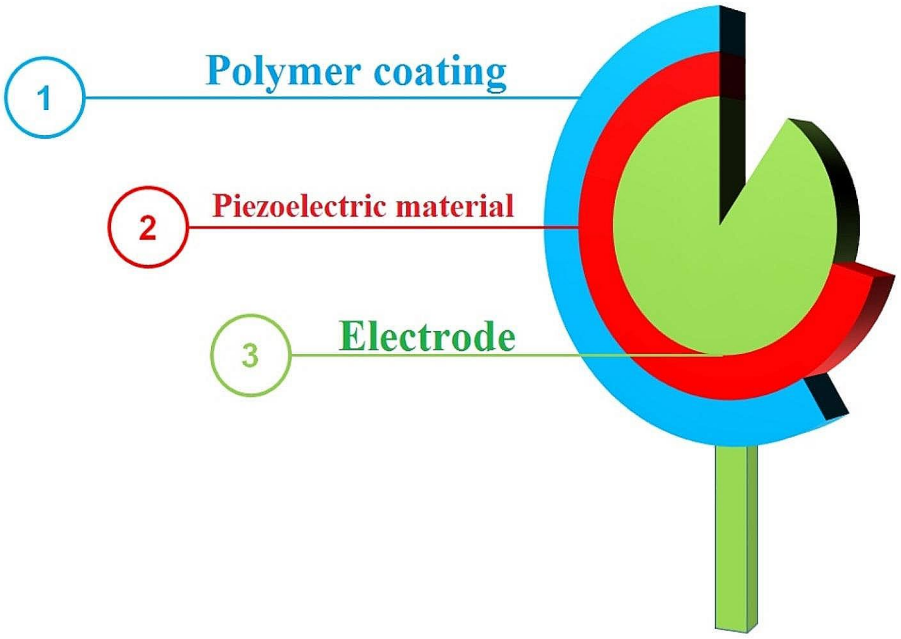

Fig. 7 Schematic of piezoelectric gas sensor

piezoelectric material and the gas absorption process in the adsorbent. Humidity changes can also have a substantial impact on the gas absorption process and the sensor's base level (Wilson and Baietto 2009; Arshak et al. 2004).

6.5 Resistive gas sensors

The resistive gas sensor is one of the most common types of gas sensors. At operating temperature, the target gases interact with the sensing material causing changes in the resistance reading. The sensing material can recover to its inherent resistance when analytes are removed. The target gas is detected by measuring the resistance change with a simple electronic circuit (Lakkis et al. 2014; Yamazoe et al. 2003).

Figure 8 shows a typical schematic of a resistive gas sensor. The body or gas-sensitive semiconductor layer, insulating substrate, microheater, and metal electrodes are the major components of this sensor. The substrate is typically formed of an alumina chip with a few millimeters of diameter and a few tenths of a millimeter of thickness. Conventional coating layer procedures are used to deposit gas-sensitive semiconductors on the substrate surface (thin layer or thick layer). The high-power electric resistor serves as a microheater on the other side of the substrate; as the electric current passes the microheater, the heated substrate reaches the optimal operating temperature of the sensor. Two pairs of metal electrodes are used to connect the external connection pins using thick film or thin film technology one for connecting the body sensitive to the electronic circuit and one pair for supplying the microheater power (Yamazoe et al. 2003).

Resistive gas sensors are of interest for many industrial and home applications due to their simple structure, low cost, great sensitivity to diverse gases, and detection of a wide range of dangerous and combustible gases (Karami et al. 2020b, 2021). The disadvantages of these sensors are low selectivity and high operating temperature (in resistance sensors based on oxide semiconductors) and low lifespan (in sensors based on organic semiconductors) (Bae et al. 2001; Barsan et al. 2007). There are now two types of resistive gas sensors in use and study as outlined below.

6.5.1 Resistive gas sensors based on metal-oxide semiconductor

Currently, resistive gas sensors based on metal oxide semiconductors detect a wide range of combustible and hazardous gases (including carbon monoxide, methane, alcohols, and hydrogen) as well as many other simple and complex gases and odors. Tin oxide is the first and most widely utilized sensitive material in commercial gas sensors, having been on the market since the 1970s. Zinc oxide and titanium oxide are two more frequent oxides (Eranna et al. 2004).

Because of the width of their restricted energy band, metal oxide semiconductors are frequently employed as insulation in various cases. However, the abundance of oxygen in the crystal structure of most metal oxides leads the composition to diverge from the stoichiometric ratios. Because of the prevalence of oxygen vacancy, SnO_2 is usually SnO_2-δ, where δ is a positive number whose magnitude depends on its environmental conditions. The existence of oxygen vacancies balances the distribution of electrons in the allowed energy bands, resulting in states in the forbidden band close to the conduction band. The forbidden band states behave similarly to donor impurities in the III-V family of semiconductors. At

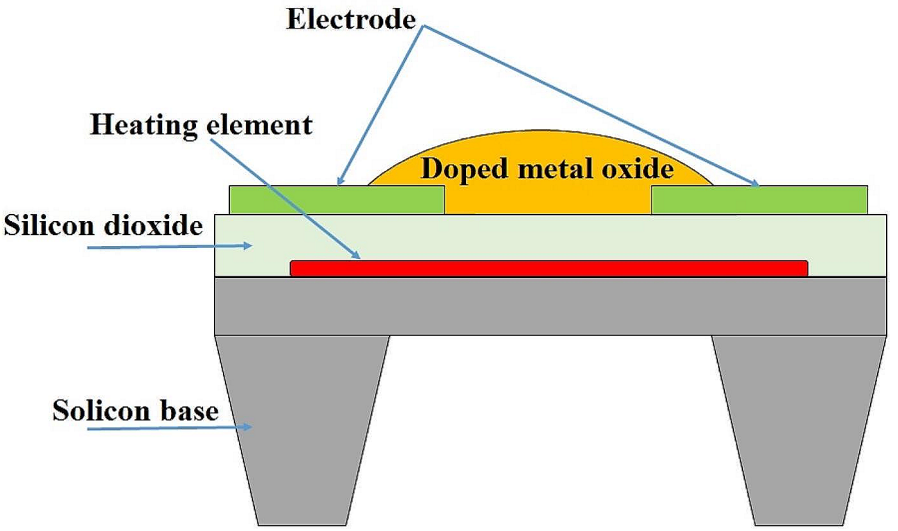

Fig. 8 Scheme of a gas resistance sensor

room temperature, these ionized states cause electrons to be present in the conduction band, increasing the crystal's conductivity. For the previous fifty years, the physics of this process has been explored, and few conclusions addressing equilibrium states in various environmental and structural situations are published in most important sources (Lantto et al. 2001; Li-Zi et al. 1994; Hahn 2002). The gas detecting method of metal oxide gas sensors is based on the interaction of the sensitive body with the oxygen gas in the surroundings. Different forms of interaction can be represented, which can be practically separated into two primary mechanisms, "Bulk" (A) and "Superficial" (B):

A): Changing the partial pressure of oxygen in the atmosphere alters the vacancy density in the ventricle of a metal oxide single crystal body, hence altering its electrical conductivity. According to Le Chatelier's principle, the drop in oxygen vacancy density is explained by a modest increase in oxygen pressure in the environment. This conductivity shift is caused by a change in conductivity in all polycrystalline layer grains. At room temperature, this reaction is very slow due to the slow entry of oxygen into the crystal structure, and reaching equilibrium density can take hours. As a result, this system detects oxygen at temperatures greater than 500 °C. This mechanism is totally reversible, and when the oxygen pressure returns to its normal value, the conductivity of the oxide body recovers to its original equilibrium level. As a result, at high temperatures, the ventricular mechanism is basically only capable of detecting small oxygen pressure changes (Al-Hashem et al. 2019).

B): The main mechanism for detecting the presence of the target gas is the gas's surface interaction with the effective surface of the polycrystalline material. The charge carrier in polycrystalline materials must cross a significant number of crystalline particles as well as the border between the two electrodes. One charge carrier must overcome the potential energy between two adjoining grains in order to cross each "grain boundary." This barrier forms in metal oxides, mostly as a result of oxygen absorption at the grain surface. The difficulty in passing this barrier accounts for a sizable amount of the electrical resistance

measured between the two electrodes. At the sensor operating temperature, the target gas reduces the surface oxygen of the crystal grains, the intergranular potential barrier, and consequently the electrical resistance of the body. The sensor's response to the presence of target gas is recorded as a decrease in resistance. Because the surface mechanism is also slow at room temperature, the sensor operating temperature is set to roughly 300 °C for practical application. This sensing method is used by the majority of commercial resistive gas sensors (Huang and Wan 2009).

Although the bulk and surface mechanisms are intrinsically distinct and derive from distinct physicochemical principles, both operate concurrently in a resistive gas sensor. The strength and weakness of each of these mechanisms are determined by the sensor's operating temperature, and their total defines the amplitude of the sensor response. References (Kim et al. 2013; Wang et al. 2010; Yamazoe et al. 2013; Barsan and Weimar 2001) explore the relationships between the two processes. Metal oxide films are deposited on various insulation substrates using a variety of chemical and physical techniques. For example, Spin coating (Mennicke and Salditt 2002), Spray pyrolysis (Jadsadapattarakul et al. 2008), Sol-gel deposition (Znaidi 2010), Thermal evaporation coating (Hutchins et al. 2006), Electron beam (Singh and Wolfe 2005), and Sputtering kinds (Kelly and Arnell 2000) are all coating processes. The deposition method and coating process parameters influence the thickness and microstructure of the sensitive body, as well as the primary properties of the gas sensor (Kakati et al. 2010). The quantitative relationship between the thickness of the sensitive layer and the chemical-resistance sensitivity of the sensor has been calculated, and it has been demonstrated that in most situations, sensitivity to the sensor gas increases as the layer becomes thinner. It has been shown that higher porosity coefficient increases sensitivity (Seo et al. 2009). Both of the aforementioned processes are clearly felt since decreased thickness and increased porosity increase the contact of a specific mass of metal oxide with the surrounding gaseous fluid. This result explains why layers of sensitive material are used instead of cylindrical or cubic bodies. Gas sensors function in high-temperature, polluted environments, and the metal connections they use must be composed of noble metals. The electrical interaction of these metal alloys with the oxide layer is critical, and the sensor response to gas is strongly affected by this behavior. There are two types of metal-metal oxide bonding: ohmic bonding and Schottky bonding. In the latter, the sensor is typically represented by two back-to-back diodes and a series resistor, and the sensor's reaction to changes in atmospheric composition is determined not only by the sensitivity of the oxide layer resistance but also by the sensitivity of the diodes. As a result, the resistance detected in these sensors comes from two sources: chemical-resistive sensitivity associated to the metal oxide layer and sensitivity to the Schottky bond gas between the oxide and the electrode. However, in resistive sensors, sensitivity is the result of the resistive-chemical sensitivity of the oxide layer (Barsan et al. 2007). The sensitivity of sensors built of pure metal oxides is low, and this degree of sensitivity is insufficient for many industrial and even residential applications. For example, in the optimal temperature and structural circumstances, the conductivity of tin oxide varies in response to the presence of 100 ppm of carbon monoxide gas less than 25%. Metal oxide sensors' features (such as sensitivity, selectivity, response time, and working temperature) must be enhanced before they can be fully developed. By introducing additives to the structure of these oxides, sensitivity increases. These additives improve the sensor's sensitivity and selectivity while decreasing response time and operating temperature. Additives are classified into two types: volumetric and surficial. Volumetric

additives, such as donor and receiver impurities, are applied to the semiconductor body. For example, contamination of tin oxide with aluminum as a receptor impurity diminishes body conductivity, making the impact of increasing gas conductivity more visible. The second group, as active particles on the surface of the sensitive layer, promotes contact between the gas and the metal oxide's surface oxygen. The arrangement of platinum particles on the surface of the tin oxide layer, for example, increases the oxygen absorbed at the layer's surface and its electrical resistance by accelerating the decomposition of the O_2 molecule into oxygen atoms. As a result, both the sensor's sensitivity to gas resistance and its dynamic range increase.

The feasibility of detecting human presence through the analysis of fluctuations in carbon dioxide (CO_2) and oxygen (O_2) levels in the surrounding atmosphere resulting from human respiration has been substantiated through the utilization of gas sensors (Huo et al. 2011). However, it must be noted that the aforementioned system, alongside several other sensor systems that have been developed for the purpose of detecting signs of life, have solely been subjected to testing within the confines of a laboratory environment. Despite the widespread publication of studies on the utilization of electronic noses for analyzing exhaled breath in recent years, the practical implementation of this technique as a screening tool beyond the confines of the laboratory and within clinical settings remains a conjecture (Becker 2020).

The utilization of MOS-type gas sensors has undergone a notable evolution from their traditional deployment in gas leak detectors and carbon monoxide detection to more specialized and varied domains, including but not limited to high-precision detection equipment, such as gas chromatographs, as well as alcohol detectors. The swift advancement in technology has paved the way for the extension of its reach into various domains, including but not limited to the analysis of breath and body odour for the purpose of health preservation, the prompt identification of illnesses in the healthcare sector, and the detection of particular ailments. A future suggested application is also in the detection of missing persons.

6.5.2 Resistive gas sensors based on organic material

These gas sensors, like metal oxide-based resistive sensors, operate on changes in the resistance of gas-sensitive layers and organic films caused by the presence of a target gas. However, how the gas affects the sensitive layer differs from what has previously been stated about metal oxide sensors. The ambient oxygen plays no part in the operation of these sensors, and the target gas molecules communicate directly with the surface of the organic layer. This relationship influences critical electrical properties of the sensitive layer, such as the majority carrier density and mobility coefficient, as well as the sensitive electrical resistance. At room temperature, the target gas molecules interact with the sensitive surface in a reversible manner. As a result, these sensors do not need a microheater. The target gas molecule's chemical interaction, for example, with a thin layer of conductive polymer, transfers electrons from the polymer to the gas molecule or vice versa. The work function and electrical conductivity of the polymer alter as electrons are transferred. The resistance of this sensor can be changed in the same way that metal oxide resistance sensors may, depending on the type of majority carrier. The presence of oxidizing gases, such as NO_2 and I_2, reduces electrical resistance in p-type polymers, while the presence of reducing gases, such as hydrogen and ammonia, increases electrical resistance. The opposite is true

for n-type polymers. Sensitivities formed of p-type polymers are typically more stable than sensitivities built of n-type polymers (Xie et al. 2002).

Polymers used to construct sensitive resistance sensors are polypyrrole, polyaniline, polythiophene, polyindole, or a combination of these. Polypyrrole and polyaniline polymers have received the most attention and utilization (Beygisangchin et al. 2021). These polymers have a low electrical conductivity (approximately 5–10 S/cm), which can be boosted with suitable contamination. The calculated change in pollutant impurity concentration in polymers can improve their gas detection properties (Bai and Shi 2007). Figure 9 depicts a schematic of a resistance sensor constructed of organic materials. This structure is fundamentally simple and comparable to that of a metal oxide sensor, but because it operates at ambient temperature, the microheater has been eliminated. Electrochemical techniques, spin coating, and physical evaporation procedures are all utilized to generate polymer films. The advantages of this type of resistive sensor are its simple form, good sensitivity to gas molecules, acceptable response time, low power consumption, and, most importantly, its ability to operate at ambient temperature. However, the inability of these sensors to withstand external variables, as well as their short life and drift, have limited their commercial application. Despite this, due to the selectivity and sensitivity and the variety of within this sensor group, the use of these sensors has been investigated in a variety of areas. In the environmental field, the gases that must be monitored mainly include NH_3, NO_2, and some VOCs, including toluene, methanol, formaldehyde (HCHO), etc.(Wang et al. 2021).

In contemporary times, there has been a conspicuous increase in the incidence of electric vehicle fires, gas pipeline leaks and explosions, and chemical toxic gas leaks. These occurrences have been attributed to the direct involvement or consequential actions of flammable and explosive gases, including H, CO, H_2S, amongst others. Consequently, the need for real-time and precise detection of these flammable and explosive gases has been established (Wang et al. 2021).

Certain gases present in the exhalation of humans are regarded as disease biomarkers, thereby enabling the identification of characteristic gases to diagnose a particular ailment. For example, isoprene (heart disease) (van den Broek et al. 2018), H_2S (halitosis) (Lee et al. 2014), NH_3 (hemodialysis) (Chuang et al. 2017), toluene (lung cancer) (Kim et al. 2014),

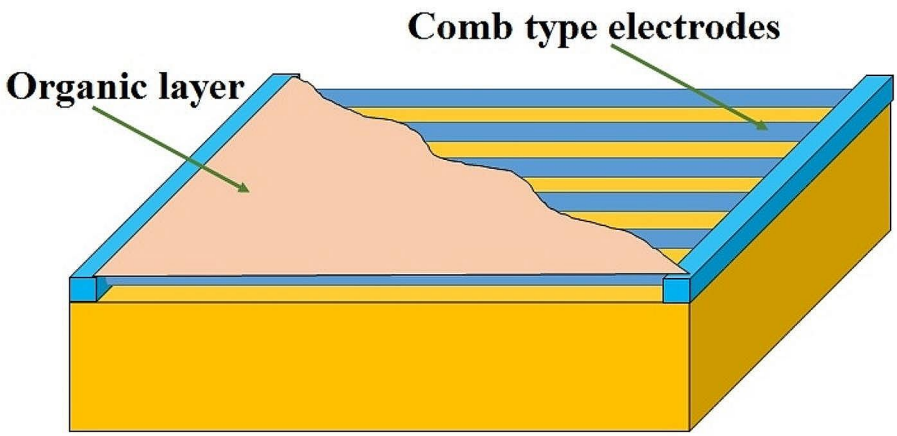

Fig. 9 Schematic of the structure of a gas resistance sensor based on a gas-sensitive polymer

formaldehyde (lung cancer) (Güntner et al. 2018b), etc. The utilization of gas sensors in medical diagnostics necessitates the attainment of low power consumption, as well as the ability to detect trace gases at room temperature while being adaptable and wearable under certain circumstances (Wang et al. 2021).

Despite their short life span (often requiring replacement after only a few weeks of operation) and expensive cost, these arrays are also employed in e-noses due to a combination of advantages with existing technology (Bai and Shi 2007). Resistive gas sensors are highly regarded as potential gas detection devices due to their extensive applicability, compactness, facile fabrication, low energy consumption, and exceptional maintenance capabilities. Resistive gas sensors can be substantially augmented in their sensitivity and response speed through the implementation of enhancements. However, the extensive utilization of these tools is presently constrained by their lack of portability, exorbitant costs, intricate operational procedures, and absence of real-time capabilities. In recent times, the advancements made in resistive gas sensors have brought about a shift in focus towards personalized and localized environmental monitoring, as opposed to the conventional global and average monitoring, thereby garnering significant attention. In the realm of environmental studies, the gases that necessitate vigilant observation predominantly encompass NO_2, NH_3, and a selection of volatile organic compounds (VOCs), inclusive of formaldehyde (HCHO), methanol, and toluene, among others. These are also potential target VOCs for missing person detection, both for living and deceased individuals.

6.6 Digital gas sensor

Semiconductor-based sensors, especially environmental ones, play a crucial role in our daily lives. These sensors collect data on temperature, humidity, atmospheric pressure, and more, then facilitate the seamless transfer of this data to computing systems, enabling "smart" decision-making. Recent advancements in both hardware and software have made it possible to equip environmental sensors with artificial intelligence (AI) capabilities (Klibanov and Boldt 2021).

BOSCH Sensortec has released the BME688, the first gas sensor with artificial intelligence. This innovative four-in-one air quality sensor integrates gas, humidity, temperature, and barometric pressure sensing with AI capabilities. The BME688 is a MEMS sensor designed for applications requiring small size and low power consumption, measuring just $3.0\times3.0\times0.9$ mm³. It detects most volatile compounds and other indoor air pollutants and features a customizable gas scanner function. BOSCH Sensortec specializes in MEMS sensors for smart devices, AR/VR, drones, and robots, and this AI gas sensor is a unique addition to its product portfolio (BOSCH 2021b). The BME688 gas sensor can detect VOCs, Volatile Sulfur Compounds (VSCs), and other gases such as carbon monoxide and hydrogen. The sensor's signal intensity typically scales with the chemical reactivity of the gas. Unlike other gas sensors that are selective for a single specific component, the BME688 measures the sum of contaminants in the air, providing a more accurate picture of the environment. The integrated temperature sensor, with an absolute accuracy of ±0.5 °C at room temperature, can be used for temperature compensation of the gas, humidity, and pressure sensors, as well as for estimating ambient temperature. The BME688 gas sensor from BOSCH Sensortec features exceptionally high accuracy and low noise resolution for its pressure sensor, with a sensitivity error of $\pm0.25\%$. The humidity sensor is also highly accurate, with an

accuracy tolerance of ± 3% and a fast response time of eight seconds. The BME688 supports various operating and power modes, optimizing it for different applications. As an evolution of the proven BME680 model, the BME688 offers an extended measurement range and innovative artificial intelligence features. Both models are compact, featuring an 8-pin Land Grid Array (LGA) package with metal (BOSCH 2021a). The BME688 is the first gas sensor with AI capabilities, making it ideal for developing new applications. It can detect the concentration of VOCs, VSCs, carbon monoxide, hydrogen, and other gases, and its AI can determine possible causes based on user-defined programs in the BME AI-Studio. This tool allows for easy customization without needing data scientists, enabling users to program recognition outcomes for each sample of sensor data collected.

Its small size and low power consumption make the BME688 ideal for portable and battery-powered devices, allowing for field data collection that accurately reflects real-world conditions. A notable application with significant global impact is wildfire detection. In 2020, wildfires burned over 10.3 million acres in the United States, the highest acreage affected in a year since 1960 (CRS 2021). Timely detection of wildfires using the BME688 could help reduce the damage caused. The sensor's customizable artificial intelligence opens up a vast range of potential applications. Users can design a generic system suited to their needs and create custom systems for specific cases or customers without lengthy development processes. The BME688 gas sensor is a novel and innovative product with a wide array of applications, thanks to its compact size, low power consumption, and customizable AI. It also paves the way for the use of artificial intelligence in devices previously unexplored. An increase in AI-enabled devices is expected in the coming years, particularly those tailored for specific and unique applications.

6.7 Field-effect gas sensors

In reality, these sensors are floating gate MOSFET transistors. The interaction of the target gas with the gate metal or gas-sensitive compounds placed on the gate metal drives the operation of these devices. This interaction modifies the gate metal's work function as well as the MOSFET threshold voltage. As a result, gas access to the gate surface is critical. In some circumstances, the gas-sensitive substance is removed from the device structure straight from the gate metal oxide. Because the gas molecules interact with the gate surface, the sensor's sensitivity is proportional to the effective gate surface. As a result, the porosity and roughness of the gate surface increase the sensor's sensitivity. The performance of these sensors, like that of resistive sensors based on organic material depends on the interaction of a sensitive layer with gas molecules, and the field-effect transistor only amplifies the signals created by the target gas. The MOSFET sensor was created using standard silicon technology methods. Gate metal is often a catalytic metal such as platinum, palladium, or iridium that is physically placed on a layer of silicon dioxide. The operating temperature of these gas sensors is determined by silicon device constraints or the maximum temperature tolerance of organic material on the gate. Field effect sensors typically operate in the 170–50 °C temperature range and are heated by a silicon microheater (Wilson and Baietto 2009; Arshak et al. 2004).

Because of the use of silicon technology, field effect gas sensors have very tiny dimensions and great manufacturing reproducibility. As a result, these sensors are less expensive than others. These sensors can be connected with control circuits, allowing the sensor and

microprocessor to be integrated on a single chip. However, drift in response and sensitive material instability are issues with this type of gas sensors. Consider a field-effect transistor with its floating gate completely exposed to the air to understand the source of the drift. Because of this flaw, field effect sensors lack the dependability required for use in sensitive applications. This sensor type is therefore not likely to be a suitable alternative for victim detection where trace volatiles are expected.

In the case of a sensor utilizing metal oxide, specifically a chemiresistive sensor, alterations in the sensor's signal are attributed to an ion sorption phenomenon and can be comprehended as a transfer of charge carriers, which are free, from the sensing layer to the adsorbed surface species (or the reverse). The inclusion of pre-adsorbed species has a substantial impact on the adsorption mechanism and consequently on the sensing response. Typically, operation of a metal oxide-based sensor takes place in the presence of humidity and residual gases within an air environment. At temperatures that are considered normal for its operation (200–400 °C), diverse oxygen species (O_2^-, O^-, O^{2-}), water, and carbon dioxide-related species are present at the surface of the metal oxide. Certain species are capable of establishing associations with particular surface locations, i.e., surface atoms, through the exchange of electrical charges. Such interactions may lead to the formation of dipoles, albeit without any discernible impact on the concentration of free charge-carriers or the resistance of the sensitive layer (Mirzaei et al. 2019).

Organic field-effect transistors (OFETs) are a fundamental component in contemporary organic electronics. Despite several decades of successful high-performance OFET production, there is a growing interest in the sophisticated functionalization of OFETs to external stimulations. This attention has emerged as a field of general concern due to the intrinsic merits of organic semiconductors, such as diverse molecular design options, affordability, lightweight, mechanical flexibility, and solution process ability. Furthermore, the inherent advantages of OFETs, including easy access to multiple parameters and ease of large-scale manufacturing, offer great potential in the production of portable yet reliable sensors with high sensitivity, selectivity, and quick response times (Zhang et al. 2015).

7 Industrial requirements and future generation of gas sensors

Existing gas sensors neither meet the current need nor the future needs. For example, there is currently a high demand for a gas sensor that monitors carbon monoxide gas in residential environments all day long, does not confuse it with the smell of perfume and cologne, has a detection threshold several times lower than the dangerous level of CO, has low power consumption (so it can be used with a battery), has a useful life of about five years, and costs less than ten dollars. Another example of current demands is requirement for ammonia (NH_3) gas environmental monitoring sensors. In continuous inhalation, the standard limit for this gas is less than 25 ppm (ammonia concentration in the breath of a healthy person is in the range of 0.25–2.9 ppm). Organic resistive sensors capable of detecting such quantities of ammonia are already available in laboratory samples. However, such sensors are susceptible to humidity, changes in ambient temperature, and other contaminants (such as ethanol vapor) that are present in larger concentrations in the environment. Error prevention necessitates the integration of infor-

mation from these sensors with information from other sensors such as temperature, humidity, and so on. The target gas density is calculated by the smart system using the gathered information. The requirement for smart gas sensors is further demonstrated by this example. Smart gas sensors are currently one of the most active areas of gas sensor development. Essentially, one topic of activity associated with gas sensors is research on software and technology for processing data collected from sensor responses. Because of the delayed progress in the industrial presentation of new sensor architectures, there has been increased attention and executive pressure in this field. The transient responses of a gas sensor contain a wealth of information, and the feature vectors extracted from them for target gases are inherently defined in more than 100-dimensional feature spaces, which typically slow down the operation and cause errors (this category is referred to as "large-scale spell" in the relevant literature). The studies in this context include filtering compact information and information integration, feature extraction, dimension reduction, pattern recognition, classification, error determination, optimization, and so on.

The utilization of environmental quality monitoring sensors is a complimentary approach. This approach will create invaluable additional data that can be used to infer human presence, particularly for the living victims. The gaseous carbon-based chemicals, known as volatile organic compounds (VOCs), are indicative of the overall metabolic state of an individual (de Boer et al. 2014). Air quality degrades when a poorly ventilated space is occupied by people, this can be exploited in e-nose technology. The indicators of air quality are those which pertain to the presence of human beings, albeit with certain modifications. Rather than regulating the internal air composition of a given space by means of heightened ventilation, the electronic nose ascertains the air composition within enclosed areas and deduces the existence of human presence. Elevated concentrations of carbon dioxide (CO_2) and moisture, combined with diminished levels of oxygen (O_2), are noteworthy markers of significance given their status as direct byproducts of human metabolic processes induced by respiration. Ammonia (NH_3) is another marker of interest as it result from the bacterial decomposition of urea contained in urine by Urease (Bebrone 2013; Callahan et al. 2005). When people are entrapped they not only loose urine, but also stool/feces. Therefore, methane (CH_4) will be another indicator of interest (Teodoro-Morrison et al. 2014). It is anticipated that humans who are entrapped for prolonged periods of time will experience the excretion of urine. Acetone is another potential marker which is present in the breath of fasting individuals and can also be used as an indication of living victims in disaster events where hours may have passed since their last meal. In addition to these compounds more advanced VOCs are also required to demonstrate presence of living and deceased humans. To develop a suitable e-nose detection tool, the gas sensor technology also need to function under variable conditions of humidity and temperature.

In the aftermath of a disaster, reaching victims quickly is imperative for rescue and first aid delivery. Conventional search and rescue operations are typically carried out through ground exploration or aerial surveillance depending on the expanse of the area. Ground exploration requires direct entry into the disaster zone to achieve proximity allowing visual recognition, sound detection, or scent discovery. This is both dangerous and time consuming because of the unguaranteed structural stability and unknown hazards. The need for a new and safer approach is therefore evident to better handle disaster search events.

8 Current e-nose approaches for victim location

The viability of utilizing an economical and uncomplicated gas/chemical monitoring technique for the purpose of identifying the whereabouts of victims is assessed (Anyfantis and Blionas 2019, 2020b). A first prototype system was built by Anyfantis and Blionas (2020a), whereby the e-nose was tested to real time victim localization under realistic conditions (simulation of human entrapment). That system was only tested in one scenario and the e-nose required the use of a flexible air sampling tube inserted through openings in the disaster area to locate victims. This system could provide enough sensor information to infer victim detection, but was too complicated and time consuming for actual use in the field and would not be applicable in hazardous areas. The devices that were previously presented as capable are found to have certain limitations. Huang and Wu (2020) used an e-nose for the measurement and identification of three VOCs in a mixture. Their system employed commercially available MOS gas sensors and used the transient sensor response to produce near real time results. The system was only tested on simple volatiles; ethanol, isopropyl alcohol and acetone, and may not be capable of detecting the more complex volatiles associated with humans, living and deceased. In another study, a sensor array for the detection of human presence was presented which could measure ammonia, isoprene and acetone at very low (parts-per-billion (ppb) concentrations) (Güntner et al. 2018b). It accomplished this by utilizing three tailor-made MOS sensors. The system demonstrated the ability to identify the presence of a human being through the detection of skin emissions. This system was tested in controlled laboratory conditions and the effect of environmental conditions and hazardous gases often present at disaster sites was not investigated (Güntner et al. 2018b) and is therefore unknown. There is a need for improved e-nose technology and further testing and development of the sensor technology outlined above with particular focus on low detection limits, ability to analyses complex VOCs and field usability.

9 Conclusion

The global incidence of mass calamities has escalated in recent times, primarily owing to the transformations in the ecosystem that have been triggered by the phenomenon of global warming and the amplified menace posed by acts of terrorism. In the event of such calamities, it is paramount to quickly ascertain the whereabouts of human casualties, comprising of both the survivors as well as the deceased. The Chernobyl nuclear disaster, 9/11, New Zealand's White Island eruption and the earthquake in Turkey and Syria are just some of the tragic events synonymous not just with loss of life but also the courage and professionalism of those who go in to recover bodies. The recent helicopter crash involving the Iranian President demonstrated some of the challenges with victim detection as the remote location and communication issues hindered search and rescue operations. Current methods of search and rescue require physical effort and machinery – and the risk of injury to rescuers and surviving victims. Detector dogs are proficient but expensive to train and hard to deploy on site, especially if they need to be flown in. Search and rescue canines are often employed to locate living individuals; on the other hand, canines trained for cadaver detection are generally assigned to the task of locating deceased individuals. The need for differing scent detection dog capabilities add an additional complication as it is likely that both living and

deceased victims will be present in the disaster area. There is therefore a need for instrument approaches that can search for both victim types simultaneous. E-nose devices are new class of analytical instruments that may be a suitable option to other detection methods. As scientific developments in the knowledge of biomarker volatiles and improvements in gas detection methods progress, the employment of e-noses is likely to have a major role in the early discovery of victims in mass disasters.

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Declarations

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