DOI: 10.1478/AAPP.98S1A41

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 98, No. S1, A41 (2021)

CHEMORESISTIVE METAL OXIDE GAS SENSOR: WORKING PRINCIPLES AND APPLICATIONS

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ABSTRACT. The aim of this paper is to explain to young students why chemoresistive metal oxide semiconductors (MOS) gas sensors are important and widely employed in many applications. The paper deals with the fundamentals principles of these devices and their continuous improvement, due to high level of compatibility with microelectronics technology and the employment of nanostructured materials as sensing interfaces. The main operating conditions and mechanisms are also described, in order to better understand the guidelines followed to improve these devices in terms of sensing performances (sensitivity, selectivity, fast response/recovery time, repeatability, and reliability) finalized to their practical applicability. Finally, we suggest a possible brief activity on how to explore gas sensor employment and operating features in a classroom.

1. Introduction

The evaluation of the gas concentration values have always received widespread applications in many fields of science and technology. Taking apart the traditional fields like industry and automotive, the variety of applications spans from biomedics to homeland security, from defense to internet of things and information and communication technology. The reported application fields employ several gas sensor typologies based on the transduction mechanism such as:

- Electrochemical (Ruiz Simões and Xavier 2017)
- Resonant (Aloisio and Donato 2014)
- Optical (Hodgkinson and Tatam 2012)
- Resistive (see below)
- Capacitive (Arena *et al.* 2009)
- Catalytic (Lee *et al.* 2011)

Among these devices, the resistive gas sensors based on metal oxide semiconductors (MOS) are the most studied and widely applied ones due to their features such as operating simplicity, low cost, compatibility and integration with electronic devices. The initial technical limitations in terms of low selectivity (the capability to discriminate

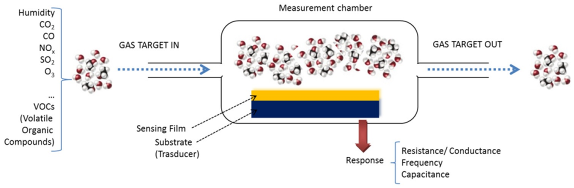

FIGURE 1. Diagram of a gas sensor.

among different gases) and low long-term stability are now overcome by the continuous progress in microelectronic technology and in nanomaterial science. Nano structured materials brought to and increasing of the gas sensor market, by drastically improving the performances of the new generation devices in terms of: (a) sensitivity (detection of gas concentrations at the ppm or ppb level); (b) selectivity (detection of a specific gas target among mixed gases) and (c) stability(Seiyama *et al.* 1962; Yamazoe 1991; Göpel 1994; Göpel and Schierbaum 1995; Barsan *et al.* 1998; D'Amico and Natale 2001; Shimizu and Egashira 2013; Sberveglieri n.d.). A gas sensor is a device able to transduce a variation of gas concentration into a corresponding variation of an electrical signal.

In order for a device to be a good gas sensor, it should satisfy the following main requirements:

- Detection of low levels of the gas target concentration in the surrounding environment (sensitivity);
- Discrimination of the gas target from the others simultaneously present (selectivity);
- Reproducibility of response in the short, medium, and long period (stability). Moreover, to meet the commercial and industrial requirement (Yamazoe, 2005), gas sensors must be:
- Cheap;
- Low power consuming;
- Easy to use;
- Durable;
- Resistant;
- Miniaturizable.

The aim of this work is to explain to young students why these gas sensors are so important and widely employed in many applications.
MOS resistive gas sensors were introduced for the first time in the practical use by Taguchi at the beginning of the 70' years [1]. MOS devices are used as:

- alarms for the presence of hazardous levels of explosive gases, avoiding domestic accidents,
- humidity sensors in the alimentary, food storage or electronic industry and in control systems for air conditioning or ovens,
- sensors in the automotive sector,
- breath analyzers for medical diagnosis.

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[1] Taguchi, N. (1971). Patent No. 3.631.436. U. S.

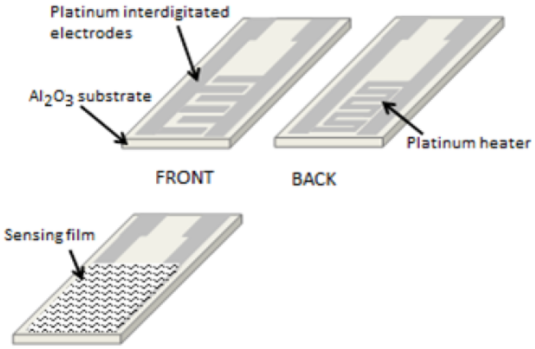

FIGURE 2. Planar structure of chemoresistive sensor with front side coated thick/thin film and the heater on the backside.

The continuous needing of top performance MOS gas sensors with improved sensitivity and selectivity, faster response/recovery times, alongside high reliability, and low power consumption, brought to an increasing of the activities aimed at the development new metal oxide sensing materials.

Nanostructured materials are characterized by specific electrical properties that can be tailored to the realization of top-performance chemical sensing devices. In fact, by choosing specific size and shape of the material it is possible to improve the sensing performance. One of the main reasons is the larger surface-to-bulk ratio in nanomaterials, when compared with coarse micro-grained materials. Furthermore, the sensing layer particles size reduction enhances some functional features of MOS gas sensors and particularly sensitivity and response/recovery time. Therefore, the gas sensing efficiency of MOS increases drastically when the sensing layer was in a nanostructured form (Comini 2006). The over listed features are mainly linked to:

- The reduction of the grain size that brings to a larger surface area and the simultaneous approximation of the depleted/sensing zone with the whole grain size.
- Structural and morphological factors.

Therefore, great efforts in fundamental and applied research on MOS sensors was dedicated to the optimization of new syntheses procedures able to modify the nanostructure of pure and mixed metal oxides.

The easiness of fabrication of resistive gas sensors is one of the keys contributing to their large use. A solid-state gas sensor device is generally composed by a layer of a sensing element deposited on a patterned ceramic substrate Figure 2.

Based on the thickness, the sensing element can be classified as:

- Thick film (thickness more than $1\mu m$); thick films are easy to deposit by means of relatively cheaper techniques (i.e., screen printing), but present poor selectivity, long stabilizing times, and large power consumption.
- Thin film (thicknesses between 5 nm and $1\mu m$); thin films present lower power consumption, but are more expensive requiring complex systems for the deposition (sputtering, chemical vapor deposition) and result somewhat unstable.

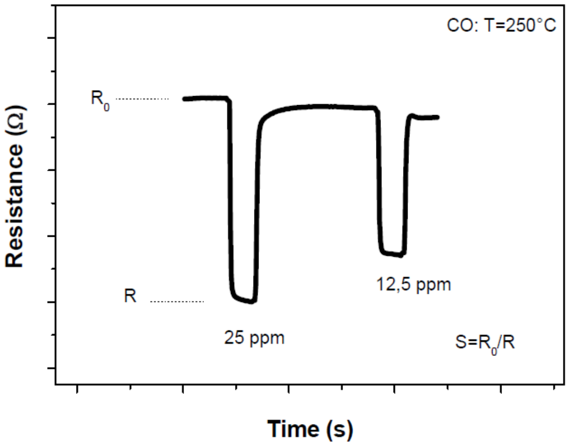

FIGURE 3. Output of a MOS gas sensor vs. gas target concentration.

A heater track is also present usually on the backside of the ceramic substrate to ensure to the sensing element to work at the optimal temperature value, whereas an additional layer having the role to filter and/or transform interfering compounds, hence hindering them from reaching the sensing surface, can be placed over the sensing element.

By applying a fixed voltage, U, at the electrodes, the electrical current, I, passing through the sensing element is a function of the partial pressure of the target gas in the surrounding atmosphere and operating temperature. The change in electrical resistance value, due to a corresponding change in the target gas concentration, represents the output of the sensor, is shown in Figure 3.

The ratio $S = R_0/R$, where R_0 is the resistance in air and R the resistance in the presence of gas target, represents the response of the sensor being directly related to the gas target concentration value. Of importance is also the dynamic of the sensor response, characterized by the response and recovery time. The response and recovery times depend on the film thickness and working temperature, being both slow at low temperature and fast at higher temperatures.

Semiconducting metal oxides are the most widely used sensing elements for gas sensors applications. Since Seiyama introduced the use of semiconducting metal oxides for gas sensing, many studies have been aimed on materials that show changes in electrical conductivity to a corresponding change in the gas composition (Seiyama *et al.* 1962). A non-exhaustive list of semiconductor oxide materials and the related sensitivity towards different gas targets is shown in Table 1.

Thin or thick film of nanosized metal oxide particles can be deposited on the substrate by different methods (screen-printing, spin coating). The deposited layer is then fired at high temperature values to stabilize the microstructure and to form a porous layer adherent to the substrate.

Solid state chemoresistive sensors features have been improved by optimizing the sensing layers, i.e. by using nanostructured materials (Neri 2010). The sensing behavior primarily depends on the nature of the sensing layer, in such context, the most of conventional sensors

Metal Oxide	**Semiconductor type**	**Target gas**
SnO_2	n	H_2, CO, CH_4, H_2S, NO_2
TiO_2	n	H_2, C_2H_5OH, O_2
Fe_2O_3	n	CO
ZnO	n	$H_2, CH_4, C_2H_5OH, C_4H_10$
In_2O_3	n	O_3, NO_2
Ga_2O_3	n	O_2
WO_3	n	NO_2, NH_3
$LaFeO_3$	n	NO_x
$Cr_{1.8}Ti_{0.2}O_3(CTO)$	n	NH_3, H_2S

TABLE 1. List of semiconductor metal oxides and target gases.

used metal oxides (SnO_2, ZnO) based sensing films, or conducting polymers. In the first typology of sensors, i.e. MOS sensors, a power supply is generally required in order to set the operating temperature value of the sensitive layer deposited on the interdigitated contacts, the operating temperature value range spans from 100° C to 1000°C is reached by supplying a heating layer. The polymer-based ones operate at lower temperatures, they are characterized by high sensitivity and selectivity, but with a limited lifetime. Furthermore, some organic materials are not suitable for large scale production, being not compatible with microelectronic fabrication technologies. One of the most important issues is that gas sensors need high operating temperature values to avoid selectivity problems. For this reason, the best sensing material candidate, among nanomaterial ones, is the one able to fulfill a tradeoff between power consumption (lower operating temperatures) and sensor performance.

Many parameters affect the sensing properties of the metal oxide layer (thickness, porosity, surface-area, etc.), therefore the deposition process and successive posttreatments should guarantee a reliable deposition of the nanoparticles layer on the substrate. Moreover, to ensure the long-term stability of the sensor, it is also important that the sensing layer does not undergo any significant structural/morphological change during working. This is a crucial aspect because the small metal oxide grains are highly reactive and then strongly subjected to sintering phenomena with consequents grains growth.

The sensing mechanism of MOS sensors relies on reactions which occur between adsorbed oxygen species and the probed gas on the surface of the sensing layer (Sberveglieri, 1992). When exposed in air, the bulk electrical resistance of the sensing film (semiconductor) depends on the coverage of ionosorbed oxygen species acting as electron traps. In a temperature range spanning from 150°C and 500°C, the resistivity variations in the presence of trace levels of target gas in air, depend on gas reducing or oxidizing behavior, and on the semiconductor type (n or p). Several studies have been focused on the operating conditions of sensing mechanism, the response variations of resistive gas sensors have been evaluated with respect to chemical reaction and to surface adsorption (Shimizu and Egashira 2013). In first approximation, oxygen adsorbed on the surface of n-type metal oxide semiconductors plays a key role, trapping free electrons because of its high electron affinity, and forming

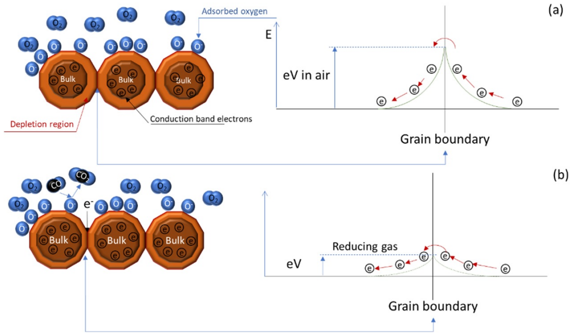

FIGURE 4. Gas sensing operation on n-type MOS with reducing gases.

a potential barrier at the grain boundaries. The main effect is a restriction of the flow of electrons, causing an increasing of the electric resistance. If the sensor is exposed to an atmosphere containing reducing gases, e.g., CO, the gas molecules adsorbs on the surface and reacts with active oxygen species, e.g., O^-, which liberates free electrons in the bulk, as follow:

$$CO + O^- \rightarrow CO_2 + e^-$$

This lowers the potential barrier allowing electrons to flow more easily, thereby reducing the electrical resistance. When exposed to oxidizing gases such as NO2 and ozone, the adsorption process brings to an increasing of the surface resistance. On the other hand, the opposite behavior can be observed for p-type oxides, where electron exchange due to the gas interaction leads either to a reduction (reducing gas) or an increase (oxidizing gas) in electron holes in the valence band.

Based on the sensing mechanism above described, MOS sensors can sense many gases with the same chemical structure and/or properties. Then the selectivity remains one of the main problems to fulfill for many applications (Neri, 2015).

2. Effect of grain size

It is well recognized that the sensitivity of MOS sensors is greatly improved when it is nanostructured (Xu *et al.* 1991; Baraton and Merhari 2001; Korotcenkov 2008). In this size range many atoms (up to 50%) are in the surface or the interface region, this bring to a huge difference of chemical, electronic, and sensing properties of nanoparticles when compared with the bulk. The sensing behavior is also associated with the depth of the surface space charge region that depends on the gas adsorption and finally on the particle size. MOS sensitivity is strongly affected by crystallite size, D, when it is in the nanometer range (Yamazoe 1991) More in detail, the sensor response significantly increases when the crystallite size is about twice the adsorption depth of oxygen adsorbates, 2L (where L is the depth of the space-charge layer). It follows that the improvement of sensing features incurs when both D decreases and L increases, bringing a major area of material (i. e. the oxygen adsorbates) to interact with the target gas even if the grain size is not excessively small. In

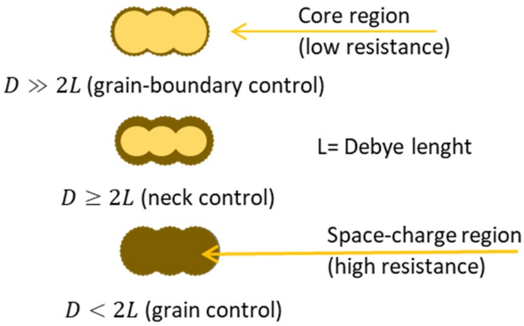

FIGURE 5. Effect of the crystallite size on the sensitivity of metal-oxide gas sensors: (a) D » 2L; (b) D $\geq$ 2L; (c) D < 2L

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Addition, the doping with higher valence cations brings an increasing of the response since the carriers concentration is reduced, and L increases (Yamazoe 1991). Furthermore, if the particle size is small respect with the Debye length, the interaction zone at the analyte-grain interface extends over the whole grain, i.e. the particle is fully depleted (Malagù *et al.* 2002; Yamazoe *et al.* 2003). When the diameter of grains is comparable with or even smaller than this value, the sensing layer will interested by the charge transfer process, causing a strong response of the device (Figure 5).

For instance, Singh et al. claimed that the sensing response of indium oxide nanoparticles sharply increases if the particle size is reduced down to 5 nm, by this way the available sensing surface is increased (Singh *et al.* 2007) Nanoscaling changes the relative proportion of exposed surface atoms and planes (Hardeveld and Hartog 1969), and this affects the surface/gas target interaction.
Furthermore, a different location of the atoms in the surface of the semiconductor oxide can exhibit a different reactivity towards the same gas approaching the sensing layer. Considering these effects, it is possible to improve the sensing properties for a nanostructured material both improving the sensitivity and selectivity of the device.

Based on these considerations, nanosized metal oxides are playing a key role in the development of gas sensors, increasing the number and the variety of devices and systems for practical applications.

sectionEffect of metal doping The increasing of the technological applications demand, however, needs for more affordable and reliable gas sensors. The doping of the base metal oxide with suitable additives it one of the most effective ways to increase the performances of semiconductor gas sensors. A thorough understanding of the effect of doping on the electronic and sensing properties of MOS is far to be complete, despite this, there is a wide-spread use of dopants in such context (Smyth 2000). These additives can improve the sensitivity by increasing the carrier concentration and mobility, increasing sticking coefficient or inducing microstructural changes in the sensing material down to the nanometer scale. The improvement of selectivity can be achieved by choosing additives that enhance gas adsorption, or that promote specific chemical reactions via catalytic or electronic effects, or that bring to surface modification.

The sensing properties can be affected by metal promoters in very different ways more related with the behavior of the metal (such as oxidation state, work function, particle size, dispersion, and loading of the promoter) or with the morphological and microstructural modification of the MOS caused by the metal additive. Furthermore, these effects are also related with the metal loading, thermal treatments, additive dispersion etc. (Neri *et al.* 2003). Furthemore, the morphology and microstructure modifications, frequently observed with increasing the thermal treatment, change the relative proportion of exposed surface atoms and planes.

As described before, the metal doping can bring to an increasing of sensitivity, selectivity, and rate response, furthermore, in some cases, it can also strongly decrease the operating temperature. From a practical point of view, sensor devices which operate at low temperature, are desired because of the low power consumption required. The relationships between the sensitivity and the temperature depends by several activated processes that involve processes of adsorption/desorption/reactions of the target gas on the surface of the MOS, the behavior can be generally described by a volcano curve (Figure 6) (Yamazoe *et al.* 1983; Shimizu and Egashira 2013). The temperature value TM at which the maximum sensitivity KM is observed, jointly depends by the interaction of the target gas with the sensing layer. The undoped semiconducting oxides are sensitive in a temperature range spanning from 150°C to 500°C, while the doping procedure generally shifts the volcano curve toward lower temperature values.

The shift is due to an increasing in the rate of oxidation of the target gas, that is enhanced by the catalytic action of the metal additives. By considering that, the amount of oxygen in the steady state is expected to decrease with the increasing of catalytic activity, it would bring to a consequent increasing of the sensitivity (Yamazoe *et al.* 1983). On the other hand, if the catalytic activity become very high the reaction of oxygen consumption will mainly occur on the external surface of the sensing layer, not sufficiently allowing the diffusion of the target gas in the bulk to change the electrical resistance. The geometric characteristics of electrodes have a great impact on the gas response as well as the porous structure and thickness of the sensing layer, confirming the importance of the diffusion of gases on the sensitivity (Sakai *et al.* 2001)

Selectivity is the most important parameter when analyzing gas mixture. Beside metal doping, another effective way of improving selectivity is to promote selective catalytic processes by means of metal-doped filters, placed on the top of the sensing layer (Sauvan and Pijolat 1999; Park *et al.* 2002). With this solution it is possible to avoid the influence of interfering gases, by blocking these species from reaching the sensing layer.

3. Target gases

Many toxic or explosive combustible gases (such as NOx, CO, SO2, VOC, H2, etc.) can be detected by MOS sensors. These gases are used for example in the chemical industry or can be found in the emission of a number of stationary or mobile sites acting as pollutants for the environment. Primary pollutants are those in which the substance emitted is itself hazardous (see Figure 7).

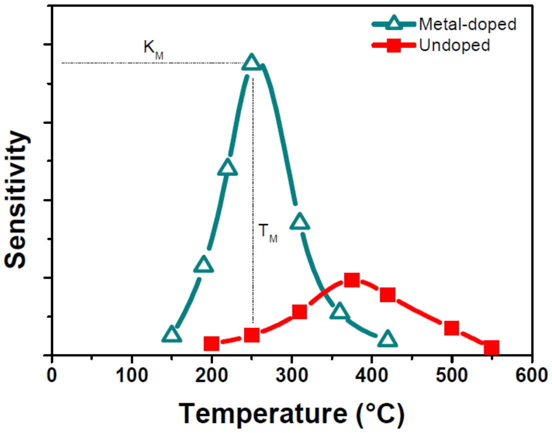

FIGURE 6. Response curve as a function of the operating temperature for a pure and metal-modified sensor

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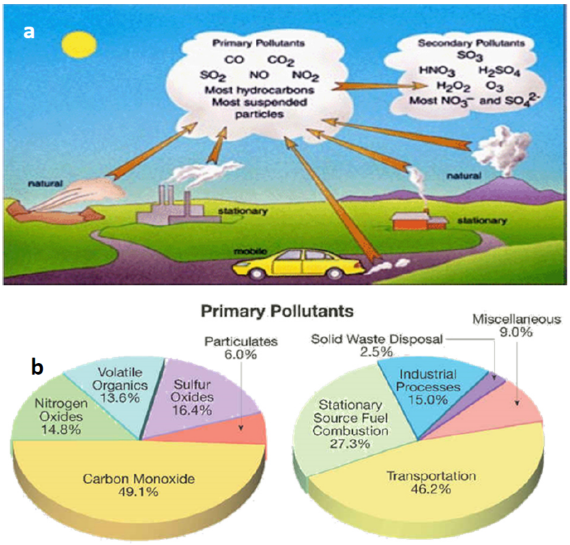

FIGURE 7. a) Types and sources of air pollutants. b) Major pollutants and their sources

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Some primary pollutants are able to react and produce in the atmosphere other dangerous substances, also labelled as secondary pollutants. Among primary pollutants, NOx are considered particularly hazardous and toxic for human health. These gases are produced by the oxidation of nitrogen during the combustion of air, being mixtures of nitric oxide (NO) and nitrogen dioxide (NO2). A large amount of NOx is produced in engine emissions, although other sources can have significant local impact. The NOx is also a contributor to several secondary pollutants, NO2 at low concentration values is a respiratory irritant while at high ones is able to corrode metals.

SO_2 is another important primary pollutant, arising mainly from the oxidation of sulfur in the combustion processes of oil, diesel and coal. The 90% of the production is of human origin and is mostly concentrated in the most industrialized countries. The prolonged exposure to SO_2 leads to respiratory effects such as tracheitis, bronchitis, pneumonia. The presence of SO_2 in the atmosphere contributes to the acidification of precipitations, with toxic effects on plants, acidification of water sources and impact on aquatic life. It is also the main responsible of the acid droplets in the volcanic smog (VOG), a mixture of gas and an aerosol of tiny particles and acid ones. During the eruption, expelled gases are affected by chemical reactions with oxygen in the atmosphere and the sunlight, with a consequent increasing of the acidity level. At low concentration values, it causes a slowdown in the growth of plants, while at higher doses it generates physiological alterations such as to lead the plants to death. Finally, acid rainfall can have corrosive effects on different types of materials.

MOS sensors have been also proposed for the monitoring of pollution levels in vehicle cabin (Pijolat *et al.* 1999). CO and NOx are the main pollutants monitored (**20**; Oto *et al.* 2001).For instance, CO produced from the incomplete combustion of fossil fuels from car engines causes high concentrations of CO in urban area and particularly in closed ambience such as in the cabin vehicles, garages, tunnels and underwear parking. Thus, the combination of air quality sensor and air ventilation/conditioning systems can modulate the air quality increasing passenger comfort and health.

Monitoring carbon dioxide (CO_2) concentration is of great importance in many fields such as in chemical industry, agriculture, biotechnology, environment and medicine (Star *et al.* 2004). SO_2 is a greenhouse gas, which traps heat near the earth's surface, and prevents it from being radiated back into space. CO2 is also an important indicator for indoor air quality. Due to its inert character, it is used in food packaging, where CO2 considerably extend the storage and shelf life of meat, cheese, as well as fruit and vegetables (Neethirajan *et al.* 2009). The measurement of carbon dioxide levels in breath is a standard procedure during intensive care and anesthesia and is a primary tool in the diagnosis and management of respiratory function [2].

Hydrogen is also largely monitored by gas sensors because it is extensively used in industry, notably in steel manufacture and in refining of petroleum products well as. It is also among the most promising clean energy carriers for use in future fuel cells and combustion engines (White *et al.* 2006).

Hydrogen sensor technology is a critical component for safety and other practical concerns of the present and future hydrogen economy. Real-time monitoring of hydrogen flow in these applications is crucial to their effective operation. Therefore, the development of rapid and precise sensing systems continues to be a subject of great interest (Hübert *et al.* 2011).

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[2] Patent No. 10/940,324. US

4. Applications of MOS gas sensors

The extensive range of gas detected by MOS resistive sensors, makes them potential solid state gas sensors that can be used in many application areas(Ehrmann *et al.* 2000; Frank and Meixner 2001; Park and Akbar 2003; Varghese and Grimes 2003; Vergara *et al.* 2008).

The high level of compatibility with microelectronics technology brought to a variety of devices and systems based on MOS sensors, spanning from miniaturized single devices to arrays mounted in on field-portable instruments, able to be employed in many applications. In particular, these system can be valid solutions in environmental monitoring, security, biomedical field giving a valuable alternative to accurate, but more expensive and time-consuming, conventional analytical techniques.

The future of MOS sensors based on nanosized sensing elements looks set to expand into areas that could have been little contemplated so far. This is due both for the economic aspects of the technology either for specific technical features. For example, the feature to withstand high temperatures jointly with packaging reliability and miniaturization are strong technical merits for automotive applications. In such a context,the exhausts usually reach high temperature values, and MOS (Oxygen – λ) sensor have to operate in a harsh ambient and in a temperature range spanning from 600°C to 900°C. Further requirements for this specific application are also the reaction measurement speed usually of the order of fraction of seconds and 5–10 year service life.

Chemical sensors for vehicle diagnostics have been utilized from long time by the automotive industry to monitor the combustion process in order to improve engine efficiency and control exhaust emission (Moos 2005). Currently, the introduction of emergent technologies in the automotive industry bring new solutions for vehicle diagnostic sensors and related services: engine functioning, monitor several emission gases ($NO, NO_2, SO_2, HC, O_2, CO, CO_2, etc.$), and the evaluation of the air quality in the vehicle cabin.

Today, sensing devices are widely employed in the healthcare and well-living fields, for example a large number of wearable devices are now in the market, exploiting new applications and services. In particular, in modern medicine prevention plays a fundamental role for the economic sustainability of national health systems and to allow a high level of assistance to patients for the years to come. Prevention relies on the periodic monitoring of some substances (markers) predictive of specific pathologies. Although enzymatic assay kits have simplified the analysis of these markers in the blood, many methods rely on laboratory instrumentation and trained personnel, requiring a constant presence in people's everyday life. At the present time, more rapid blood tests are currently marketing for use both in clinical laboratories either in patient home. MOS sensors are able to detect very low concentrations of gases (in the ppt–ppm range) present in the human breath. This characteristic make them potential detectors breath test where the concentrations of gaseous species to be detected, coming from biochemical processes occurring in the human body, are very small. The breath analysis is becoming an affordable and noninvasive tool to perform the monitoring and the diagnosis of metabolic diseases, this technique relies on the fast exchange of endogeneous volatile compounds between pulmonary blood and air in the alveoli of the lung (Miekisch *et al.* 2004).

Examples of such compounds strictly correlated to various diseases include: nitric oxide (NO) for asthma, acetone for diabetes, ammonia for renal disease, etc. Breath testing devices equipped with solid state metal oxide sensors can offer a user-friendly, noninvasive diagnostic tool for these pathologies (D'Amico *et al.* 2008). These systems are opening new perspectives in the healthcare applications, having performance almost comparable with conventional analytical techniques, that are generally expensive and time consuming, increasing the number of user and spreading the monitoring in a larger number of potential patients.

5. Didactic activity for students on gas sensors

In the context of chemoresistive gas sensors, here we suggest a possible activity designed for students on how to explore gas sensor employment and operating features in a classroom. In recent years, in the school context, there is increasing talk of innovative teaching strategies. The most relevant from a pedagogical point of view are: cooperative learning, peer education, problem solving, laboratory teaching, spaced learning, flipped classroom. In this period, marked by the COVID-19 pandemic, the use of “virtual classrooms” is becoming increasingly essential, so we want to focus our attention on the Flipped Classroom model.

The Flipped Classroom model is a way of doing teaching that sees the use of teaching technologies as protagonists and through these reverses the traditional teaching/learning scheme and consequently the teacher/pupil relationship. The various materials and the different educational paths proposed by the teacher are made available to the students within a virtual environment created for the class group in digital platforms. These materials can be explored by students alone or in groups (even virtual) outside the classroom. In the classroom, with the teacher, the contents learned through technology become the object of cooperative activities. Thus, the classroom is no longer the place for the transmission of notions, but a space for work and discussion where one also learns to deal with the teacher. in this way the student becomes more active, more protagonist of the learning process.

The activity here designed is described in Figure 8. As we can see, it is based on the employment of a microcontroller-based board (Arduino-like embedded system) connected to a commercial gas sensor. The gas sensor choice was made considering the gas target (ethanol for example), the biasing voltage, and the current absorbed by the device. If we have to keep at minimum the number of devices involved in the experience is better to choose 3.3 V or 5 V, these voltage values are present in the most of microcontroller boards.

Many gas sensors in the market are equipped with libraries, commands, and examples to be interfaced with microcontroller board, then the firmware (the commands to be written inside the microcontroller) for the experience can be easily written by students. In order to expose the sensor to the gas target, we can put the device on the top of a container filled with ethanol, then the ethanol vapors will reach the sensor changing its electrical resistance. Of course, this is a merely qualitative approach. For a successive quantitative stage, we can prepare different solutions of ethanol in water diluted in graduated containers, changing the percentage of ethanol (in volume). Then we can mount the sensor and the container inside a small hermetic box, in order to reach a saturated ambient with a fixed ethanol concentration value (% in v/v). To avoid the saturation of the sensor, the concentration range allowed by

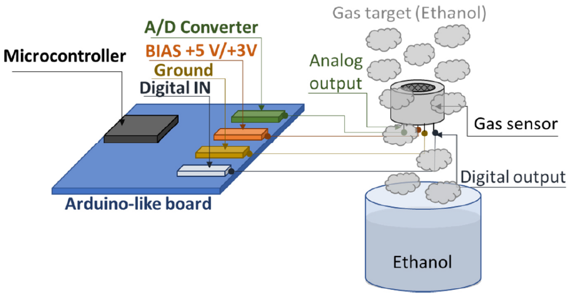

FIGURE 8. Didactic activity example for gas sensors: qualitative one.

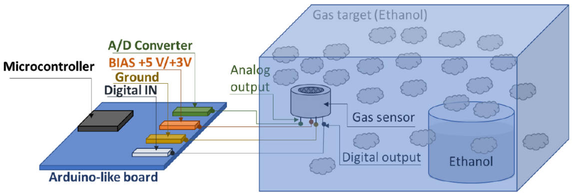

FIGURE 9. Didactic activity example for gas sensors: quantitative one.

the chosen device should be considered. By exposing the sensor at several concentration values, we will be able to record the corresponding responses.

Conclusions

Here it was reported about the importance of monitoring gas in many applications and of the employing of MOS gas sensors to fulfill the required performance. The paper can be considered a guide for young students to better understand the fundamental principles, operating parameters, and sensing mechanisms of these devices. The primary role played by the employment of nanomaterials suited for specifics sensing layers, leading to new applications, and operating scenarios, has been also highlighted. Finally, a didactic activity for students is also described, focused on the gas sensor operating conditions and employment.

Acknowledgments

The authors acknowledge the PON project AEROMAT.

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Paper contributed to the international workshop entitled “New Horizons in Teaching Science”, which was held in Messina, Italy (18–19 november 2018), under the patronage of the *Accademia Peloritana dei Pericolanti*

Manuscript received 17 November 2020; published online 30 September 2021