ZnO/NiO heterostructure-based microsensors used in formaldehyde detection at room temperature: Influence of the sensor operating voltage

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ABSTRACT

Recently the emissions of volatile organic compounds (VOCs) in the atmosphere have increased dramatically with rapid development of urbanization and industry. This led to a large decline in air quality around the world, which resulted in a heavy impact on human health. Therefore, new/cheap detection devices for VOCs are of high interest. Formaldehyde (FA) is a very toxic VOC, which damages the respiratory system even in the smallest doses and short exposure time. Zinc oxide (ZnO)/nickel oxide (NiO) heterostructures were synthesized using an economical route: firstly, NiO was prepared by liquid exfoliation technique and deposited by dip-coating on alumina ceramic transducers with two interdigital gold (Au) electrodes, followed by low-temperature hydrothermal growth of ZnO. The as-prepared sensors were characterized by atomic force microscopy (AFM), scanning electron microscopy (SEM-EDAX), and X-Ray fluorescence (XRF). The response/recovery of ZnO/NiO heterostructure-based microsensors for formaldehyde was investigated at room temperature, in agreement with modern sensing requirements. The sensor operating voltage was varied between 1.5 and 5.0 V direct current (DC), to achieve the best sensor performance.
1 Introduction

High levels of air pollution and indoor air quality are of great concern to scientists due to their effects over human health. Formaldehyde (FA), a volatile organic compound (VOC), is a major indoor gas pollutant, being generated by building materials, the furniture industry and interior decoration. More than 50 branches of industry use formaldehyde and its derived products in glues, resins, bakelite and other industrial applications [1]. As people spend more time indoors lately, which has been imposed by the COVID-19 pandemic, closer monitoring of human exposure to indoor pollutants is also needed.

Formaldehyde is highly toxic, causing various symptoms like skin or nasofacial irritation for exposures in the 0.1–1 ppm range, and swelling of the throat or burning of the lungs at higher concentrations, even cytotoxic effects (carcinogenic to humans, causing leukemia or nasopharyngeal cancer) for exposures to concentrations over 3 ppm, which is why the World Health Organization (WHO) has set the exposure limit at a maximum of 0.08 ppm for longer periods of time [2]. In this context, the use of easy-to-handle portable devices with integrated miniature sensors is very useful for continuous monitoring of indoor air [3].

Semiconductor metal oxides are widely used in gas detection applications, due to certain advantages such as: simple methods of preparation/cheap synthesis, adapted morphological and conductivity characteristics, fast response/recovery time, high variety [4].

Zinc oxide (ZnO) is one of the most promising n-type multifunctional semiconductors, due to the considerable diversity of nanostructures it configures (nanoparticles, nanocenters, nanowire matrix, nanorods and nanotubes). ZnO is used in a considerable number of applications, such as: piezoelectric [5], optical, optoelectronic nanogenerators, sensors, actuators, biosensors, biomedicine, etc. [6–8]. However, given the state of the art, pristine ZnO, as a sensing material, has a low response for certain target gases and high working temperatures (as high as 350 °C-31) or expensive preparing techniques (atomic layer deposition [30, 38], thermal decomposition/screen printing [31], electrospinning [41], spray pyrolysis [42], etc.). The literature referenced there describes detection limits for formaldehyde situated between 0.001 and 100 ppm, but in the case of low concentration formaldehyde detection a high working temperature is used, which constitutes an issue from the economical point of view. A heater added to the sensing device means additional electronics which in turn add to the dimensions of the sensing device, a higher energy consumption and an overall higher retail cost of the product.

In this paper, a new approach was used to obtain microsensors based on ZnO/NiO heterostructures, with microrods type morphology, having a very large active surface area, favorable to increase the detection properties of the sensing material.

The goal of this paper is to achieve a sensor capable of formaldehyde detection at room temperature, obtained by a cheap and also an eco-friendly making heterostructures with other semiconductor oxides. Of these methods, the latter has been used by other researchers to obtain formaldehyde sensors. For example, the obtaining of various oxide heterostructures based on ZnO/CuO has been reported, [13], ZnO/graphene [14], SnO2–ZnO [12, 15], Cr2O3–ZnO [16], etc.

On the other hand, nickel oxide (NiO), which is a p-type semiconductor [17], can be used in sensor applications, solar cells, electrochromic devices [18, 19] and can easily form heterojunctions with ZnO. The combination of NiO and ZnO oxides has been previously described in the literature and used successfully for various gas detection applications [20–23].

Creating ZnO-n/NiO-p heterojunctions is a simple and effective way to improve gas detection properties, which increases sensor response and decreases recovery time, to develop applications for gas sensors [20, 21]. References [21–23] describe NiO-ZnO combinations as efficient materials used for the development of gas sensors at low working temperatures. Structural/morphological advantages, such as adsorption density, shape and large surface area, lead to improved performance for VOC detection.

The state of the art described in Table 1 refers to sensors having as sensing materials nanomaterials or nanostructures, even some microstructures with high working temperatures (as high as 350 °C-9, 31) or expensive preparing techniques (atomic layer deposition [30, 38], thermal decomposition/screen printing [31], electrospinning [41], spray pyrolysis [42], etc.). The literature referenced there describes detection limits for formaldehyde situated between 0.001 and 100 ppm, but in the case of low concentration formaldehyde detection a high working temperature is used, which constitutes an issue from the economical point of view. A heater added to the sensing device means additional electronics which in turn add to the dimensions of the sensing device, a higher energy consumption and an overall higher retail cost of the product.

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The goal of this paper is to achieve a sensor capable of formaldehyde detection at room temperature, obtained by a cheap and also an eco-friendly
technique. ZnO/NiO based sensing films were prepared by hydrothermal growth of ZnO microstructures on NiO nanoparticles, previously deposited on alumina ceramic transducers. The obtained microsensors were found to exhibit promising sensing performance at room temperature for formaldehyde detection with short response/recovery time (60 s), and a good sensor recovery.

### 2 Materials and methods

#### 2.1 Transducer fabrication

The porous alumina substrate from Kyocera (an excellent porous ceramic support for gas sensing experiments [24, 25]) was the basis of the transducers, which contain two Au interdigital electrodes (IDE) on the front side, and a Pt heater on the backside (Fig. 1). Manufacturing was consistent to the procedure reported in detail in our previous paper from Ref. [24]. The masks for the heater and the IDE were patterned using photolithography, etching and lift-off processes.

The miniaturized transducer from Fig. 1 has the following dimensions: 10 × 20 mm (width/length); 200 μm (alumina substrate thickness); 1200 μm...
(width of the Pt resistor heater). The sensitive area (built on the front side of the alumina wafer) of the transducer has 53 pairs of interdigital electrodes and is 6400 μm in length, 25 μm wide, and the electrode pairs are separated by 25 μm [24].

2.2 Obtaining ZnO/NiO heterostructure-based sensing film

All the raw materials were purchased as analytical reagent grade from Merck and used as received without further purification. The sensitive layer was obtained through a simple, cheap, and environmentally—friendly chemical approach (Fig. 2). In the first step, through a standardized process, 0.05 M nickel nitrate hexahydrate, \([\text{Ni(NO}_3\text{)}_2\cdot6\text{H}_2\text{O}]\) was dissolved in deionized water (DI). An equivalent volume of 0.1 M NaOH was added drop by drop with constant stirring. The obtained light green precipitate was washed multiple times with deionized water and was filtered to acquire a powder of bulk Ni(OH)\(_2\). The as-prepared Ni(OH)\(_2\), dried overnight in air at ambient temperature, was homogenously dispersed in dimethylformamide (DMF) by the ultrasound method, for 7 h, to obtain layered Ni(OH)\(_2\) flakes. The stock dispersion of exfoliated Ni(OH)\(_2\) was used as NiO thin film precursor. Liquid exfoliation is an easy synthesis method for obtaining resistive gas sensors [26]. Direct exfoliation of layered materials in a suitable liquid seems to be a promising route to produce sensing materials especially if combined with dip-coating, drop casting or inkjet printing techniques [27]. The transducers were dipped into the stock dispersion of exfoliated Ni(OH)\(_2\), with an immersion speed of 50 mm/min and maintained for 10 min. After extraction, the resulting thin film was dried 2 h in the ambient conditions and then annealed in air, 1 h at 350 °C, with a heating rate of 5 °C/min.

Fig. 2 Schematic diagram with the two stage deposition of the sensing film (transparent) onto the alumina transducer.
In the second stage of the preparation (Fig. 2), ZnO microstructures were grown hydrothermally on the previously deposited NiO layer, to obtain ZnO/NiO heterostructures. During the growth, the NiO-coated transducer is immersed in the zinc precursor solution: 0.05 M zinc nitrate hexahydrate, \([\text{Zn(NO}_3\text{)}_2\cdot\text{C}_1\text{H}_2\text{O}]\), dissolved in 80 ml deionized water, and 4 ml of 25% ammonia solution were added afterwards on it. The mix was obtained through constant magnetic stirring for 30 min until the solution that initially was milky white became transparent. During the growth, the NiO-coated substrate is immersed in a sealed vessel and placed in a preheated oven for 4 h at 90 °C. After cooling to room temperature, the substrate was washed with deionized water, allowed to dry, and annealed at 350 °C for 1 h, with a heating rate of 5 °C/min. The microsensor (transducer + deposited sensing film) thus obtained was used to detect formaldehyde in air, with tested concentrations for formaldehyde between 0.5 and 4.0 ppm.

After thermal film stabilization the sensor sample was weighed, and compared to the blank transducer; it was found that the amount of sensing material deposited on the sensor surface is exactly 0.0035 g.

### 2.3 Characterization methods

The sensor samples were characterized by AFM, SEM-EDAX, and XRF techniques.

AFM measurements were carried in noncontact mode with an XE-100 apparatus from Park Systems (2011), using sharp tips (<8 nm tip radius; PPP-NCHR type from Nanosensors). The XEI (v.1.8.0) image processing program developed by Park Systems was used for displaying the images and subsequent statistical data analysis.

The SEM equipment is a FEI Nova NanoSEM 630. It is equipped with EDX analysis system: EDAX Smart Insight produced by AMETEK Materials Analysis Division. SEM investigations were performed at energy values of 15 keV and a current of 88 pA for the electron beam. EDX analyzes for the ratio of two scan areas were obtained for electron beam energy of 15 keV.

Elemental analysis of the sample was performed in a vacuum atmosphere using Rigaku ZSX Primus II wavelength dispersive X-ray fluorescence (WDXRF) spectrometer. The XRF result was analyzed using EZ-scan combined with Rigaku SQX fundamental parameters software (standardless).

### 2.4 Gas sensing protocol

On the transducer's IDE a sensing film was deposited using the procedure described above, thus obtaining the sensors, which were introduced in a specially designed gas sensing cell [24]. The sensor sample was decontaminated before each sensing experiment, by heating it in dry air, at 300 °C, for minimum 1 h, to eliminate previously adsorbed contaminants on the surface of the sensing film. In this manner all the sensing experiments were made possible using the same sensor sample, which maintained its detection capabilities during the entire cycle of sensing experiments, consisting in multiple investigations regarding: identification of the correct working temperature, cross-sensitivity tests, reproducibility tests, sensor operating voltage values testing, etc. After sensor insertion and decontamination, gas sensing experiments were performed under lab conditions in a continuous flow, using dry air as carrier gas and different concentrations of formaldehyde (0.5–4.0 ppm) as target gas. Two separate gas lines were used as the gas sources: one gas cylinder containing 5.0 purity dry air, and a gas cylinder containing a calibrated mixture of formaldehyde in nitrogen (20 ppm total concentration in the gas cylinder), which was diluted with the carrier gas using a calibrated mass-flow controller system (MFC) in a special mix glass vessel (situated prior to the sensing cell on the gas line), to obtain the desired target gas concentrations. Sensor operating voltage was varied between 1.5 and 5.0 V DC to achieve the best sensor performance. The changes in overall sensor resistance upon target gas insertion in the sensing cell were acquired automatically, using custom made Labview-based software installed on a Windows XP workstation connected with the RLC bridge via a GPIB interface. The results were plotted without further filtering, as obtained directly from the sensing experiment.

The sensor sample was initially maintained in the carrier gas for 5 min, to acquire a sensor resistance baseline. After this stage a precise concentration of target gas was injected for 5 min into the sensing cell, and the changes over the sensor resistance were recorded (sensor response). Next, the target gas injection is stopped, and the sensor is maintained in the carrier gas, for another 5 min (sensor recovery). The resistance changes are permanently monitored and recorded. This protocol was successfully used in
our previous work [24, 25], to detect dangerous gases using resistive gas sensors.

The sensing experiments were conducted over a 6 months time-frame, during which reproducible results were obtained.

3 Results and discussion

3.1 Sensor characterization

The morphology/structure of the samples was investigated by AFM and SEM-EDAX in different stages of the sensor preparation.

The thin NiO layer, deposited by dip-coating technique, was examined by AFM (Fig. 3). From the images recorded at the scale of (8 \times 8) \mu m^2 (Fig. 3a and b) it can be seen that the NiO film is continuous, covering the large crystallites of the alumina transducer (as suggested by the line scan from Fig. 3d). The morphology consists in small particles; nevertheless, some deposits of materials (NiO “islands”) are formed during growth—indicated by arrows in Fig. 3a. The morphology of the NiO film is detailed in Fig. 3e and f, suggesting that the film exhibits small superficial nanoparticles (20–40 nm in diameter—see line-scan from Fig. 3g). Both AFM images recorded at the scale of (1 \times 1) \mu m^2 (Fig. 3e and f) suggest that the NiO film is poorly crystallized, possible due to its small thickness, in line with the digital picture (x700 magnification) from Fig. 3c, where the Au-IDE electrodes are still visible beneath the optically transparent NiO film.

After NiO layer deposition the sensor entered the final stage of preparation, involving ZnO hydrothermal growth (Fig. 4), onto the NiO layer, to yield the final form of the ZnO/NiO based sensing layer. Note that the sample sensor was characterized by SEM-EDAX after gas testing measurements.

The SEM images acquired in the IDE area of the investigated sensing surface of the sensor from Fig. 4 reveal ordered ZnO microrods grown preferably on the Au electrode digits. To obtain information about film thickness, the sensor was placed on the sample holder of the electron microscope and tilted at a precise angle. The sensing film thickness was evidenced to be of 3.81 microns, using a 45° angle tilted SEM image, so the sensing film may be categorized as thick. The measured thickness dimension, visible as green markings of 2.70 microns, must be corrected by multiplying the value indicated on the image by 1.414, corresponding to a 45° angle of inclination of the sample.

NiO content could not be highlighted by the EDAX spectra, due to the high thickness of the ZnO microstructures grown onto the NiO thin layer, in agreement with literature data presented in Ref. [28], but was evidenced by the X-ray fluorescence (XRF) analysis (Fig. 5a). The heavy elements spectrum shows Zn KA, Zn KB1, Au (LA, LB and LG), and Ni-KA, Ni-KB1 spectral lines. The presence of Al is confirmed by the Al KA and Al SKA3 spectral line (Fig. 5b), thus evidencing the alumina support of the sensor. The chemical composition (expressed in mass %) obtained from XRF analysis for the investigated sample was: Al2O3-74.489%; ZnO-23.770%; NiO-0.024%, and Au-1.717%.

The Ni-KA, Ni-KB1 spectral lines present in Fig. 5a are clearly assigned to the NiO present in the obtained ZnO/NiO heterostructures from the sensing film.

3.2 Gas sensing experiments

Sensing properties of the obtained ZnO/NiO heterostructure-based films were studied under lab conditions through a gas sensor assessment system, fully described in our previous work, from Ref. [24]. The optimum working temperature (T_w) was found by investigating the sensor performance at temperatures between room temperature and 300 °C. Several gases were also tested as target gases, namely benzene and carbon monoxide (see Ref. [24]—the most relevant for this transducer prototype), to check the cross-sensitivity and sensor selectivity.

As previously mentioned, the gas sensing experiments were performed under laboratory conditions, using two separate gas lines:
- dry air from a standard gas cylinder (with 5.0 purity), as carrier gas (SIAD manufacturer)
- dry formaldehyde in nitrogen calibration mixture (20 ppm total) from another standard gas cylinder, as target gas (from LINDE Gaz manufacturer).

Usually for a resistive gas sensor a DC voltage is applied on the sensor IDE (sensor operating voltage)
“activate” the sensor. In our previous works [24, 25] the applied voltage was 1.5 V DC. Different operating sensor voltages were tested (in the range of 1.5–5.0 V) during the sensing experiment (Fig. 6), using the RLC bridge multiple voltage capabilities.

Benzene and carbon monoxide sensing tests generate a weak sensor signal (not shown), at high working temperature (300 °C). However, the main goal of this paper is to develop a room temperature (r.t.) selective sensor for VOC gases.

The experimental results were acquired in triplicates, to check the reproducibility of the obtained results (as it can be seen in Fig. 6).

By varying the sensor operating voltage, different noise levels were obtained for the recorded sensor response, when 3.5 ppm formaldehyde was injected into the sensing cell. As presented in Fig. 6 reproducible results and a low noise level were obtained only when 5.0 V DC is applied to the IDE. For the 1.5–4.0 V DC range the noise was considerably higher, so the recorded signal for the sensor response was severely affected. As seen in Fig. 6, three
consecutive formaldehyde injection cycles were performed during the same sensing experiment, with identical experimental parameters (working temperature, target gas concentration, sensor operating voltage).

The best sensor response was obtained at room temperature (Fig. 7). As the working temperature
(T_w) increases over room temperature (r.t.), the sensor response becomes noisier, to the point of being non-intelligible. The initial sensor resistance in air decreases with increasing temperature (Fig. 8), a normal behavior due to the semiconductor nature of the sensing film.

This feature is very important, economically speaking, because the presence of a heater circuit (made of Pt in our case) on the back of the sensor is no longer required, translating into lower wide-scale production costs.

Using the integrated MFC system from the experimental setup, target gas concentrations between 0.5 and 4.0 ppm were successively injected into the sensing cell (Fig. 7) according to the gas sensing protocol described previously.

Sensor response was plotted directly as obtained from the digital acquisition process (resistance values—Fig. 7). A short sensor response time (60 s) even at small FA concentrations (0.5 ppm) and a full sensor recovery (60 s) was attained. An increase in sensor response, once the concentration of the target gas increases over 1.5 ppm, was also evidenced. The sensor responses obtained for lower concentrations (0.5–1.5 ppm) are very close in value, indicating that the sensor’s detection limit is reached. Taking into account the good sensor response/recovery characteristics and the low noise of the acquired signal, the fact that the sensor responds only to formaldehyde at room temperature, which can be considered as selective sensing, the tested sensor can be recommended for further development in VOCs selective detection at low temperatures.

According to the literature, there is a major difference between our present results and those published by other research groups, as described in Table 1. In those papers room temperature formaldehyde detection was achieved using either expensive synthesis methods [44] for the sensing layer or with much higher detection limits for formaldehyde [43]. To our knowledge room temperature—selective—low concentration formaldehyde sensing was not yet achieved using sensing films based on ZnO/NiO oxide combinations, which accomplishes the main goal stated at the beginning of our paper: low-cost sensing film deposition used for room-temperature formaldehyde detection.

3.3 Gas sensing mechanism

If a resistive chemical gas sensor with an oxide sensing layer is involved, usually a reaction with charge transfer occurs on the surface of the sensing layer of the sensor. The proposed mechanism for formaldehyde detection at room temperature involves the following equations taking place on the surface of the sensing film:

\[ O_2^{\text{gas}} \leftrightarrow O_2^{\text{ads}} \]  
\[ O_2^{\text{ads}} + e^- \rightarrow O_2^-^{\text{ads}} \]  
\[ HCHO + O_2^-^{\text{ads}} \rightarrow CO_2 + H_2O + e^- \]

This mechanism was consistent with data found in literature, regarding formaldehyde oxidation at low temperatures [45, 46].

The oxygen molecules in the gaseous environment will adsorb on the active centers present on the surface site of ZnO/NiO heterostructures (Eq. 1). Free electrons near the top surface of ZnO will interact with surface-adsorbed oxygen species, forming \( O_2^- \) by extracting one electron from the n-type ZnO (Eq. 2). By increasing the sensor operating voltage more electrons will be supplied to the ZnO surface, resulting in a higher number of \( O_2^- \) adsorbed species. Further, the \( O_2^- \) species will interact with the VOCs (formaldehyde) thru a redox process, with consumption of the \( O_2^- \) species and release the trapped electrons back to the ZnO, process detected by the measuring equipment (RLC bridge) attached to the experimental setup, resulting in a recorded signal.

This is in agreement with the experimental data presented in Fig. 6, which show a decrease of sensor signal noise when sensor operating voltage increases (more electrons supplied to the sensor interdigital electrodes).
According to the literature [47, 48], the working principle of ZnO/NiO heterostructures is entirely different from that of pristine ZnO-based sensor. It is well-known that electrons are the majority carriers in n-type ZnO semiconductor, whereas in p-type NiO semiconductor holes are the majority carriers. The superior sensor response of ZnO/NiO is due to the creation of a heterostructure between n-type ZnO and p-type NiO semiconductor. When the ZnO/NiO heterostructures are formed, the electrons in ZnO and the holes in NiO diffuse in reverse direction owing to the large concentration gradient of the charge carrier [47]. This process results in buildup of electric field at the oxide interface, hence energy band bending, until system attains uniform Fermi level [47]. The electrons can transfer from p-type NiO to n-type ZnO easily [48], but the migration of the holes will be blocked due to the higher potential barrier. This proves that the ZnO/NiO obtained heterostructures exhibit an n-type sensing behavior.

The formation of ZnO/NiO heterostructures thus plays a very important role in improving the detection of formaldehyde at low temperature, compared to the pristine ZnO.

Because the sensor operates at room temperature, the rate of oxidation of formaldehyde to carbon dioxide (CO₂) and water (H₂O) end products is very low. On the other hand, the higher porosity of ZnO/NiO heterostructures increases the adsorption of gas molecules on the surface which will result in further enhancement of sensor response.

4 Conclusions

ZnO/NiO heterostructure-based sensing film has been synthesized in two stages (liquid exfoliation technique of NiO, followed by hydrothermal growth of ZnO microstructures) directly on the alumina ceramic transducers, using environmentally friendly methods. The resulting sensor was characterized using AFM (during stage 1), SEM-EDAX and XRF (after stage 2). The AFM evidenced that the NiO film initially deposited on the transducer exhibits small superficial particles (20–40 nm in diameter) covering the large grains (a few microns in size) of the alumina transducer. It appears that the NiO film is poorly crystallized, possible due to its small thickness. The ZnO microrods were grown preferentially on the Au interdigits. NiO (0.024% mass) was found in the sensing film using XRF analysis only, due to the high thickness (3.81 microns) of the ZnO layer.

The obtained microsensor had the highest sensing performance at room temperature and 5.0 V DC operating voltage, with short response/recovery time of 60 s, and a good sensor recovery characteristic. Formaldehyde detection at room temperature is rarely achieved using oxide combinations, according to literature studies covering this topic. No selective formaldehyde detection (in low concentrations) at room temperature was achieved until now, using ZnO/NiO heterostructure-based sensing films, deposited using a cheap eco-friendly technique. The lowest concentration detected for formaldehyde was 0.5 ppm, in agreement with international health monitoring organizations requirements for indoor spaces. The operating sensor voltage plays a crucial role in the sensing experiment, the noise of the recorded sensor response decreasing with the increasing sensor operating voltage (1.5–5.0 V DC range), due to the additional electrons supplied to the surface of ZnO.

Although the rate of oxidation of formaldehyde to CO₂ and H₂O end products is very low due to the low operating temperature (room temperature), the higher porosity of ZnO/NiO heterostructures increases the adsorption of gas molecules on the surface which will result in further enhancement of sensor response to the target gas.

Several target gases (benzene, CO) were investigated to test cross-sensitivity and sensor selectivity over a wide range of working temperatures (room temperature-350 °C). A weak signal was recorded for both benzene and CO at T_w = 300 °C, which means that the sensor can be considered selective for formaldehyde detection at room temperature.

A detection mechanism was formulated for the investigated sensor. This mechanism was in agreement with literature references regarding formaldehyde oxidation at low temperatures, and with the experimental sensing results, regarding sensor operating voltage. Oxygen species from the investigated gas environment will adsorb on the surface of the ZnO/NiO heterostructures. Free electrons near the top surface of ZnO will interact with surface-adsorbed oxygen forming O₂⁻. Increasing the sensor operating voltage means that more electrons will be supplied to the ZnO surface, resulting in a higher number of O₂⁻ adsorbed species. Further, the O₂⁻ species will interact with more VOCs (formaldehyde) species and release the trapped electrons back to ZnO, leading to electrical resistance changes detected by the measuring equipment (RLC bridge) attached.
to the experimental setup, resulting in a sensor signal which can be converted using electronics in a sound and/or visual alarm.

The promising results obtained so far may be used for further development of low-cost room temperature gas sensing devices for VOCs detection.

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Authors contributions

MC: conceptualization, methodology, PC: writing—original draft, writing—review & editing, visualization, investigation, validation, data curation, MA, CH, IA, GC: investigation, DM, CB: resources, CM: project administration, funding acquisition, MGh: conceptualization, MG: supervision. All authors read and approved the final manuscript.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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