

Article

Highly Sensitive and Selective VOC Sensor Systems Based on Semiconductor Gas Sensors: How to?

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Abstract: Monitoring of volatile organic compounds (VOCs) is of increasing importance in many application fields such as environmental monitoring, indoor air quality, industrial safety, fire detection, and health applications. The challenges in all of these applications are the wide variety and low concentrations of target molecules combined with the complex matrix containing many inorganic and organic interferents. This paper will give an overview over the application fields and address the requirements, pitfalls, and possible solutions for using low-cost sensor systems for VOC monitoring. The focus lies on highly sensitive metal oxide semiconductor gas sensors, which show very high sensitivity, but normally lack selectivity required for targeting relevant VOC monitoring applications. In addition to providing an overview of methods to increase the selectivity, especially virtual multisensors achieved with dynamic operation, and boost the sensitivity further via novel pro-concentrator concepts, we will also address the requirement for high-performance gas test systems, advanced solutions for operating and read-out electronic, and, finally, a cost-efficient factory and on-site calibration. The various methods will be primarily discussed in the context of requirements for monitoring of indoor air quality, but can equally be applied for environmental monitoring and other fields.

Keywords: low-cost sensors; VOC sensor systems; sensitivity; selectivity; virtual multisensor; calibration

1. Introduction

Measurements of volatile organic compounds (VOCs) are becoming ever more important due to stringent environmental regulations and increasing health concerns. Typical compounds with high relevance are benzene, naphthalene, formaldehyde, and tetrachloroethylene, but there are many more depending on the specific environment and the target application. Exposure to VOCs for a long time can have negative effects on human health, including damage to the respiratory system and skin irritations [1]. Moreover, VOCs are the main cause of the sick building syndrome [2,3]. Besides these unspecific adverse health effects, some VOCs are proven to be carcinogenic (e.g., benzene [4]) or are suspected to be carcinogenic (e.g., formaldehyde [5]). The specific challenge for VOC measurements are the low target concentrations: the respective guideline threshold values for some critical substances (in indoor air) are 0.1 mg/m³ (81 ppb) for formaldehyde and 0.01 mg/m³ (1.9 ppb) for naphthalene according to the World Health Organization (WHO) [4], and 5 µg/m³ (1.6 ppb) for benzene according to EU guidelines [6]. In other fields such as industrial monitoring and workplace safety, higher values apply, but these are currently trending down sharply, e.g., in Germany [7].

Furthermore, very high selectivity is required to discriminate highly toxic or carcinogenic VOCs from inorganic gases such as carbon monoxide (CO), nitrous oxides (NO_x), ozone (O₃), or hydrogen (H₂), all of which occur naturally or are generated by (other) pollution sources less toxic or from benign VOCs such as ethanol. For the total VOC concentration (TVOC), WHO suggests a limit value of 1 ppm, i.e., three orders of magnitude above the lowest threshold limit values for hazardous VOCs. In other applications, the ratio between target VOC and interferent can even reach five orders of magnitude, e.g., for smoldering fire detection on coal mines, where 100 ppb ethane (C₂H₄) should be detected against a background of up to 1% methane (CH₄) [8]. A field that has gained increasing interest in recent years in monitoring of odor compounds, which, while often not having a direct health effect, nevertheless considerably impact our quality of life. Typical compounds in this context are isovaleric acid (“sweat odor”), organosulfur compounds (thiols or mercaptan, e.g., (di-)methyl sulfide) as well as many esters, terpenes, amines, ketones, and, of course, aromatic compounds as well as hydrogen sulfide as an important inorganic odorant. Odor monitoring plays an increasing role in indoor air quality, but also in outdoor environmental monitoring, both at the source (emission measurements at the stack or the fence line) and at the impact side (odor nuisance monitoring) for various industries, e.g., waste treatment. Figure 1 gives an overview over VOC monitoring applications, also indicating relevant target gases and interferents. A more comprehensive overview is given in [9].

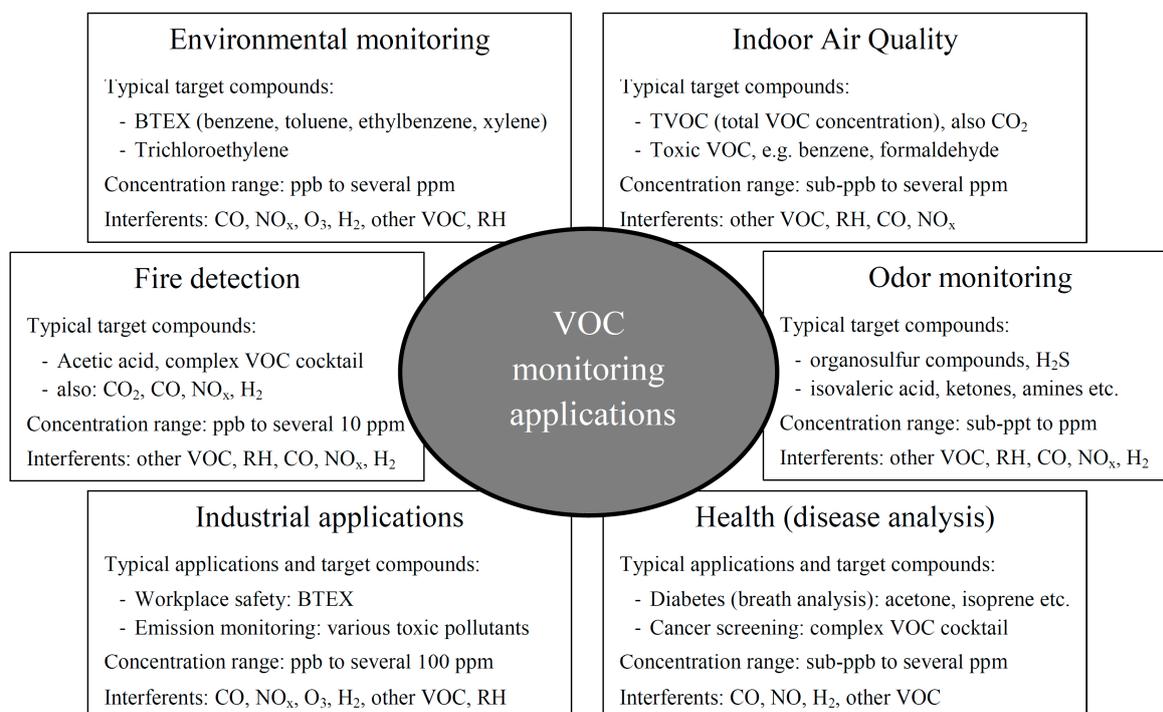


Figure 1. Overview over various applications requiring monitoring of VOCs plus typical target gases and relevant concentration ranges. Due to the wide variety of gases and applications in the specific fields, this is indicative only. Common challenges for most applications are the low target concentrations and the complex matrix. Note that in some cases the same compounds can be seen as target and interfering gases due to different sources.

Very few monitoring techniques actually achieve ppb (or even sub-ppb) level sensitivity so that sampling techniques are generally used for VOC monitoring. The standard method for VOC monitoring is sampling, e.g., with Tenax[®] as absorbent material, and then releasing the sampled gas into a gas chromatograph followed by identification of the VOCs by mass spectrometry (GC-MS). This method, while widely accepted, does however pose serious problems for comprehensive VOC monitoring as both very volatile organic compounds (VVOCs) and semivolatile organic compounds

(SVOCs) will not be sampled with the standard technique [10]. VVOCs will simply pass through the sampling material, while SVOCs are not released due to their very high boiling point. One prominent example for this shortcoming is formaldehyde for which a specific separate sampling and quantification protocol is required [11]. On the other hand, weak sorbents are required for trapping SVOCs. This means that standard measurement techniques are actually blind to a fairly wide range of compounds and that our understanding of environmental pollution and health effects is somewhat limited due to missing data on these compounds. Research is ongoing in finding suitable sorbent materials, e.g., multibed focusing traps, to allow the acquisition of more complete information on VOCs [12]. In addition, sampling only allows determining time-weighted average (TWA) values either for the long term (1 h to 24 h) or the short term (5 min to 60 min), thus possibly missing relevant short concentration peaks. Sensor-based monitoring, on the other hand, would allow both an improved temporal resolution and a wider detection spectrum, as sensors will respond to practically all VOCs including VVOCs and SVOCs.

2. Highly Sensitive Semiconductor Gas Sensor Principles

One candidate sensor principle for direct monitoring of even sub-ppb level VOC concentrations are metal oxide semiconductor (MOS) gas sensors [13,14], but gas-sensitive field effect transistors (GasFETs), e.g., based on silicon carbide (SiC-FET), have also proven their suitability for this task [15]. For simplification, we will concentrate on MOS sensors in the following discussion, but many aspects also apply to SiC-FET sensors, so the approach is presented for semiconductor gas sensors. Note that both sensor principles allow low-cost sensor solutions, at least for markets with high volumes. Even taking into account the advanced electronics and data processing that are necessary to achieve high sensitivity, selectivity, and stability, high performance sensor systems can be realized for well below 1.000€, as has been demonstrated for fire detection [16]. In mass applications, the system cost can drop to below 10€. Commercial screen-printed ceramic MOS sensors achieve detection limits down to sub-ppb levels due to the well-known grain boundary effect [17]. A small grain size down to nanocrystals [18] also improves the sensitivity as the bulk conductance of the material is not affected by gas adsorbed on the grain surface. Recently, nanostructured sensors based on nanowires [19] have been proposed and sometimes postulated as being necessary for achieving very low detection limits due to the high surface area achieved. Especially carbon nanotube-based sensors have been extensively studied with the expectation that these provide the key for very high sensitivity [20–22]. However, so far no rigorous study has proven that MOS nanowires or carbon nanotubes in fact achieve superior sensitivity compared to standard granular materials. Novel manufacturing methods for metal oxide layers, especially Pulsed Laser Deposition [23], achieve highly porous sensor layers with well-controlled morphology that can even reach high selectivity for some relevant target VOCs such as naphthalene [24].

On the other hand, we have recently developed a model that shows that the sensitivity of MOS sensors can be improved significantly by temperature cycling. The first benefit of varying the sensor temperature over a broad range is immediately obvious as the sensor will at some time in the cycle reach the optimal temperature, i.e., with the highest sensitivity, for the target gas(es). In addition, temperature cycling with fast temperature changes will lead to non-equilibrium surface conditions and thus reaches states that cannot be achieved in static operation at constant temperature. By carefully choosing the operating parameters, the sensitivity can actually be boosted considerably, e.g., by first operating the sensor at high temperature which leads to a high surface coverage with ionosorbed oxygen. If the sensor is then cooled down rapidly, this leads to a surface at low temperature but with an abundance of reactive oxygen ions—a condition that cannot be achieved in static mode. Without gas, the ionosorbed oxygen will slowly desorb to reach the equilibrium state with only few oxygen ions at low temperature. A gas interacting with the adsorbed oxygen will strongly influence this relaxation process leading to faster equilibration. The sensitivity and the respective sensor response $G_{\text{gas}}/G_{\text{zero}}$ during dynamic operation have been shown to be orders of magnitude higher than in static operating

mode [25]. Figure 2 describes this effect schematically. The non-equilibrium states during dynamic operation can also improve the selectivity, so optimized cycling can be used to address the three “S’s”—sensitivity, selectivity, and stability—the key aspects for chemical sensor systems [26].

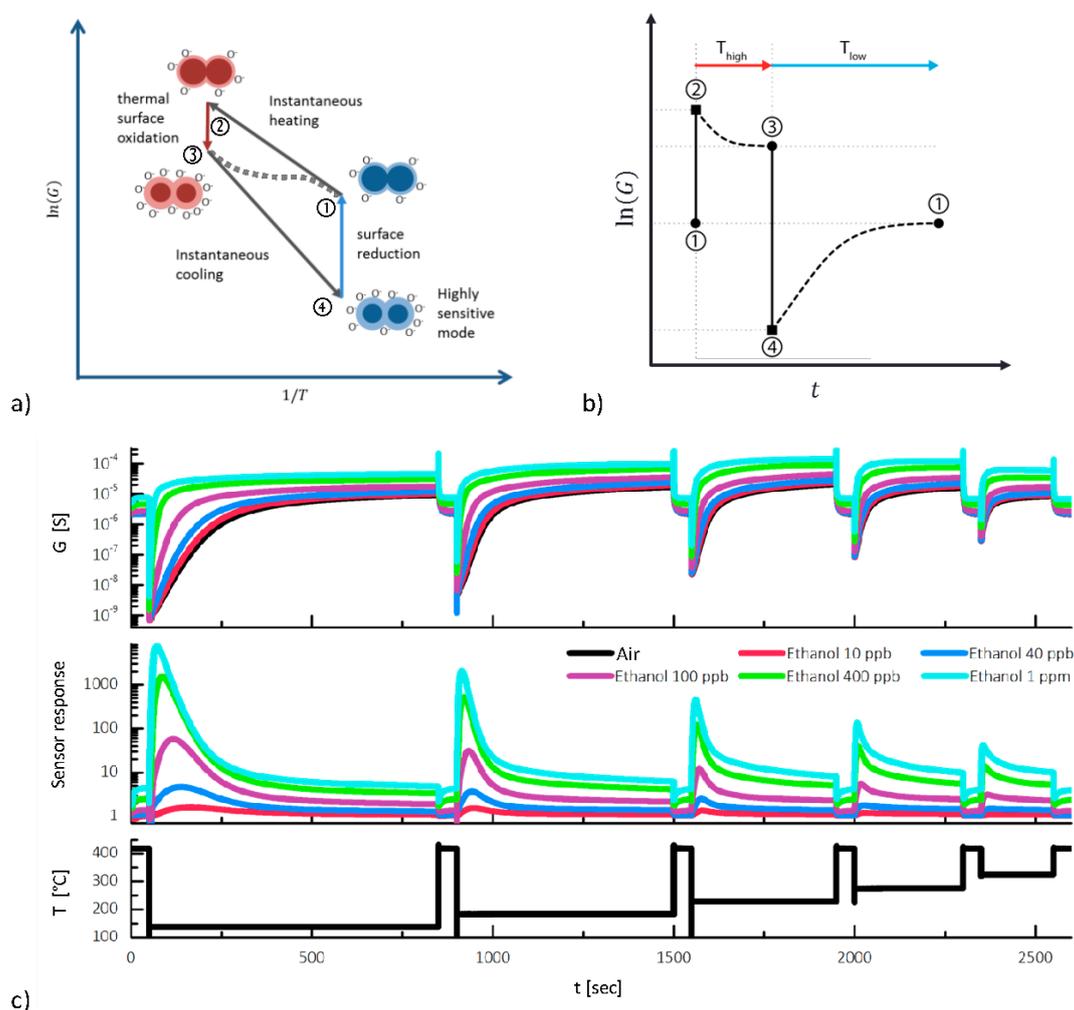


Figure 2. Boosting sensitivity of MOS sensors with temperature cycled operation (TCO): (a) MOS sensors show low oxygen coverage at low temperatures ① and high coverage at high temperatures ③ in steady state conditions (dashed line indicates equilibrium conditions between min and max temperature). Non-equilibrium surface states (②, ④) are achieved by fast temperature changes. Especially high oxygen coverage at low temperature will lead to a highly sensitive mode as target gases will react with the adsorbed oxygen. (b) Dynamic relaxation of the conductance after fast temperature changes boosts the sensitivity. (c) Admixture of VOCs leads to faster relaxation compared to pure air. Plotting the sensor response shows that a huge increase in sensitivity of several orders of magnitude can be achieved compared to the steady state response reached at the end of the relaxation process. The relaxation behavior at various temperatures is typical for the specific target gas and can thus be used to increase the selectivity of MOS-based sensor systems.

There are also other possibilities to enhance the response and increase the sensitivity of semiconductor gas sensors, especially optical excitation, which has been addressed by various groups [27,28]. Especially excitation with quantum energy above the bandgap energy of the semiconductor allows low-temperature operation and/or achieves higher sensitivity. In addition, light modulation can be used to extract signal patterns similar to TCO which can also increase the selectivity and stability of the overall sensor system.

3. Highly Selective Sensor Systems

The drawback of MOS (and SiC-FET) sensors is their inherent low selectivity, which is due to the sensor function principle. The high sensitivity of MOS sensors is due to the grain-boundary effect that is caused by ionosorbed oxygen leading to band bending at the surface of the grains and, thus, an energy barrier between grains with the conductance of the sensor being exponentially dependent on the height of this energy barrier. Any gas that either chemisorbs on the surface or interacts with the ionosorbed oxygen will change the energy barrier. Therefore, MOS sensors show a response to practically all relevant target and interfering gases except carbon dioxide (CO₂). To achieve the required high selectivity for gas discrimination and/or quantification of target gases in a background of interfering gases, several approaches are possible: (a) enhancing gas measurement systems with analytical tools, i.e., a GC tube to separate the various gas components (which will, however, suffer from similar drawbacks as sampling techniques for VVOC and SVOC); (b) making use of multisensor arrays and pattern recognition (often referred to as electronic nose) [9]; and (c) using dynamic operation, e.g., temperature cycling, to realize a virtual multisensor, which is also evaluated using typical pattern recognition methods [29]. The different methods employed for increasing the selectivity can also be combined, for example, by integrating several dynamically operated sensors in a hybrid sensor array or combining gas pre-concentration (see below) with temperature cycling to boost sensitivity and selectivity. Especially temperature cycled operation (TCO) has proven a very powerful and versatile tool for various sensor principles (MOS sensors [14,30–32], SiC-FETs [33], pellistors [34]), which is easily understandable as the chemical interaction between sensor and gas atmosphere is strongly influenced by the surface temperature. For example, some gases such as CO or H₂ will react at relatively low temperatures, while others such as CH₄ are more stable and thus require higher activation energies to cause a sensor reaction. Due to its simple implication and low cost (only some additional electronics are required), TCO is now widely accepted as a method to boost selectivity, especially as it also improves the stability of the sensor system due to self-cleaning of the sensor surface at higher temperatures [35] and the possibility to use features which are stable over time [32]. Furthermore, in addition to identifying and quantifying target gases, this approach allows sensor self-monitoring [36], which is a crucial aspect especially for applications in safety and security. For VOC monitoring, selective identification of hazardous VOCs down to concentrations of 1 ppb could be demonstrated even in a background of other VOCs of several ppm and against changing humidity using a commercial ceramic MOX sensor at least under lab conditions [14]; similarly, quantification of VOCs at low ppb levels was demonstrated with this approach both for MOS [26] and SiC-FET [15,37] sensors. Further approaches to improve the performance of semiconductor gas sensor systems with dynamic operation are optical excitation [27,28] and impedance spectroscopy [38] often applied to MOX sensors or gate bias cycled operation for GasFETs [39]. These approaches can also be combined to boost the selectivity further [40,41].

One often underestimated aspect for highly sensitive and selective sensor systems is the electronics for sensor operation and signal read-out. To make use of the full potential of dynamic operation, dedicated electronics that allow exact control of the sensor operating parameters and synchronized data acquisition are required. For temperature cycling, exact temperature control is key. Here, the heater integrated in each MOS (and SiC-FET) sensor is preferably also used as a temperature sensor to allow exact closed-loop control. This allows exact control even for highly dynamic cycles, especially for microstructured gas-sensors based on micro-hotplates, which exhibit thermal time constants of typically a few ms. This type of sensor is now manufactured at high volumes by various companies, e.g., ams Sensor Solutions, CCMOSS, Figaro, and SGX Sensortech, achieving very low-cost sensor elements. Appropriate electronics have been developed over several generations [42–44] and are today commercially available from 3S GmbH (3S Toolbox, [45]), which has been successfully employed also for outdoor odor nuisance monitoring [46]. To make full use of the TCO mode for MOS sensors, the sensor resistance has to be acquired with high temporal resolution (≥ 1 kHz) over a wide dynamic range of several orders of magnitude from k Ω (high gas concentrations at high operating

temperatures) to $G\Omega$ or even $T\Omega$ (low gas concentration, non-equilibrium state after fast cool down, cf. Figure 2), ideally with constant relative resolution. The voltage across the sensor layer is limited, typically to ≤ 1 V, to prevent unwanted effects such as electromigration in the layer leading to sensor drift. However, this voltage limit (or more exactly the maximum field strength) also depends on the operating temperature, allowing higher voltages and thus more sensitive measurement at low temperature. Thus, electronics are required that allow fast and accurate measurement of very low currents in the pA range. One suitable approach is the use of logarithmic amplifiers, which achieve a measurement range of up to 8 orders of magnitude (Figure 3), and another is dynamic signal amplification to adapt the output voltage to the current signal level [47]. Both approaches can and need to be closely integrated with the sensor element to achieve a high signal quality also under field conditions. Similarly, electronics suitable for field use were developed for Electrical Impedance Spectroscopy (EIS), allowing novel sensor self-monitoring strategies for MOX sensors [48,49] as well as for Gate Bias Cycling (GBC) of SiC-FETs [41] in both cases combined with TCO.

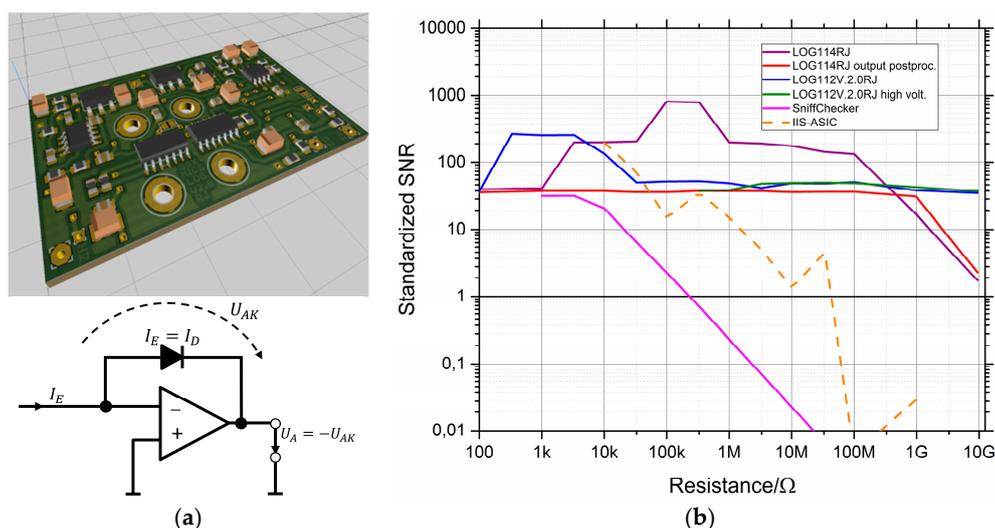


Figure 3. (a) Operating principle of a logarithmic amplifier based on the exponential current-voltage characteristic of a diode or transistor and PCB implementation. (b) Signal-to-Noise-Ratio (SNR) standardized to the same bandwidth of different logarithmic amplifiers compared to conventional electronics based on a linear AD converter (“SniffChecker” by 3S) and an integrated ASIC solution based on dynamic variation of measurement voltage and gain factor (IIS-ASIC, [47]).

4. Novel Integrated Pre-Concentrator Gas Sensor Microsystem

Despite the impressive sensitivities and very low detection limits that are achieved with MOS and SiC-FET sensors, some application targets are still difficult to achieve either due to very low target gas concentrations well below 1 ppb, e.g., trimethylamine with an odor threshold of 0.21 ppb; ethyl acrylate (and hydrogen sulfide) with an odor threshold of 0.47 ppb [50], or due to strong interference by other gases. Especially for measurements at very low gas concentrations, adsorbent materials are often used to achieve the required detection limits. Typical methods for detection of low VOC concentrations are based on sampling a defined gas volume using, e.g., Tenax[®] tubes. From these, the adsorbed gas is thermally desorbed during subsequent lab analysis based on gas chromatography (GC), often coupled with mass spectrometry (MS), to allow sensitive and selective gas detection. This approach has been miniaturized with the goal to achieve sensor systems for nearly continuous monitoring operating in adsorption/desorption cycles. However, these systems today are typically based on closed pre-concentrators combined with micro-pumps leading to systems that are not low-cost [51,52]. We have developed a new approach based on open pre-concentrators, i.e., absorbing material based on metal organic frameworks (MOF) deposited on a micro-hotplate similar to the gas sensor substrates.

These μ -pre-concentrators are integrated with the sensors in a common package with a small gas access. VOCs present in the ambient enter the package through the gas access and accumulate in the MOF material which has a large inner surface reaching partition coefficients orders of magnitude better than standard Tenax[®] [53]. Heating the μ -pre-concentrator will release the adsorbed gas molecules resulting in a considerably increased gas concentration within the sensor package, which is detected by the sensors [54]. Figure 4 illustrates the function principle of this novel approach which is based on gas transport by diffusion only thus requiring a miniaturized packaging solution. The function principle is also illustrated in a video to allow better understanding of the complex interaction within the microsystem [55]. Note that after release of the target gases from the pre-concentrator and subsequent cool-down, the pre-concentrator actually achieves a zero-air atmosphere within the package, at least for all gases adsorbing on the pre-concentrator [54]. This will actually allow an internal reference, as the sensors are briefly exposed only to permanent gases such as CO and H₂, thus improving the performance for target VOC detection and quantification by taking this into account in the signal evaluation. Furthermore, discrimination of different VOCs can be improved by taking into account the desorption temperature, i.e., for slow heating of the pre-concentrator. To make full use of this potential to boost sensitivity and selectivity, an application specific operating mode has to be designed as slow heating will decrease the peak concentration, while fast heating will release all VOCs simultaneously, thus limiting the selectivity. This novel integration approach is compatible with existing mass fabrication technologies and achieves sensor systems with greatly improved sensitivity at very low cost—at large volumes, the cost for the integrated system with, e.g., two sensors and one pre-concentrator could be less than one euro.

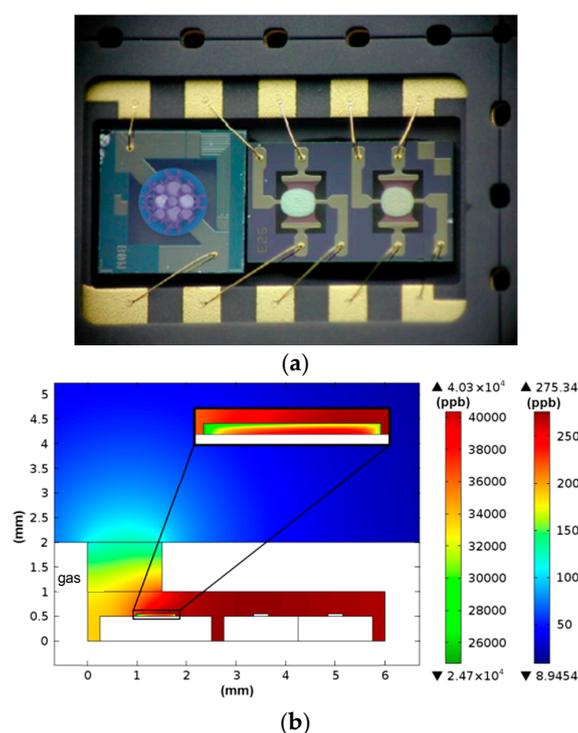


Figure 4. (a) Novel integrated pre-concentrator gas sensor microsystem combining a micro-pre-concentrator realized by deposition of MOF material on a micro-hotplate (left) with one or two gas sensors (right) in a single SMD package. Gas access is through a small opening above the pre-concentrator only. (b) Simulated gas concentrations inside the pre-concentrator material (left scale) and in the air (right scale), simulated for benzene and HKUST-1 as pre-concentrator material 1.5 s after start of desorption at 200 °C. The highest gas concentration is obtained inside the microsystem, i.e., at the locations of the two gas sensor chips S1 and S2. Adapted from [54].

5. Sensor System Testing and Evaluation

The impressive sensitivities and very low detection limits reported above can be achieved under well-defined laboratory conditions, which are, however, not easily achieved—in fact, very few test systems actually allow reliable testing of sensors at ppb and sub-ppb levels in a complex matrix. A pre-requisite for testing ultra-low concentrations is a suitable test setup, i.e., a gas mixing apparatus allowing exact control of gas admixtures under realistic and controlled ambient conditions. Some publications present very low detection limits, but these are sometimes just extrapolations from measurements at (much) higher concentrations or achieved in pure nitrogen as carrier gas, i.e., without oxygen or humidity, which has a huge influence on many sensors. Furthermore, standard zero air, which is also used for mixing of test gases, typically contains contaminations of approx. 10 ppm (zero air 5.0) and even the best zero air standards still contain approx. 1 ppm of unwanted and uncontrolled contaminations. While many of these do not influence the measurement (i.e., noble gases or CO₂), relevant trace contaminations can occur at concentrations orders of magnitude higher than the target gases to be tested. As the zero air used for the test gas is different from that used in the rest of the test setup, the observed sensor response can be caused by the contamination and not by the intended target gas when standard test gases with very low concentrations are used for direct measurement at ppb-level. Suitable approaches are the use of permeation tubes to introduce the target gas directly into the (zero air) carrier gas stream or two-stage gas dilution, allowing the use of test gases with concentrations much higher than any contaminations [56]. In both cases, the gas to be tested is injected into a carrier gas stream, which still contains contaminations, but the setup, which uses the same zero air throughout the system, ensures that the concentration of all contaminants stays constant, allowing the measurement of the sensor response to a change of only the target gas concentration. Further sources of error can be due to either VOC sources inside the system, e.g., from lubricants in valves or mass flow controllers, or due to adsorption of VOCs on inner surfaces preventing the target gas from reaching the sensor. The latter is especially problematic for SVOC which will then slowly diffuse out of the system, which can lead to large carry-over or “memory” effects. These effects can only be monitored by regular reference measurements of the overall system with analytical methods. Note that a gas test bench for broadband sensors such as MOS and SiC-FET should be based on a flow-through approach instead of gas re-circulation as reaction products from the interaction of the test gas with the sensor might otherwise lead to false results.

Finally, to accurately reflect measurements in ambient air, the typical mixture of natural air, which contains, in addition to nitrogen, oxygen, CO₂, and RH, approx. 1.8 ppm methane (CH₄), 550 ppb H₂, 325 ppb nitrous oxide (N₂O), and 150 ppb CO [57,58], has to be taken into account. CO shows the strongest variations with an annual cycle between 100 and 250 ppb [58]. While the effect of CH₄ is negligible, even the low-level exposure to H₂ and CO can easily change the baseline resistance of MOS sensors by one order of magnitude. At the same time, this will also reduce the sensitivity to other gases and distort the response pattern of sensor arrays and virtual multisensors. To achieve realistic test results, relevant background gases therefore have to be added to the zero air in gas test systems, and the natural variations have to be taken into account when determining detection limits and quantification resolution.

6. Factory and On-Site Calibration

To make full use of the potential of low-cost sensors for ultra-low VOC concentrations, calibration is an often underestimated challenge. The more complex the expectations, i.e., several target gases, mixtures of target gases, complex and variable background, the more complex the calibration procedure. This is due to the fact that data analysis is not based on a physical model of the sensor(s) but instead only on calibration data combined with pattern recognition techniques [29]—the calibration therefore has to span the full range of gases and concentrations expected in the later application. Due to slight variations in the individual sensors, at least part of this calibration has to be performed for each sensor individually, which can considerably contribute to the overall cost of the final gas

sensor system. Furthermore, as the background can vary considerably for individual application environments, an extended calibration on-site might be necessary—this basically depends on the expected data quality to be achieved. While a scale-up of standard test benches (see above) can allow efficient factory calibration even for large production volumes, a test with various test gas cylinders would be impossible for on-site calibration. To address this issue, we have developed a novel approach for on-site calibration [59] based on VOCs dissolved in squalane, a long-chain alkane with low vapor pressure. This approach also allows producing a “zero air” atmosphere on-site within a confined volume in which the sensor and a vessel with squalane are kept: due to the large Henry constant, practically all VOCs present in the ambient will dissolve in the squalane resulting in a practically VOC free reference atmosphere (which will, however, still contain most inorganic gases such as CO, H₂, and NO_x). Note that this is similar to the pre-concentrator briefly achieving a VOC free atmosphere after cool-down, cf. Section 4. Similarly, using squalane loaded with a defined target VOC concentration will provide a source desorbing with a defined amount of the VOC, which can be used to calibrate sensors on-site. Note that this approach not only allows cost-efficient testing of the correct function of the sensor system, but also quantitative re-calibration to counteract sensor drift.

7. Conclusions and Outlook

Bringing together the different aspects outlined above—highly sensitive sensor elements; optimized dynamic operation (TCO, EIS, GBC) of the sensors; high-performance electronics for dynamic operation combined with advanced signal processing to achieve high sensitivity, selectivity and stability; low-cost pre-concentration to boost sensitivity and selectivity further; gas test bench for ppb and sub-ppb VOC concentrations, efficient factory, and on-site calibration—is a pre-requisite for the systematic development of low-cost sensor systems for VOC detection in various applications and for their validation in field tests. This integrated approach is at the core of the EU project SENSIndoor [60] addressing indoor air quality and demand controlled ventilation based on sensor systems placed in each room, i.e., offices, living and sleeping rooms, public buildings, transport, etc. On the one hand, the approach is used for optimization of the sensor elements themselves, i.e., based on novel nanotechnology approaches such as Pulsed Laser Deposition (PLD) and novel sensor materials [23,24,61–64]. On the other hand, extensive field tests are required which include reference tests based on existing standards. These developments will also lead to the development of new standards for VOC testing because existing standards do not cover the high spatial and temporal resolution that can be achieved with networks based on low-cost sensor systems. This aspect is currently addressed in the KEY-VOCs project under the European Metrology Research Program (EMRP) [65,66].

Note that in this contribution we have addressed sensor systems as a somewhat abstract concept, i.e., a device able to detect and quantify specific VOCs against a background of interfering gases. Not addressed here, but equally relevant to providing solutions for real world problems is a somewhat wider view that includes a structural model similar to the ISO-OSI model used in the field of communications. Systems based on low-cost semiconductor gas sensor principles will never achieve a universal performance independent of their application field, i.e., specific interferences and ambient conditions. Instead, application specific sensor systems are required—systems that would function well in the context for which they are designed, i.e., workplace safety monitoring or indoor air quality control, but that cannot be used to cover the full range of applications outlined in Figure 1. The structural model would cover the full range from expected benefits and application parameters at the top end down to the VOC atmosphere and the sampling method at the lower end [67] for realization of application specific sensor systems. By following this approach, it will be possible to address many different applications in environmental monitoring, indoor air quality, and industrial safety and health applications based on VOC monitoring, thus attaining a better understanding of VOC sources and effects to achieve a safer and healthier environment for all.

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Conflicts of Interest: The authors declare no conflicts of interest.

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