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Innovative Sensor Technology for Emergency Detection in Life Science Laboratories

Kerstin THUROW[a,1] and Sebastian NEUBERT[b]
[a] *Center for Life Science Automation, University Rostock*
[b] *Institute of Automation, University Rostock*

Abstract. Chemical, analytical and biological laboratories use a variety of different solvents and gases. Many of these compounds are harmful or even toxic to laboratory personnel. Permanent monitoring of the air quality is therefore of great importance regarding the greatest possible occupational safety and the detection of dangerous situations in the work process. An increasing need exists for the development and application of small and portable sensor solutions that enable personal monitoring and that can be flexibly adapted to different environments and situations. Different sensor principles are available for the detection of gases and solvent vapors, which differ in terms of their selectivity and sensitivity. Besides simple sensing elements, integrated sensors and smart sensors are increasingly available, which, depending on their scope of functions, require a distinct effort in integration. This chapter gives an overview of available sensors and their integration options, and describes ready-to-use sensor systems for personal monitoring in life science laboratories.

Keywords. gas sensors, gas monitoring, laboratory automation, life sciences, laboratory monitoring

1. Introduction

Humans are regularly exposed to different toxic compounds in the indoor and outdoor environment. Poor air quality can cause various health problems, which can finally result in life-threatening and expensive emergency care. The development of suitable sensors for monitoring a wide variety of toxic components is therefore of enormous importance.

The classic pollutants in our air include nitrous gases, sulfur dioxide and hydrogen sulfide, which are released by natural processes or processes induced by humans (industrial exhaust gases, exhaust gases from combustion plants or motor vehicles, etc.).

In addition, contamination with toxic components can also arise in the work environment. This includes in particular chemical, analytical and biotechnological laboratories in which a wide variety of gases and solvents are used.

Carbon monoxide, for example, is produced in various chemical reactions or is used directly as a reaction gas. It is a highly toxic colorless, odorless, and tasteless gas. Human exposure to CO leads to the formation of carboxyhemoglobin, since CO is bound to hemoglobin with 250 times higher affinity than oxygen. The resulting insufficient supply

[1] Corresponding Author; Kerstin Thurow, Center for Life Science Automation, University of Rostock, F.-Barnewitz-Str. 8, 18119 Rostock, Germany; E-mail: Kerstin.Thurow@celisca.de.

of oxygen initially leads to headaches and dizziness. At high CO concentrations, unconsciousness and death occur.

Volatile organic compounds (VOC) is the collective term for organic substances that can easily vaporize at room or elevated temperatures. According to the World Health Organization (WHO) this includes all organic compounds with boiling points between 50-260 °C. Classic VOCs that are used in laboratories are e.g., hydrocarbons, alcohols, ethers or organic acids. Symptoms such as headache, hypersensitivity reactions, tiredness, decreased performance, sleep disorders and irritation of the respiratory tract are summarized under the term "sick building syndrome" [1]. The WHO does not define the clinical picture in an internationally binding manner. Effects on the nervous system are also known [2].

Another class of substances frequently used in laboratories are volatile halogenated hydrocarbons. These include, for example, chloroform, perchloroethylene or vinyl chloride (basic material for PVC production). These compounds form a component in many commercial products and chemical preparations, as well as in solvents and extraction agents. They can damage the ozone layer; some representatives (e.g., vinyl chloride) are also carcinogenic and mutagenic [3].

Dimethylformamide (DMF) is also a frequently used solvent. DMF is irritating to the skin, eyes and respiratory tract and can cause headache, nausea, dizziness, weakness, confusion, and a drop in blood pressure. Liver damage and alcohol intolerance reactions can occur [4].

Monitoring the air quality in laboratories is of particular importance both in preventing accidents with chemicals and in minimizing the exposure of laboratory personnel. Many sensory solutions have been developed for this purpose and are used to monitor room air and comply with limit values. The majority of classic systems are permanently installed systems. They enable entire rooms to be monitored, but are difficult to reconfigure if the laboratory environment changes. Such systems are also associated with high costs. In addition to permanently installed systems, there are also many transportable devices. These can be used flexibly in changing environments and changing applications. Due to their size, however, they cannot be used for personal monitoring of laboratory personnel either.

For the personal monitoring of laboratory personnel, the development of small sensor solutions that can be worn on the body or on clothing makes sense. While there are numerous wearable systems for personal monitoring that measure different physiological parameters, there are hardly any systems available for corresponding monitoring of chemical parameters. Suitable sensors must have the smallest possible dimensions. The sensor principles should be robust even under general environmental conditions. Sensitivity and selectivity should be appropriate to the applicable limit values for maximum concentrations of the various pollutants.

Hazardous situations for human can be categorized into oxygen deficiency/excess, explosion hazards and intoxications. Depending on the type of hazard, different measurement principles of gas sensor can be used [5] [6]. Oxygen measurements are often based on electrochemical principles. A higher risk of explosion especially exists in environments where combustible gases and vapors occur, as e.g., in the mining, chemical and oil refining industry. Here, often infrared and catalytic bead gas sensors are used. Intoxications include metal fumes as mercury, narcotic-acting gases and fumes as organic solvents, propane and butane, hydrides as arsine and phosphine or war gases as sarin. For these gases, primarily electrochemical and photoionization gas sensors are deployed.

2. Innovative Gas Sensors

Gas sensors belong to the class of chemical sensors and are used specifically for the detection of gaseous substances. Sensors for measuring physical quantities such as temperature, pressure, and acceleration are usually sealed watertight and airtight. Instead, gas sensors have to interact directly with their environment to detect the chemical component. This makes them much more susceptible to poisoning (environmental influences that make the sensor insensitive). In addition, they also show a certain cross-sensitivity (substances besides the target component that cause a sensor signal) and are characterized by corrosion, long-term drift, zero point drift and temperature drift [7].

Different principles can be used as measuring method. Physical principles use molecular properties such as the molecular mass, the diffusion behavior, the molecular structure (e.g., magnetic properties or paramagnetism), the molecular stability (as binding energies) or the molecular mobility for detection. Chemical measurement methods, on the other hand, use chemical properties such as reactivity, oxidizability, or reducibility.

The decisive factor for detecting hazardous gas situations is the correct selection of suitable measurement principles. Every principle is optimized for specific groups of gases with a characteristic behavior, and has consequently own advantages and limitations.

Depending on the target application, different criteria need to be considered for the sensor selection. The following key parameters are most important for the decision of a convenient sensor solution:

- **Detection range** – minimum and maximum of the allowed/detectable concentration
- **Sensitivity / resolution** – smallest change of the signal that can be detected/observed (often only one is given)
- **Accuracy / repeatability –** maximum deviation/variance (often only one is given)
- **Pre-operation time** – required time before the sensor is ready to use. For some gas sensors, a warm-up time of the heaters is required.
- **Response time** – required time of the sensor signal from zero to commonly 90% (T90) of the full-scale by exposing the sensor to an instantaneous full-scale concentration change [8]
- **Recovery time** – required time of the sensor to fall back to the baseline or to 10% of final value after step removal of measured variable [9][8]
- **Sensor lifetime** – expected duration of the sensor's operation; an often seen specification is around 5 years, depending on the principle and the using conditions
- **Environmental conditions** – required working range for environmental parameters such as temperature, humidity, and atmospheric pressure

For the use of sensors for personal monitoring, the sensor systems should be as small as possible in their design.

2.1. Catalytic Bead Gas Sensors

For the detection of combustible gases such as natural gas, methane, butane, propane or hydrogen, the catalytic bead method is particularly suitable, since here the combustible characteristics of gases are exploited. Especially in the detection of hydrocarbons of the lower explosive level (LEL) or hydrogen (H_2) this method is used to monitor explosion limits [10][11].

The sensors consist of two platinum heating coils (detector and reference coil), which are enclosed by ceramic beads (smaller than one millimeter), also designated as pellistors (combination of pellet and resistor). The detector bead additionally is coated by a catalytic active substance, e.g., platinum, palladium or metal oxides such as manganese oxide [12]. The reference bead remains passive without a catalytic substance. Both pellistors are encapsulated by an explosion-proof housing with a sintered metal flame arrester on the gas exchange side. This is necessary since minor explosions can arise, which should not have impacts on the environment.

In the measurement process, the coils are usually heated up to 300-500 °C, depending on the target gas [13]. The catalyst of the detector bead effects a decrease in the activation energy, and intermediate states of the reaction arise on its surface. This influences the speed of reaction, depending on the temperature and the concentration of the reactants, and leads to the combustion of the absorbed gases on the catalysts surface. Through the combustion, the temperature around the detector bead increases, resulting in an increase in the resistance of the coil. No change in temperature and resistance is observed for the reference bead. Environmental effects such as temperature fluctuations have the same influence to both pellistors and their resistance. By utilization a Wheatstone bridge (half bridge) these effects are compensated and the resulting bridge voltage (by resistance change of pellistors) is quantitatively proportional to the concentration of the combustible gases in the chamber (see Figure 1) [14].

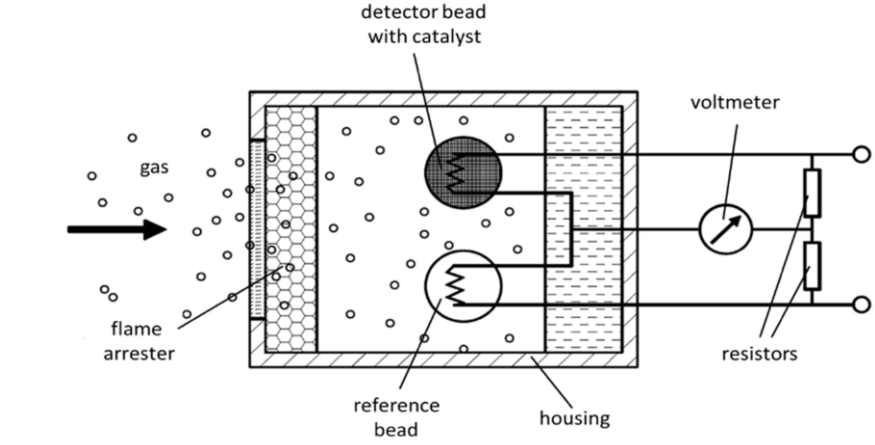

Figure 1. Principle of a catalytic bead sensor.

Catalytic bead sensors are inexpensive and robust and can easily be calibrated due to the linear sensor reaction depending on the gas concentration. A necessary condition for using catalytic bead sensors is the presence of oxygen, since it is required for the burning

process. With less than 10 seconds, the response time of catalytic bead sensors is relatively short [15]. The average lifetime of these sensors is commonly 5 years [16], which can be significantly reduced by catalyst poisoning, whereby the catalysts are partially or completely deactivated by gases containing sulfides, halides, and silicones [15]. A disadvantage is their low sensitivity in the percentage range, since relatively high gas concentrations are necessary for a sufficiently high heat release. They also show only a low selectivity: every gas that burns on the catalyst surface of the pellistor and causes a measurable heat release is registered as an increase in resistance, so that a selective determination of the gas type is difficult. Due to the required heating, these sensors consume a significant electrical power, which reduces their use in mobile applications.

Catalytic bead sensors are often used for the detection of flammable gases, such as methane. Examples are the SGX VQ21TB (SGX Sensortech, Neuchatel, Switzerland) or the Figaro TGS681x (Figaro USA, Inc., Arlington Heights, IL USA).

2.2. Electrochemical Gas Sensors

Electrochemical gas sensors (also: electrochemical cells, EC sensors) work similarly to batteries or fuel cells. The basic components of an electrochemical sensor are a working electrode, a counter electrode, and usually also a reference electrode. These electrodes are enclosed in the sensor housing and are in contact with a liquid electrolyte. The working electrode sits on the inside of a porous hydrophobic membrane that allows gas to pass through, but not the electrolyte (see Figure 2) [17][18].

Once the gas gets in contact with the sensor, it flows through the membrane to the working electrode. Depending on the type of gas, it is either

- oxidized (e.g., $CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^-$) or
- reduced (e.g., $O_2 + 2\ H_2O + 4e^- \rightarrow 4\ OH^-$)

at the measuring electrode. The resulting ions (H^+, OH^-) diffuse through the liquid electrolyte and are

- reduced (e.g., $O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$) or
- oxidized (e.g., $4\ OH^- + Pb \rightarrow PbO_2 + 2\ H_2O + 4\ e^-$).

at the counter electrode. A current flow is created between the two electrodes, which is proportional to the gas concentration [19][20].

To prevent the measured values from drifting, a reference electrode is used that generates a constant potential. The gas concentrations are displayed in part per million (ppm) for toxic gas sensors and in percent by volume for oxygen. The great advantage of electrochemical gas sensors is their high specificity and sensitivity to target gases. Due to their principle of action, there is little or no cross-sensitivity to other substances. Further, these sensors consume low power and offer an intrinsically safe operation. Because of their capacity for miniaturization [13] they have ideal features for mobile sensor solutions. A drawback of electrochemical gas sensors is their high sensitivity to humidity and gas concentrations (electrode poisoning). In addition, the temperature dependence of the electrochemical potential has to be considered. These factors can lead to irreversible damages and offset the baseline readings or influence sensors response time [21].

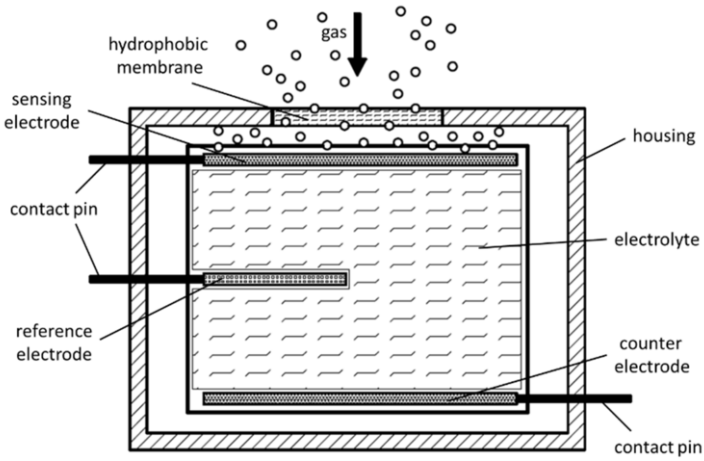

Figure 2. Principle of an electrochemical gas sensor.

The electrochemical gas sensors include the ZE08-CH 20 (Winsen Electronics Technology Co., Ltd., Zhengzhou, China), which is used for the determination of formaldehyde. The measuring range is between 0 and 5 ppm, with a resolution of <0.01 ppm. The interference with alcohol and carbon monoxide is disadvantageous.

Another representative of this group is the SPEC Sensor Package (SPEC Sensors LLC, Newark, CA, USA) for the determination of ethanol in the range up to 1,000 ppm with a resolution of <5 ppm and a service life of 5-10 years.

Small electrochemical sensors are also available for the detection of carbon monoxide (CO: 0-2,000 ppm), hydrogen sulfide (H_2S: 0-1,000 ppm) and nitrogen oxides (NO: 0-250 ppm; NO_2: 0-2,000 ppm) as well as sulfur dioxide (SO_2: 0-2,000 ppm). In addition, these air quality sensors detect oxygen (O_2: 0-30%), hydrogen (H_2: 0-1,000 ppm), chlorine (Cl_2: 0-200 ppm) and chlorine dioxide (ClO_2: 0-1 ppm) (SGX Sensortech, Neuchatel, Switzerland).

2.3. Photoionization Gas Sensors

By exposing gases to ultraviolet light (UV) the ionization of specific molecules can be observed, which is practically used for the detection of chemical compounds by the photoionization detection (PID). This principle is primarily used for the detection of harmful VOC's in the environmental air [22].

The base of this measurement method is a UV light source and two electrodes (sensing and counter electrode). The components are positioned in a measurement chamber, which is continuously supplied by environmental gas molecules. If the gas molecules enter the chamber, they are exposed to the UV-light inside. The UV lamp emits photons with a sufficiently high energy to strike out an electron and to form positively charged ions (see Figure 3). Often light sources with 10.6 eV are used since a wide range of harmful substances respond to it. In contrast, this energy is not high enough to ionize classical air compounds such as nitrogen, oxygen or noble gases. These light sources have the longest life expectancy, of approximately 6,000 hours [23]. The

electrodes establish an electric field in the measurement chamber, and an ionization current arises from the ionized molecules. The resulting intensity of the ionization current is directly proportional to the concentration of the ionized gases [24][25]. The so-called response factor represents the sensitivity of the sensor relating to a reference substance (mostly isobutene) and allows the determination of the gas concentration. This is important if the target gas cannot be used for calibration or different gases are detected by one sensor. The determination of a specific gas concentration requires the separation of the target gas, since otherwise the concentration of all ionizable gases (depending on the UV lamp's photon energy) in the chamber are added up.

Modern PID solutions are already capable of measuring concentrations of organic compounds around 1-10 ppb and have typical response times of a few seconds [26]. The size of the ionization chambers typically is between 40-200 µL [27] but can be reduced to a few microliters (0.5-10 µL [24]). Accordingly, this method is suitable for portable gas detection solutions.

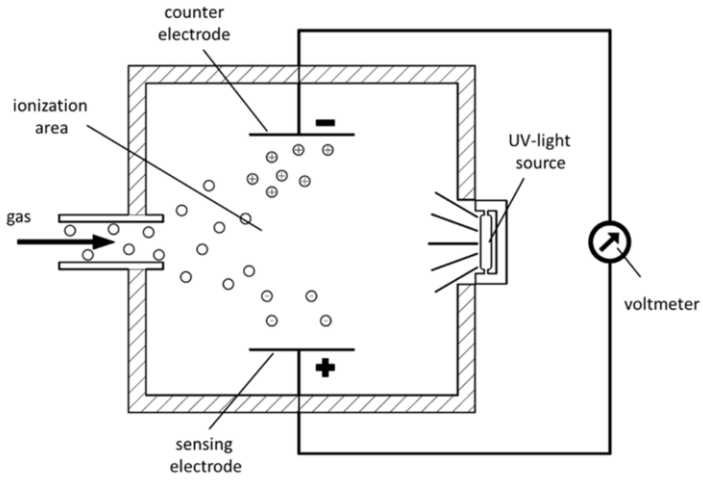

Figure 3. Principle of a photoionization sensor.

An example of a photoionization detector is the ION MiniPID2 (Ion Science, Royston, UK) for the detection of highly volatile organic compounds (VOC). Different versions allow detection in ranges from 0 to 40 ppm, 0 to 100 ppm or even up to 4,000 ppm; the detection limit is 100 part per billion (ppb). The 11.7 eV MiniPID2 extends the range of detectable compounds with chlorinated hydrocarbons, unsaturated fluorocarbons, formaldehyde, ethylene, and methanol. The sensors can be used in the temperature range from -40 °C to +65 °C with humidity from 0 to 99% RH. The ION MiniPID2 HS achieves better detection limits with 0.5 ppb, although it can only be used in the range up to 3 ppm. It is well suited for clean rooms and the detection of volatile contaminants. The lifespan of these sensors is over 5 years.

2.4. Non-dispersive Infrared Gas Sensors

One characteristic of most gas molecules is their absorption of light of specific wavelengths. If a photon hits the gas molecule, the photon's energy stimulates the molecule to oscillate. Some gases can absorb visible light if the concentration is high enough (e.g., chlorine appears in yellow-green and iodine vapor in violet) but generally the absorption occurs in the infrared area. Typical absorption lines are 9.6 µm for ozone (O_3) [28], 3.3 µm or around 7.8 µm for methane (CH_4) and 4.24 µm for carbon dioxide (CO_2) [29][30][31]. This behavior can be used effectively to differentiate gases. The selectivity of this method is limited, since several gases show similar absorption lines as e.g., CO_2 and H2O, at 2.7 µm [32].

An established optical gas-detection method is the so called NDIR-approach (non-dispersive infrared). It is especially convenient for determining the concentration of hydrocarbons, carbon monoxide and carbon dioxide.

Main parts of this sensor are a broadband infrared light source, a measurement cuvette (sample chamber), two bandwidth filters and two infrared detectors (measurement and reference detector). The cuvette connects the opposite positioned light source and the detectors in such a way that the emitted light has to pass the whole cuvette to reach the detector's site. In front of each detector, a narrow bandwidth filter is positioned, which only lets pass through a specific spectrum of the emitted light. The spectrum of the filters is different, so that the measurement filter can be selected for a specific absorption wavelength of the target gas. The reference filter uses a wavelength, which is not affected by the target gas, and is detected by the reference detector (see Figure 4).

In the measuring process, the cuvette leads the gas flow lengthwise to the emitted light. If the target gas passes the cuvette, the gas-specific wavelength of the emitted light will be absorbed and cannot be detected by the measurement detector. The reference detector in this case does detect light, and confirms the detection. If influences such as power and temperature fluctuations, polluted optical parts or dust disturb the measurement, both detectors are affected in the same way [32][33].

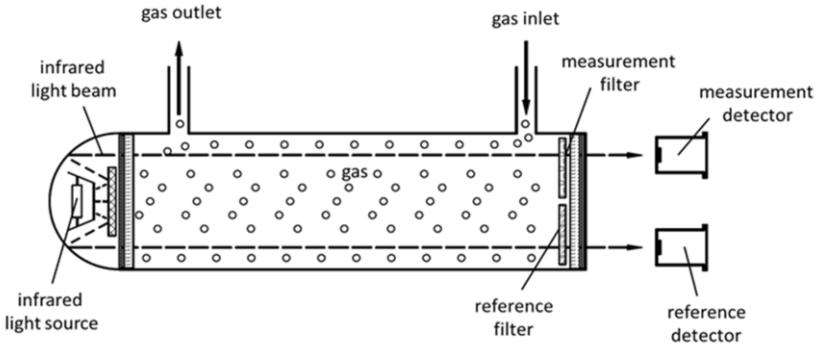

Figure 4. Principle of an NDIR gas sensor with two infrared detectors.

The NDIR method is a robust and cost-effective way to measure different gases with a medium resolution. The reaction time of these sensors is roughly around 20 seconds. By using a reference detector, many disturbances can be recognized and used to avoid

false detections. This method also allows small constructions, which can be used for portable sensor solutions. One restriction of this method is the condition that the required gases need to absorb infrared light and that the wavelengths of these gases need to be known. Measuring several gases in parallel is possible but restricted since for every gas, an own filter-detector unit needs to be installed. Further, the length of the cuvette is very close to the absorption characteristic of the gas [34]. A combination of gases with different absorption characteristic requires a separation of the measurement canals with own cuvette and filter-detector unit [35].

An example of non-dispersive portable IR sensors is the SGX IR12 GM (SGX Sensortech, Neuchatel, Switzerland) for the detection of methane and hydrocarbons with a minimum detection level of 30 ppm methane (CH_4). A further example is the IRC-A1 sensor (Alphasense, Sensor Technology House, Essex, UK) for the measurement of carbon dioxide (CO_2) in the range of 0 to 5,000 ppm.

2.5. Metal Oxide Semiconductor Gas Sensors

Under the influence of gas, some metal oxides, such as tin(IV) oxide (SnO_2) or titanium dioxide (TiO_2), but also organic semiconductor materials, show a change in their conductivity. Oxygen vacancies in the crystal structure of the oxides act like n-doping of the material. This effect is used in metal oxide semiconductor gas sensors (MOS) to detect gases [36].

In a first step, oxygen molecules from the ambient air are adsorbed onto the sensor surface. The oxygen accepts electrons from the inside of the semiconductor and is therefore negatively charged. As for an n-type semiconductor (SnO_2), this reduces the charge carrier density, which leads to the formation of a depletion zone and lowers the conductivity in the edge zone (see Figure 5). If the surface of the semiconductor is exposed to a reducing gas, this reacts with the resulting oxygen ions, changing the conductivity. While reducing gases such as carbon monoxide or hydrogen increase the conductivity, it decreases in the case of oxidizing gases such as oxygen, oxygen producing gases or fluorine. Due to the correlation between the gas concentration and the change in conductivity, a quantitative determination of the concentrations can be carried out in addition to the determination of the gas. To enable a reaction between the ambient gases and the sensitive material and for controlling the selectivity [37] an operating temperature between 250°C and 450°C [38] is required, thus usually a platinum heater is included [37].

One of the most known MOS sensors based on tin oxide is the "Figaro sensor" developed by Naoyoshi Taguchi [39]. Depending on the design, these sensors can be used to detect natural gas and methane gas (type TGS 813), but also to determine alcohol, ammonia, etc.. MOS sensors are quite inexpensive due to the possibility of mass production. They are characterized by high sensitivity in the ppm range and a long service life [40]. One disadvantage is the non-linear sensor reaction depending on the gas concentration, which makes calibration considerably more difficult. In addition, there is a certain cross-sensitivity, especially regarding air humidity. The selectivity of the sensors is low so that they can only be used for screening purposes or the determination of known compounds. The sensitivity of the semiconductor for a certain gas can be changed via the temperature of the semiconductor.

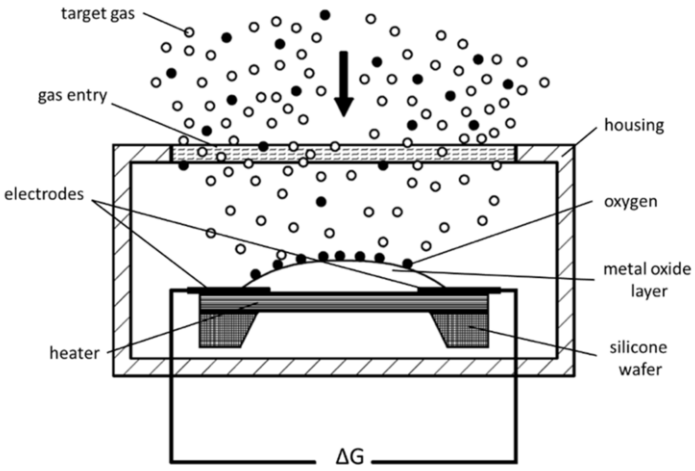

Figure 5. Principle of a metal-oxide gas sensor.

Another disadvantage is the high-energy consumption due to the required operating temperature. Miniaturization and the use of thin-film technology [41] can be used here to reduce the energy demands. The reduction of energy consumption of MOS gas sensors is a topical issue in research regarding the growing interest in adapting gas sensors for wearable devices [42][43].

The MiCS 5524 (SGX Sensortech, Switzerland) is an example of a MOS sensor which is used for indoor air quality monitoring. It allows the measurement of carbon monoxide (CO, 1-1,000 ppm), ethanol (C_2H_5OH, 10-500 ppm), hydrogen (H_2, 1-1,000 ppm), ammonia (NH_3, 1-500 ppm), methane (CH_4, >1,000 ppm). The MOS sensor TSG 8100 (Figaro USA, Inc., USA) for detecting air contaminants detects similar gases in the range of 1-100 ppm.

2.6. Graphene-Based Gas Sensors

Another type of gas sensors is based on graphene. Due to properties such as high surface-to-volume ratio, low electrical noise and remarkable transport properties related to the two-dimensional structure, graphene is an interesting material for different new applications. Numerous sensor applications are known for the determination of different biochemical components such as glucose in tears or sweat [44], lactate in sweat [45], ascorbic acid in tear films [46] or cortisol in sweat or saliva [47].

Ko et al. showed in a study that graphene can easily absorb/desorb NO_x molecules [48]. The conductivity of graphene layers changed depending on the concentration of NO_2 molecules. The resulting graphene-based sensors were characterized by a fast response, good reversibility, selectivity and high sensitivity. With UV LEDs and silicon microelectronics, this new technology can be used for the development of nano-sized gas sensors with very high sensitivity.

Ultrasensitive NO_2 gas sensors based on epitaxial graphene have been reported by Novikov et al. [49]. An optimized graphene/metal contact configuration resulted in a low contact resistance. A significant improvement of the sensing sensitivity was further

achieved by complementary annealing of the sensor at 120 °C in the carrier gas flow. The limit of detection was estimated to be 0.6 ppt.

A graphene-based sensor has also been reported for environmental monitoring [50]. The prototype showed fast and reproducible measurements of NO_2 in environmentally relevant concentrations between 5 and 50 ppb.

NO_2 sensors are operated in ambient environments. Thus, possible cross-selectivities have to be minimized. A study conducted by Melios et al. showed that graphene has similar sensitivities for NO_2 and SO_2 at 70 °C. However, operating the sensor at higher temperatures at 150 °C significantly enhanced the sensitivity for NO_2. In addition, higher temperatures could also decrease the sensitivity of typical concentrations of CO in ambient air [51].

Other sensors have been developed for the determination of ammonia (NH_3) [52][53]. The level of detection (LOD) was determined at 500 ppb. The determination of hydrogen with LOD of 20 ppm was reported by Chung et al. [54]. Ren et al. described the determination of sulfur dioxide using a graphene-based sensor [55]. A detailed review of graphene-based sensors for the determination of different toxic gases and organic vapors including methanol, acetone and toluene can be found in [56].

2.7. Summary

The sensor market has developed very dynamically recently. The focus was on ever-increasing miniaturization. Smaller sensors form the basis for personal monitoring of people in their workplaces.

Numerous technologies are now available for determining different compounds. Unfortunately, the majority of the sensors do not have sufficient selectivity, which would be necessary for the determination of individual compounds. Chemical sensors are the exception, which, due to their very selective operating principle, can be used specifically for the quantitative detection of a wide variety of different inorganic and organic compounds.

Table 1 shows a summarizing overview of compounds and suitable sensors.

3. Hardware for Sensor Integration

3.1. General Requirements

Depending on the target application, specific sensors can be selected. For their integration into technical solutions, different selection criteria need to be considered. These parameters may differ depending on the technical measurement principle. One of the most important parameters for the sensor operation is the energy supply, which is required for the vast majority of gas sensors. Typical voltages are 1.8 V, 3.3 V or 5V. The power consumption – required electrical energy – is another important parameter.

For the determination of the sampling rate, it is important to consider that the response time of the sensors commonly requires several seconds to reach the final value, depending on the principle and the construction. A change in the sensor's sampling rate often has an influence on the sensor's behavior and consequently requires an individual calibration.

Table 1. Selected sensor principles for the determination of different inorganic and organic components

Compound	Sensor Principle Detection Range ppm	Example
Inorganic Gases		
Ammonia	EC / 0-200 ppm	FECS44-200[a]
Carbon dioxide	IR / 0-5%	IR601[b]
Carbon monoxide	EC / 0-1,000 ppm	FECS40-1000[a]
Chlorine	EC / 0-10 ppm	FECS45-10[a]
Hydrogen	MOS / 1-30 ppm	TGS 2600[a]
Hydrogen Sulfide	EC / 0-100 ppm	FECS50-100[a]
Nitric oxide	EC / 0-300 ppm	FECS41-250[a]
Nitrogen dioxide	EC / 0-30 ppm	FECS42-20[a]
Oxygen	EC / 0-100%	KE-25[a]
Sulfur dioxide	EC / 0-20 ppm	FECS43-20[a]
Organic Gases and Solvents		
Acetylene	IR / 0-100 ppm	IR604[b]
Alcohol / Solvent vapors	MOS / 50-5,000 ppm	TGS2620[a]
Aromatic compounds	PID / 5ppb-100 ppm	10 eV MiniPID2[c]
Butane / Propane	MOS / 1-25%	TGS 2610-C00[a]
	CAT / 0-100%	TGS6810-D00[a]
Chlorinated hydrocarbons	PID / 0.1-100 ppm	11.7 eV MiniPID2[c]
	MOS / 5-100 ppm	TGS3830[a]
Chlorofluorocarbons	MOS / 5-100 ppm	TGS 3830[a]
Combustible gases	CAT / 0-100%	VQ549ZD[b]
Ethanol	MOS / 1-30 ppm	TGS 2602[a]
	MOS / 10-500 ppm	MiCS 5524[b]
Formaldehyde	PID /0.1-100 ppm	11.7 eV MiniPID2[c]
Methane	MOS / 1-25%	TGS 2611[a]
	CAT / 0-5%	MP7217[b]

[a] Figaro (Arlington Heights, USA); [b] SGX Sensortech (Neuchatel, Switzerland); [c] Ion Science (Royston, UK)
EC: electrochemical; MOS: metal oxide semiconductor; CAT: Pellistor; IR: Infrared

Output signal and data interfaces have to be defined to deliver the measurement results, depending on the sensor's technical configuration. This includes analog signals, pulse width modulation signals, serial interfaces as UART (Universal Asynchronous Receiver Transmitter) or busses for embedded systems as I^2C (Inter-Integrated Circuits) or SPI (Serial Peripheral Interface). Commonly, analog interfaces or I^2C are used. Available sensor interfaces are strongly dependent on the sensor's configuration and equipment. While simple analog interfaces do not require the analog to digital conversion or further processing effort, but protocols often require the inclusion of small microcontrollers.

Finally, the mounting technology is of importance. This can be realized by through hole technology (THT) or surface-mount technology (SMT). The decision for a mounting technology is decisive regarding the final construction size, which is significantly smaller using SMT.

Other parameters as environmental conditions or sensor life-time also can influence the sensor's integration. Additional sensors might be required to monitor different environmental parameters for correcting the measurement results. In case of lower sensor life times, it is recommended to use an exchangeable design for the sensor.

3.2. Sensor Types

Generally, three types of sensors can be categorized – sensing elements, integrated sensors and smart sensors (see Figure 6) [57]. These three types differ in their functionalities.

Gas sensing elements, which work on the base of measurement principles as introduced in section 2, receive a signal or stimulus and respond in a distinctive manner. They generally require a further signal conditioning and often the adaption of standard interfaces or busses for their integration. The signal conditioning includes a bundle of measures to adapt and to optimize the signal of the sensing element for the subsequent processing steps. Depending on the sensors' individual characteristic, these measures need to be considered in the sensor electronic.

Integrated sensors already have signal conditioning measures. This approach allows the sensors to send signals that can be used immediately, without an additional circuit design for signal amplification or processing. The combination of sensing and signal processing enables an easy integration. Since the data acquisition method is already integrated, the development time for a new device can be reduced. Integrated sensors can be designed for space and weight saving compared to other solutions. Another advantage is their easy replaceability in case of malfunctions or errors. For integrated sensors, often sensor modules (small PCBs including a sensing element) are provided by manufactures or third-party companies, which contain the required electronics.

If, in addition to sensing and signal conditioning, signal processing is also integrated into the sensor, they are defined as *smart sensors.* Such complex sensors usually contain microprocessors or microcontrollers with a low-power consumption. Thus, the implementation of device internal interfaces as UART, SPI or I^2C or external interfaces as USB (Universal Serial Bus) are available. The microcontrollers are can not only realize bus communications, they also offer the implementation of a software-based data processing [58] such as data fusion, signal conditioning parts, auto-calibration procedures or even threshold monitoring.

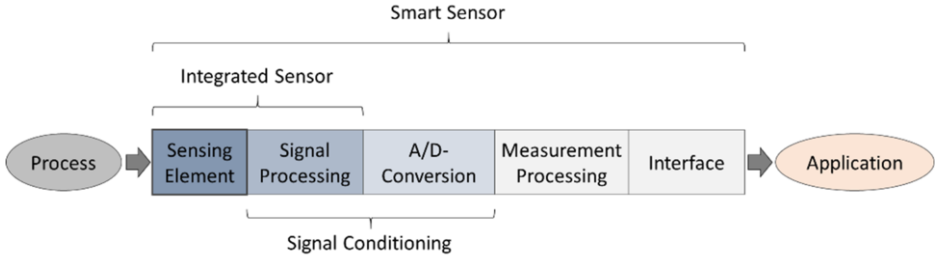

Figure 6. Simplified processing chain between sensing element and smart sensors.

For external communication, smart sensors / modules can also be equipped with active and passive radio interfaces, including Bluetooth or WLAN. This enables an easy transmission of the data obtained for visualization purposes, data storage, and data evaluation.

By integrating sensing, signal conditioning and signal processing, the entire demanding task of such sensors should be performed without an external computer.

Reasons for this include miniaturization, decentralization, an increase in reliability, a reduction in costs or an improvement in flexibility.

3.3. Integration of Sensing Elements

Since sensing elements only enable the recording of measured values, all signal conditioning and signal processing functions and the voltage supply must be implemented. The adaption and stabilization of the voltage input is an important base to ensure a safe and correct operation. This also includes the consideration of the sensor's power consumption, which can be relatively high due to the often implemented heaters, depending on the used principle. For such heater-related sensing principles, it can be important to provide a heating regulator that compensates different tempered environments for accurate measurements. The vast majority of the currently available sensing elements are through hole components, whereby their installation is simpler but also requires more space.

The required conditioning of the output signal strongly depends on the application demands (e.g., accuracy) and the aimed design of the target device (e.g., size, power consumption). Signal conditioning includes several measures, such as the signal amplification, level adjustment, signal conversion, filtering and analog/digital conversion (ADC), if required. Not all measures are always required or considered, depending on the characteristic of the used principles. Often it is, for example, necessary to convert electrical resistances or currents into a voltage signal or to linearize non-linear relations between voltage and concentration. High demands on the accuracy and reliability of the sensor results also increase the requirements for the sensor's integration. Exact measurements often depend on environmental conditions as temperature and humidity and have to be considered for data correction. The increasing miniaturization of the sensing elements also influences the signal output. E.g., smaller electrode areas inside the sensing element lead to a smaller sensor response relative to the noise [59]. By amplification and filtering of this voltage signal, an adequate sensor output has to be generated.

A general but significant condition for the integration of sensing elements is its optimal positioning. First of all, it needs to be ensured that the sensing element is sufficiently supplied by gas flow around. In some cases, pumps are used to guarantee an optimal and continuous gas flow for the measurement. Further, it is also important to make sure that no other heating element (e.g., transistors, other gas sensors) is close to the sensing element to avoid a mutual interference.

3.4. Integration of Integrated Sensors/Sensor Modules

As already introduced in section 3.2 integrated sensors contain already signal conditioning measures. Indeed, only a limited number of simple integrated gas sensors (not smart) in monolithic design can be found on the market (see Table 2). Instead, sensor boards, often from the manufactures, assume this task and equip the sensing elements with the required measures. Technically, both solutions can comprise the same measures, but regarding the installation size and the connection options, they differ. Modules are larger than monolithic solutions and often are installed via plug connectors, whereas monolithic solutions often are made for soldering.

Generally, integrated sensors/sensor modules support the hardware integration since basic conditioning measures do not have to be considered, whereby not all measures are necessarily included. Moreover, the adaption and stabilization of the voltage supply can be part of the integrated sensor/sensor module. If it is not integrated or the available voltage does not fit to the target device, an adaption is required. For the output signal, these solutions offer commonly an analog front-end interface with a predefined voltage range, which is suitable for analog inputs of microcontrollers.

Some signal conditioning measures need not necessarily to be realized by hardware and can be realized by the microcontroller. This opens up further opportunities to simplify and optimize the integration, which are often handled in smart sensors.

The installation conditions, introduced in section 3.1, for positioning the sensor regarding the gas flow and other temperature sources also apply to integrated sensors. In Table 2 some examples for integrating sensor modules are presented.

Table 2. Integrated sensors/sensor modules

Properties	**Spec ULPSM-NO2**	**Figaro CGM6812-B00**	**SGX Sensortech* MP-7217-TC**	**Winsen MQ-4**
Detected Gas	NO_2	combustible gases	methane	methane, liquefied natural gas (LNG)
Principle	EC	CAT	CAT	MOS
Construction Type	module	module	module	integrated
Power Supply	3±0.2V DC	5±0.2V DC	3±0.1V DC	≤ 24V DC (5±0.1V DC recommended)
Signal Output	analog (0-3V)	analog (1-4.5V)	analog 0-60 mV	analog (2.5V～4.0V)
Power Consumption	30±15µW	≤1.5W	≤ 126mW	≤ 950mW
Measurement Range	0-20 ppm	0-14,000 ppm for H_2	5% volume Methane in Air	300-10,000ppm
Response Time	<30 sec.	≤ 30 sec.	< 12 sec.	N/A
Special Features	on-board temperature sensor		on-board temperature sensor	

MOS: metal oxide semiconductor; EC: electrochemical; NDIR: non-dispersive infra-red
* sensor also uses thermal conductivity as sensing principle

3.5. Integration of Smart Sensors

Smart sensors, or also called integrated smart sensors, contain the features of simple integrated sensors and use microcontrollers as additional processing units. Similar to the integrated sensors, smart sensors are also available as monolithic and module solution, whereas here more monolithic solution can be found than for the integrated sensors. The advantage of smart sensors using the monolithic approach is a significant reduction of the sensor's construction size (see Table 3) and hence they usually based on surface mount technology.

Using smart sensor/sensor modules supports their hardware integration similar to the integrated sensors. Due to an integrated processing unit, recommended procedures from the manufacturers for the handling are already included and do not have to be

considered for the integration. So for example a closed-loop temperature control for possibly included heaters, software-based signal conditioning as filtering or linearization, compensation of changing environmental parameters (by using additional temperature, humidity, and atmospheric pressure sensors), automatic drift-compensation and calibration procedures can be implemented to achieve better/optimized measurement results. Due to the included processing unit for the data transmission commonly used standardized, internal digital interface as UART, SPI or I^2C also can be realized. These protocols allow a comprehensive transfer of some information (measurement values and status information such as measuring status or heater stability status) to a central processing unit, where the data of all involved sensors of the device run together and are processed. Especially for the integration of several sensors bus solutions (e.g., SPI, I^2C) are recommended, since the wiring effort can be significantly reduced. Besides the reduced hardware implementation, the integration effort for smart sensors primarily refers to the software-related adaption of the appropriated transfer protocols by the subsequent processing unit. One restriction which can arise by using smart sensors is that sensing and processing is encapsulated, and no individual post-processing can be performed. To enable extensive options for post-processing, some smart sensors also provide raw data and the manufacturers offer libraries for the processing or individual adjustment of the calibration line.

Regarding the position of the sensors on an oriented circuit board (PCB), it is recommended to comply with the installation conditions (sufficient gas-flow, avoiding temperature influence) as introduced in section 3.1. Especially the tiny small monolithic smart-sensor solutions are vulnerable to foreign temperature sources, and it is useful to separate them and therefore also milling the PCB around the sensor is recommended to reduce the thermal conduction.

In Table 3 examples for smart sensors are presented that partially contain the explained features. However, the Bosch BME 680 sensor has by far the most extensive range of functions and features in the comparison.

Table 3. Smart sensors/sensor modules

Properties	**Bosch BME 680**	**Sensirion SGP 30**	**Spec IOT-CO-1000**	**Sensirion SCD30**
Measured Data	VOC gases (CO_2), temperature, humidity, pressure	TVOC gases, CO_2eq	CO	CO_2, temperature, humidity
Principle	MOS	MOS	EC	NDIR
Construction Type	chip	chip	module	module
Power Supply	1.71-3.6 V	1.62-1.98 V	2.6-3.6 V	3.3-5.5 V
Power Consumption	0.09-12 mA (depending on operation mode)	48.8 mA at 1.8V (measurement mode)	12 mW for continuous sampling	19 mA for 1 meas. per 2 s
Interfaces	I^2C, SPI	I^2C	UART	UART, I^2C
Measurement Range	N/A	VOC: 0-60,000 ppb CO_2eq: 400-60,000 ppm	0-1,000 ppm	400-1,000 ppm

MOS: metal oxide semiconductor; EC: electrochemical; NDIR: non-dispersive infra-red

3.6. Summary

The integration of gas sensors into a target device depends on the planned operation purpose and consequently on its target properties (e.g., target gases, size, power consumption, accuracy). In accordance with these properties, suitable gas-sensor principles and types have to be found. The sensor types can be divided into single sensing elements, integrated sensors and smart sensors, which differ in the included processing features. While sensing elements only include the sensing principle, integrated sensors additionally also cover signal-conditioning features, which convert and optimize the output signal and commonly provide a voltage-based analog front-end interface. Smart sensors generally contain the functions of integrated sensors and are extended by a processing unit. The processing unit allows a digital post-processing, including temperature regulation, baseline compensation, auto-calibration (or integrated calibration lines), and allows the provision of internal digital interfaces such as I^2C or SPI.

Depending on the selected sensor type, the sensor integration requires a varying level of integration effort. With smart sensor solutions, especially for gas sensing, where many factors can influence the measurement (e.g., by sensor drift, temperature, and humidity), many procedures are covered and encapsulated in one chip or module. The integration can be reduced to the provision of the power supply and the adaption of the output protocol, which partially or completely needs to be considered for the integration of single sensing elements or integrated sensors.

However, independent of the sensor's construction type, the positioning of the sensor is most important. It is necessary to position the sensor in such a way that a continuous gas flow around the sensor is given. Further, the thermal conduction of elements around the sensor, who radiates heat, should be avoided or compensated by suitable measures.

4. Ready-to-Use Sensor Solutions

4.1. Definition and Integration of Sensor Devices

Sensor devices are complete systems which, in addition to the actual sensor data acquisition and all processing steps, also enable the visualization and evaluation of the data. The integration of gas-sensor devices primarily focuses on their connection to application-related infrastructures. The simplest integration scenario is the direct connection between one sensor device and one sensor device node. The sensor device node is a processing system such as a computer, server/cloud or mobile device. The most important condition for the integration is the compatibility of the participants' interfaces. Some interfaces have established as standards for such applications such as USB, Ethernet, wireless LAN and Bluetooth Low Energy (BLE) [60]. For low-energy requirements with wireless communication also specifications such as 6LoWPAN (acronym for: IPv6 over Low power Wireless Personal Area Network) [61], ZigBee [62] or ANT/ANT+ are used especially for wearable applications. In some cases also cellular communication standards (3G, 4G, 5G) are included in the sensor devices to permit a higher independence from local networks [63]. The used protocols and profiles on the interfaces can vary and range from the Bluetooth GATT-Profile (Generic Attribute protocol) via TCP/IP (Transmission Control Protocol/Internet Protocol) to HTTP-based/-conform web standards (including SOAP and REST) [64], which should not be

further enlarged here. The implementation of such protocols as part of the sensor-device integration strongly depends on the application and the provided features of the device. The usual approach is that the sensor-device node uses a polling routine, in which the sensor device transfers data on request. In contrast, Smart Connected Sensors (SCS) are devices that automatically use cloud services to send their data to a service platform. Here, the measurement data are processed and used for long-term analyzes and as comparison values. The integration effort for such sensor devices is reduced to a minimum if the service is configured. Authorized users can access this data via programming interfaces. Additional functions can also be managed in the cloud, and reference and limit values can be entered for comparison and alarms. By integrating sensing, signal conditioning and signal processing, the entire demanding task of such sensors can be performed without an external computer. Additional functions can also be managed in the cloud, and reference and limit values can be entered for comparison and alarms.

In many applications, the sensor-device nodes collect data from several distributed sensor devices, which allow a wide area-covering monitoring, for example, to check the general air quality or to detect hazardous gas situations. At least in these cases, an addressing for the sensor devices is required to differentiate the devices and to allocate their positions. A further important point for the integration of sensor devices is the consideration of data security, especially if data are safety related and if they are transmitted via web or other open networks. In this case, measures for the data anonymization or encryption and the manipulation protection, if necessary, have to be considered.

The sensing function combined with such connectivity features allows a simple coupling with computers, smart devices and their presence in networks. The ability to network also offers the possibility that sensor data can be directly distributed worldwide. Some solutions also provide battery options, and integrated data storage for a mobile operation. Especially such sensor solution benefit from the miniaturization of the sensing elements, the corresponding reduced power consumption and the integration of conditioning and processing features.

Today, app-based methods are usually used. This also enables the use in actual mobile monitoring systems. Sensor devices are therefore intended for use in different areas without the need for further integration work.

4.2. Examples for Gas Sensor Devices

Due to the currently great demand for gas-sensor devices, because of the increasing desire for a safe and sufficient air quality [65], solution for gas monitoring in different environments can be found. On the commercial market as well as in research, the interest can be indicated by the wide variety.

A flexible gas sensor platform for the measurement of different gases, including carbon monoxide, oxygen, ammonia, fluorine, or chlorine dioxide is the TIDA-00056 (Texas Instruments, Dallas, Texas, USA) [66]. The system sensors can be changed whereby Texas Instruments recommends the electrochemical gas sensors Alphasense A2 (Alphasense Ltd, Great Notley, UK) for oxygen (range: 0.1-20.9% O_2) and Alphasense CO-AF for carbon monoxide (range: 0-5,000 ppm CO). Prepared for a wide range of wireless interfaces as Bluetooth Low Energy (BLE), Zigbee RF4CE, 6LoWPAN and

ANT and equipped with standard coin cell battery, this device is optimized for mobile applications. The gas concentrations can be monitored via a gas sensor mobile APP.

A further ready-to-use sensor is the bluSensor® AIQ (Salzburg, Austria), which combines the measurement of humidity and temperature using the Sensirion SHTC3 and TVOC (total volatile organic compounds) using Sensirion SGP30 (range: 0-60,000 ppb TVOC and 400-60,000 ppm CO_2eq). The sensor system is made for air quality measurement and is available with USB and wireless communication (Wi-Fi and Bluetooth) interfaces. bluSensor® AIQ is a stationary system which is supplied by USB. It has different colored lights inside that indicates if thresholds are exceeded.

The Wireless CO_2 Sensor PS-3208 (Pasco Scientific, Roseville, CA, USA) bases on the non-dispersive infrared (NDIR) technology. It measures CO_2 in the range from 0 to 100,000 ppm and is designed as a data logger equipped with a lithium-polymer battery for up to 24 h operation. The data can be retrieved via USB. An integrated Bluetooth 4.0 interface allows transferring the data directly to a terminal device such as a smartphone.

In October 2020, NASA presented the first prototype of a new portable device for the determination of different gases [67]. The smartphone sized 'E-Nose Breath Analyzer' was developed for the diagnosis of breathing gases and enables the determination of 16 different chemicals including methane, hydrazine, formaldehyde, acetone, benzene, toluene, or malathion at room temperature within seconds. An array of electrochemical sensors combined with sensors for humidity, temperature, and pressure is used for real-time breath analysis [68]. The system is a further development of the electronic noses, which were developed for the indoor air monitoring of the Space Station [69].

Numerous scientific papers have been published on the determination of toxic gases using smartphones. Azzarelli et al. described a wireless gas detection with a smartphone via RF communication. The sensing strategy employs chemiresponsive nanomaterials integrated into the circuitry of commercial near-field communication tags. Thus, a portable, and inexpensive detection of gases such as ammonia, hydrogen peroxide, cyclohexanone, and water could be achieved at part-per-thousand and part-per-million concentrations [70]. A smartphone coupled handheld array reader for the determination of different toxic gases was reported by Devadhasan et al. The system uses a colorimetric monitoring approach and includes a complementary metal oxide (CMOS) image sensor. Toxic gases, including hydrogen fluoride (HF), chlorine (Cl_2), ammonia (NH_3), and formaldehyde (CH_2O) were detected using titanium nanoparticles coated with chemically responsive dyes. The different compounds could be detected with detection limits of 1 ppm for each gas. The measured signals are transferred via a specific app to a smartphone for the display of the results [71]. Suárez et al. developed a Bluetooth gas sensing module for air quality monitoring. Besides humidity and ambient temperature sensors, the prototype included four gas detection sensors (MiCS-4514, MiCS-5526 and MiCS-5914, SGX Sensortech, Corcelles-Cormondreche, Switzerland). The system has been tested with ten volatile organic compounds, including acetone, benzene, ethanol, ethyl acetate, formaldehyde, and toluene. Depending on the compound's success rates, between 88.33% and 92.22% could be achieved using a BackPropagation Learning algorithm and Radial-Basis based Neural Networks [72]. A miniaturized electronic nose with digital gas sensors for the determination of different concentrations of NOx has also been reported [73]. Four metal oxide sensors have been used: BME680 (Bosch Sensortec GmbH, Reutlingen, Germany), SGP30 (Sensirion, Staefa, Switzerland), CCS811 (Sciosense B.V., Eindhoven, Netherlands, and iAQ-Core (Sciosense B.V., Eindhoven, Netherlands). A Bluetooth low-energy communication module was developed to enable

the data transfer from the sensor module to the smartphone application. Suitable algorithms for data normalization and feature extraction were integrated. Machine learning algorithms were used to classify the data retrieved from the sensing. Test measurements were performed for concentrations between 40 µg/m^3 and 200 µg/m^3 NO_2 and 7.7 µg/m^3 to 77 µg/m^3 for NO. Interferences in the determination of the two gases could be seen for some concentrations.

A wearable sensor solution combining the measurement of gas (CO and NO_2), sound level as well as temperature, air humidity and pressure is presented in [74]. Aim of the development was the monitoring of environmental parameter in usual routine (as work or at home) and its influence on the humans body and the mental strain by a wrist-worn device [75]. Especially in work environments, the exposure of gases can reach critical thresholds. Thus, the sensors detect NO_2 up to 5 ppm and CO up to 1,600 ppm (Spec Sensor LLC, Newark, CA, USA).

A mobile gas-sensor device was further developed to ensure the occupational safety in automated laboratory environments [76]. The module's design allows the integration of smaller sub-modules equipped with gas-sensors for example BME680 (Bosch Sensortec GmbH, Reutlingen, Germany), SGP30 (Sensirion, Staefa, Switzerland) and MICS-5524 (Amphenol SGX Sensortech). As interface for the sensor modules, the device supports SPI, I^2C or analog signals. Thus, the sensor device can be used at different potentially dangerous positions or added to mobile robots that work with chemical compounds to detect hazardous situations for humans. Currently, the sensor only uses a USB interface, but wireless LAN and Bluetooth interfaces will be available soon. A central management system collects the measured gas concentrations combined with the location information of the distributed sensor devices and realizes the post-processing and visualization of the data. The system also includes an alert management to inform about areas where often no staff is present.

5. Summary

The trend towards monitoring numerous parameters in our working and living environment continues uninterrupted. Numerous commercial solutions exist for the monitoring of physiological data and movement profiles, which can be easily used and operated by the user. So far, however, there are only a few suitable solutions for continuous monitoring of environmental pollution. In addition to the classic inorganic gases such as NOx or CO, this also includes organic components that can cause severe safety problems or lead to corresponding health problem.

Theoretically, different sensory principles can be used for monitoring gases and solvent vapors. Catalytic bead sensors use changes in resistance caused by catalytic combustion reactions, which are proportional to the concentration of the compounds to be determined. Photoionization detectors ionize compounds using UV light from a gas discharge lamp. NIR sensors in turn use different absorption wavelengths of chemical compounds. Metal oxide semiconductor sensors use the substance and concentration-dependent change in the conductivity of inorganic or organic materials. Electrochemical sensors work on the principle of galvanic cells; depending on the principle, an electrochemical reaction causes a voltage change or a current.

For the exact qualitative and quantitative detection of individual compounds, sufficient selectivity is required that has little or no cross-sensitivities. This is only possible to a limited extent with the above-mentioned operating principles. For the

response of catalytic bead sensors, a heat development is required; this occurs with all substances that are flammable. This only enables a differentiation between flammable / non-flammable gases; a further targeted detection of individual compounds is not possible. NIR-based sensors enable a better selection of different compounds through the targeted selection of the wavelengths to be measured. It should be noted here, however, that there may be overlaps in the measurement signal due to similar absorption ranges of different compounds. Electrochemical sensors show excellent selectivity due to their operating principle. They can be specifically tailored to the determination of individual components. However, this type of sensor has so far mainly been used for the determination of inorganic gases.

Extensive developments in the field of metal oxide semiconductor sensors can be seen in recent years. They can be mass-produced, are therefore very cheap and have small dimensions, which makes them ideal for use in mobile solutions. The selectivity of this type of sensor is limited; the underlying operating principle only enables a distinction to be made between oxidizing and reducing gases, which increase or decrease the conductivity of the sensor material.

While numerous sensors are available for the selective determination of different gases, only limited selective sensors are available for the detection of solvents and solvent vapors. The majority of organic compounds can be detected using classic VOC sensors. Owing to the lack of selectivity, however, it is often only possible to determine sum parameters.

Sensors can be divided into different categories. Simple sensing elements only enable the pure conversion of measured values, but do not have any functionality for data conditioning or data processing. Integrated sensors represent combinations of sensing elements with data conditioning (amplification, etc.) Processes. Smart sensors / sensor modules are usually equipped with microcontrollers that have extensive functionality for data processing. Usually, they also have the option of external communication for data transmission to external and higher-level entities. The different functional scope of the sensor elements and modules used must be considered for their integration. By integrating such sensor solutions into a further microcontroller structure, which handles application-related sub-processes (configuration by users, display or indicate results, external communication for data transmission), they can be used as 'ready-to-use' systems for monitoring environmental parameters. In addition to commercial systems, there is a large amount of research activities in this area, which often combine different sensor elements.

Current and future developments in the field of monitoring systems show two main goals. Initially, the focus of the research is on increasing the selectivity of the sensors to enable better identification of individual compounds - even in mixtures. In the area of MOS sensors, this is done by testing different materials for the sensor surfaces. Different coatings can influence the responsiveness of the sensors and thus achieve a higher selectivity. Another possibility is to vary the operating parameters, which can also lead to different reactions with different substances. In addition, sensor arrays are increasingly being used; the measurement data are evaluated here using artificial intelligence methods. Graphen-based sensors will also be an interesting alternative in the future, as probe molecules can be integrated through electrochemical functionalization, which can be used for the selective determination of individual compounds according to the key-lock principle.

In addition to increasing the selectivity of the sensors, their miniaturization is of great importance, which is a prerequisite for their use in portable systems. By using

semiconductor and graphene technology, this is already possible for the actual sensing elements. However, there are still limits in the miniaturization of complete sensors in the area of energy supply. In addition to the energy required for the communication protocols, the required power consumption of the sensors is particularly important. Depending on the sensor principle used, this can be large and thus requires the power supply (usually batteries) to be dimensioned accordingly.

The user interfaces are also important for the acceptance of the sensors. Cloud-based solutions for data storage as well as suitable app-based user interfaces are the essential aspects.

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