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Aims and Scope

Chemical sensors and biosensors are becoming more and more indispensable tools in life science, medicine, chemistry and biotechnology. The series covers exciting sensor-related aspects of chemistry, biochemistry, thin film and interface techniques, physics, including opto-electronics, measurement sciences and signal processing. The single volumes of the series focus on selected topics and will be edited by selected volume editors. The *Springer Series on Chemical Sensors and Biosensors* aims to publish state-of-the-art articles that can serve as invaluable tools for both practitioners and researchers active in this highly interdisciplinary field. The carefully edited collection of papers in each volume will give continuous inspiration for new research and will point to existing new trends and brand new applications.

Preface

Stakeholders in Gas Sensing

The field of gas sensors is fascinating for people working in many different fields. Sensor researchers work in multidisciplinary teams with specialists in material science, physical chemistry, manufacturing technology, semiconductor physics and signal processing to build innovative gas sensors. The result of these efforts is key to gas sensor products in the areas of comfort, security, health, environment and energy savings. New applications in these fields have become tangible through the availability of sensing capabilities that were not available before. Moreover, gas sensors have become fascinating for an increasing number of companies which have no gas sensor-based product up to now, since their customers are more and more interested in gas sensor applications. Many of them are characterized by a significant economic potential.

However, the commercial success up to date is often found to be delayed compared to the expectations and the potential of the upcoming technological breakthroughs.

Development of a New Gas Sensing Technology

Researchers are inquisitive. They provide new creative ideas for sensing principles and readout mechanisms. However, the detection of a new physical effect eligible for sensing, by itself, is generally of limited value. Such detection principles often work well in a laboratory environment under simplified conditions, e.g. when gas X is diluted with clean and dry air. In a real application environment with changing temperature, humidity, various additional reactive gases and sometimes even strong corrosive effects, the result might be completely unsatisfactory. Such cases are often the reason that new effects are not followed up on and the economic benefit is lost.

However, the discovery, characterisation and cultivation of a new effect can be very promising, provided the existence of a strong belief of all participants in the success of this detection principle to detect gas X in a better way as well as an economically sound application scenario. The basis for success in a gas sensing application can usually be found in the choice of the appropriate physical–chemical effect that has the potential to function reliably under the given conditions of the application.

The follow-up of a new effect is even more reasonable when there is a chance to create a sensor platform that is based on this effect. Gas sensor markets are often niche markets. Due to the high cost of the commercialisation of a new sensor technology, it is beneficial to base the industrial launch on a multiple application target. The ability of a sensing principle to be adapted to different gases (e.g. by the exchange of the receptor surface, by the change of an electric control voltage or by the choice of operating temperatures) increases its chances for industrialisation. From an economic point of view, it makes much more sense to have a homogeneous but adaptable sensing technology for different applications than to approach different applications with a bundle of heterogeneous sensing principles. This rule retains its validity, even when it is a common knowledge amongst gas sensing specialists, that the heterogeneity of gas sensing applications does not allow for a "universal" sensing platform. As is the case with nearly every engineering development, we have to live with the best trade-off.

Implementation of a New Gas Sensing Application

To work efficiently, the scientist needs to be familiar with the specifications of the application. However, it also has to be made clear that the end user or financial investor needs to understand the capability of the technology as well as the timelines required to accomplish something profoundly new.

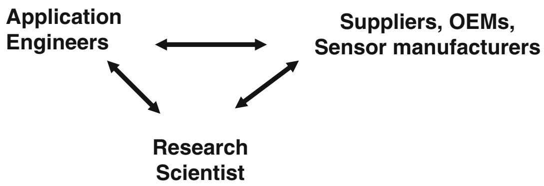
A person who is defining a gas sensor application might give a specification like: The sensor has to output a realistic gas value 1 s after power is supplied. For that request, the application engineer should scan the state of the art to find an answer for that specific problem. There might be a quick and straightforward existing solution but experience shows that this is rarely the case. Often the requirements cannot be met with an existing technology. At this point, the research scientist could step in and devise a new functional principle which fulfils the need. Unfortunately, the development of a new sensor technology lasts several years, and the application realisation according to the user or investor usually cannot wait that long.

If there is no technology available for a special application and it is not anticipated in the near future, the application scenario might be cancelled accompanied by financial losses. This can be avoided in many cases by using additional means which, in a particular way, lessen the requirements of the sensor itself in a confined way. Usually this is possible when application know-how is used to overcome the weaknesses of the sensor. For example, the existing drift of a sensor might be compensated by predicting and not measuring the gas concentration value in specific situations of the application. Such application information should be included in the evaluation of the sensor signal to make the sensor suitable for the application. We generally recommend in these situations to evaluate other gas sensor products/solutions and to learn from experts about how they realized a solution instead of giving up a promising product development. It must always be kept in mind that the gas sensor development can be a long, stony way but it is worth it if you want to stay ahead of competitors.

As a consequence we have to state that:

- Application restraints always require a pre-selection of appropriate operating principles.
- The selection of a sensor necessitates a compromise between application, performance, and cost.

For the successful implementation of a new gas sensing application, three groups have to collaborate. First, it is the application engineers who have to create a system that fulfils the requirements. They need intense exchange with the second group, the research scientists who know what a sensing principle is capable to deliver. The application engineers also need a strong exchange with the third group, the sensor suppliers to ensure that they get components with the sufficient performance at the required standard of quality. The sensor supplier needs to collaborate intensely with the research scientists to understand which production parameters are essential for a given sensing principle in order to be able to provide sensors with a sufficient quality standard at reasonable prices.



Better Communication Amongst the Stakeholders Is Needed

As stated above, a precondition for speeding up the development of a gas sensing application is strong interaction between all three stakeholders. The sometimes perceived suboptimal progress in the development of gas sensing technologies into real applications is coherent with the notion that at scientific conferences there is a remarkable participation of researchers but only a few users and application engineers can be seen. Vice versa when we visit trade fairs, we see many users but way too few scientists.

This compendium intends to contribute to open communication amongst the groups. It starts with a visionary view on how life can be improved in future buildings with the power of gas sensors. Then several contributions discuss the requirements for different application areas. The subsequent chapters address current trends in new sensing principles, followed by elaborations on how new sensing principles can be used for innovative applications. Renowned representatives report their experiences and expectations from research, applications and industrialisation in the most interesting fields of gas sensors.

This book focuses on what the research community labels as solid state gas sensors, where a gas directly changes electrical properties of a solid, which serves as a primary signal for the transducer. Therefore electrochemical, mass/viscoelastic, optical and calorimetric effects are out of the scope of this topic and have not been included.

The editors thank all the contributors of this book for their valuable chapters, and hope that it will leave the reader with a better understanding of gas sensors and encourage future research and investments in the fascinating world of gas sensors.

Munich, Germany Maximilian Fleischer
Wattwil, Switzerland Mirko Lehmann

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Part I
Requirements on Sensing

Future Building Gas Sensing Applications

O. Ahmed

Abstract It is often thought that technology drives innovation – a process that creates great values from ideas. But historically, it is a great vision that drives innovation and seeks for technologies as enablers. Take computer as a technology. "There is no reason for any individual to have a computer in their home," said Mr. Ken Nelson, the then president of Digital Equipment Corporation or DEC in 1977 (Nova Online. "Traveling Through Time – Part 2". Public Broadcasting Service. http://www.pbs.org/wgbh/nova/time/through2.html). Although immensely successful in minicomputer business, DEC failed to imagine what Home PC can do, and hence, unfortunately, saw one of the most dramatic demise of a technology company. It was lack of vision and imagination and not technology that led to such demise. Currently, Apple's success in mobile industry is driven by Steven Jobs' vision of delivering consumer infotainment by bundling technologies with flair and sleek products.

Therefore, it is important to paint a vision of what gas sensing can do in the future (Hagleitner et al., Nature 414:293–296, 2001; Moos et al., Sensors 9:4323–4365, 2009). What are the possibilities? How it can touch and benefit environment and human lives? Below is an attempt to paint vision through common-life examples. The goal here is to inspire and motivate us to think or dream big as how sensing can change our daily life experience. The dream should not be bounded by what can be achieved or not. That shall ultimately be governed by the real-life constraints such as costs, available technology, etc. But such lofty sensing vision should set a roadmap by defining requirements and seeking solutions for future.

This chapter presents a vision of solutions, particularly with gas sensing, that are achievable today with various matured and emerging technologies. The landscape

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of sensing solutions is changing fast as more and more technologies are becoming commercially available at even faster rate. Hence, once again, it is our vision that should set the pace of what we can expect tomorrow. So, let us keep imagining.

Keywords Application, Building, Built-environment, Carbon footprint, Environment, Future, Gas sensing, Innovation, MEMS, Microsystems, Sustainability

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1 Vision of Sustainable Built Environment

It was early in the morning, Adam wake up but not at the sound of alarm clock buzzer but by a voice that comes from his cell phone alerting him that his newly born baby's room has unusually high level of total volatile organic compounds (TVOC). Adam jumps from his bed and rushes toward that room. He takes a deep sigh of relief as he noted that his little daughter is sleeping well. He then checks on a new web-enabled sensor that not only measures TVOC, CO_2, CO, T, and relative humidity (RH) in that room but also transmits such data to his smart phone should there be any level of any gas that requires human attention. Adam checked the TVOC level and found that reading is somewhat high but nothing to be alarmed about. He then, using his smart phone, downloaded TVOC reading over last week and actually noticed that the TVOC level is slowly creeping up. Smart sensor on the wall really did its job by noticing gradual change in the TVOC value and sending an alarm message to the Smart Phone. This was great – Adam said to himself. He recalled that recently he painted this room with so-called Non-VOC type, but it seems that the paint is not completely free of volatile organic compounds (VOC). He decided to wait for few more days for the paint to dry before he puts his baby girl back into the room.

While Adam was on the train, he checked his Smart Phone which has a built-in sensor arrays for a variety of information besides the outside temperature and humidity such as any indication of any toxic substance or flu virus. He sat down and dialed a sensor address at an apartment where his 82-year-old mother lives by herself. He found there is no indication of alarm and all the readings from the sensor suites are normal.

Adam works in a hospital as a physician. As he enters through the hospital door, he gets a summary report of control and containment in the hospital with respect to any pathogens, biological, chemical, and radiological agents, and any disease that may be injurious to public health. The Smart Phone notifies Adam that the indoor environment quality or IEQ in the vicinity of Adam's office is good. There is no sign of any exposure of any gases or substance that may be injurious to Adam's health. It verified that the virus-monitoring system within the building is active and there is no report of any breakout of any virus within the building.

As Adam heads toward the lunch room, his Smart Phone continuously gets an update from the entire kitchen and food management systems notifying him about the freshness [1] of "Today's Catch" of Red Snapper but warns him about not to think about the frozen custard since the freezer temperature is not cold enough. The Smart Phone assures that he can drink from the faucet and does not need to buy any fancy expensive bottle water.

During the day break as Adam wants to use the toilet and he is close to it, he gets an alert that essentially asks to use another toilet because the smell inside is not acceptable due to malfunctioning of bathroom ventilation system.

What is described above may sound like a science fiction, but the description is a realistic projection of a home or building automation system of the future that is more integrated within our life to protect us and provide us a comfortable environment by using granular level, pervasive, and ubiquitous sensing.

2 The Role of Sensing Applications in Next Generation Building

The above vision can be only realized if sensing, particularly gases, become central to the future building and home automation systems. Sensing is fundamental in sustaining our life. With the advent of digital control systems in late 1970s, the sensing applications have seen exponential growth both in terms of its scope and utilization. Today, the basic sensing element is now coupled with a microprocessor that can process the sensed signal right within the sensor itself. The sensor communicates digital signal over building automation system's communication network. With the availability of inexpensive microprocessor and advancement in sensing element and sensor manufacturing technologies using latest complementary metal-oxide semiconductor (CMOS) and other integrated circuit (IC) processes, the overall sensor cost has come down significantly. The sensors are also integrating wireless communication chip and as a result offering more versatility and affordability by reducing the overall installed cost. Today's Micro-Electro Mechanical Systems technology (MEMS) allows to create an array of sensors (4–5) all into a single chip combined with the microprocessor, wireless communication, and power that can be harvested or scavenged from ambient sources, such as light, sound, or vibration, and thus not requiring plug-power that conventionally comes from fossil fuel source [2]. The power source can even come from a micro-fuel cell providing energy for years. Similar trend of converging functionalities into a single chip even to a smaller scale is evolving using nanotechnology. The technology platform [3] that can combine different functionalities using MEMS or Nano is known as Microsystems or Nanosystems, respectively. The fundamental technical advantages of such a system are better accuracy, precision, robustness, repeatability, and a smaller footprint of a sensor that is often a huge advantage to use sensors in an inconspicuous way. But what drives the advent of Microsystems or Nanosystems are compelling business reasons – a single chip that can sense multiple variables means lower manufacturing cost and combining wireless communication and self-powering means eliminating the need of field wiring altogether that can lower installed cost by as much as 70–80%. The rush is on to make the tiny microsensor or nanosensor to be almost self-sustaining with added features such as self-configuring, self-commissioning, self-healing, etc.

So, today's building automation systems (BAS) can measure, monitor, and communicate sensed values more easily and cost-effectively within a building. Using powerful computers and mass storage devices, the BAS can effectively process sensed values in creating rich and useful applications and knowledge. The building industry, which traditionally is very conservative, is slow to adapt, and first-cost conscious, finally having a major reawakening driven by the potential future that can be realized with the use of various types of gas sensors. Within buildings and outside, personal mobile device can sense, track, and monitor level of healthiness as captured in Fig. 1 depicted by different elements of sensing applications within the "Health" box or safety level as indicated by elements within

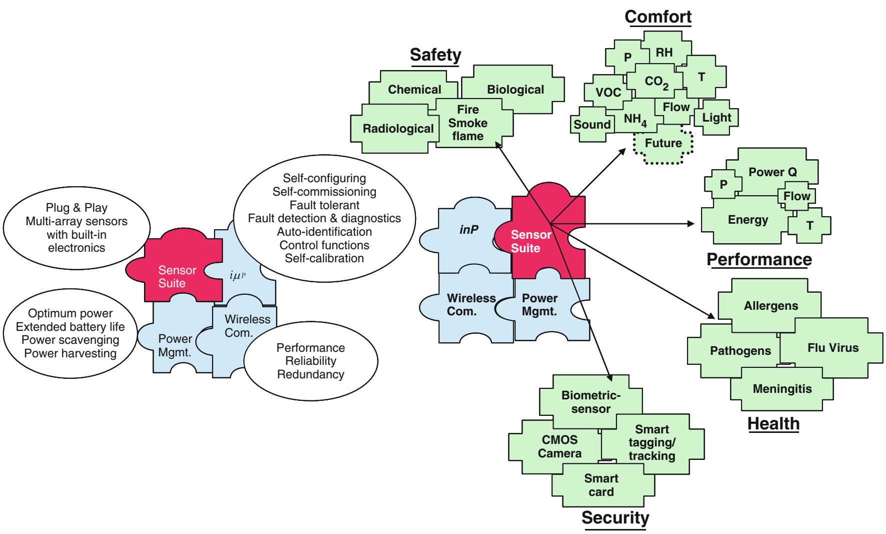

Fig. 1 Microsystems platform for sensing applications

the "Safety" box. Using same building blocks of Microsystems, various types of sensing applications can be packaged as shown in Fig. 1 [4].

While the future sensing applications are only limited by human imagination, the current scope is dictated by the legacy of the past. Although the drivers for rapid applications growth are plentiful, buildings are still lethargic and slowly overcoming the inertia of embracing new sensing technologies. However, this will change as soon as the industry reaches a threshold where demand for new applications exceeds past expectations. Following is an attempt to discuss such solutions and applications in today's buildings and beyond and more interestingly, what to expect in the future – only possible because of current and future sensor technologies.

Today, the most common sensing application in a building is dominated by space temperature control. Occasionally, relative humidity is added as a comfort variable. In a temperature centric building control system, a three-tier BAS is used. At the lowest or local level, the goal of sensing application is to maintain space temperature either by varying the flow rate of cooling or heating medium while keeping the temperature of that medium fixed or by varying the temperature of that medium while keeping the flow rate fixed.

In the future, sensing applications in a sustainable building will dramatically change. For the local comfort, additional variables will be added such as indoor air quality, often measured by CO_2 and TVOC. The result will be a complex mix and use of multiple variables that need to be sensed and controlled, and such application requires a new technology platform, for example, a Microsystems or a Nanosystem. Most dramatic change will emerge as a result of building's ability to sense the presence of individual occupant at a specific location and tailor a comfort, security, and safety solution that is suited for that particular individual via Smart Phone applications, for example. This will require execution of advanced algorithms such as adaptive learning by observing past behavior of an individual occupant. Imagine that in case of an actual fire breakout, the BAS activates floor lighting, just like in an aircraft, and guides people in the surrounding areas to the nearest fire exit. Imagine a simple building water cooler that has embedded Microsystems chips that measure, process, and communicate water flow rates, water temperature, and even water quality to a BAS for further system level processing. The results can detect problems with water quality or flow or even not having right temperature. Fixes can be made to provide fresh and good quality water throughout the building.

Building, in addition to its traditional role of providing comfort, shall be able to offer more granular knowledge-based solutions that are related to healthy environment, security, and life safety. The various embodiments of how the future building sensing solutions will look like are shown in Fig. 2 [5].

Using Microsystems as a technology platform [6], buildings will be able to offer three categories of solutions such as for healthcare, building environment that includes operation, and overall sustainable environment.

Based on vision and above examples, it is clear that in a future building and home, more advanced applications will be needed that can be categorized as

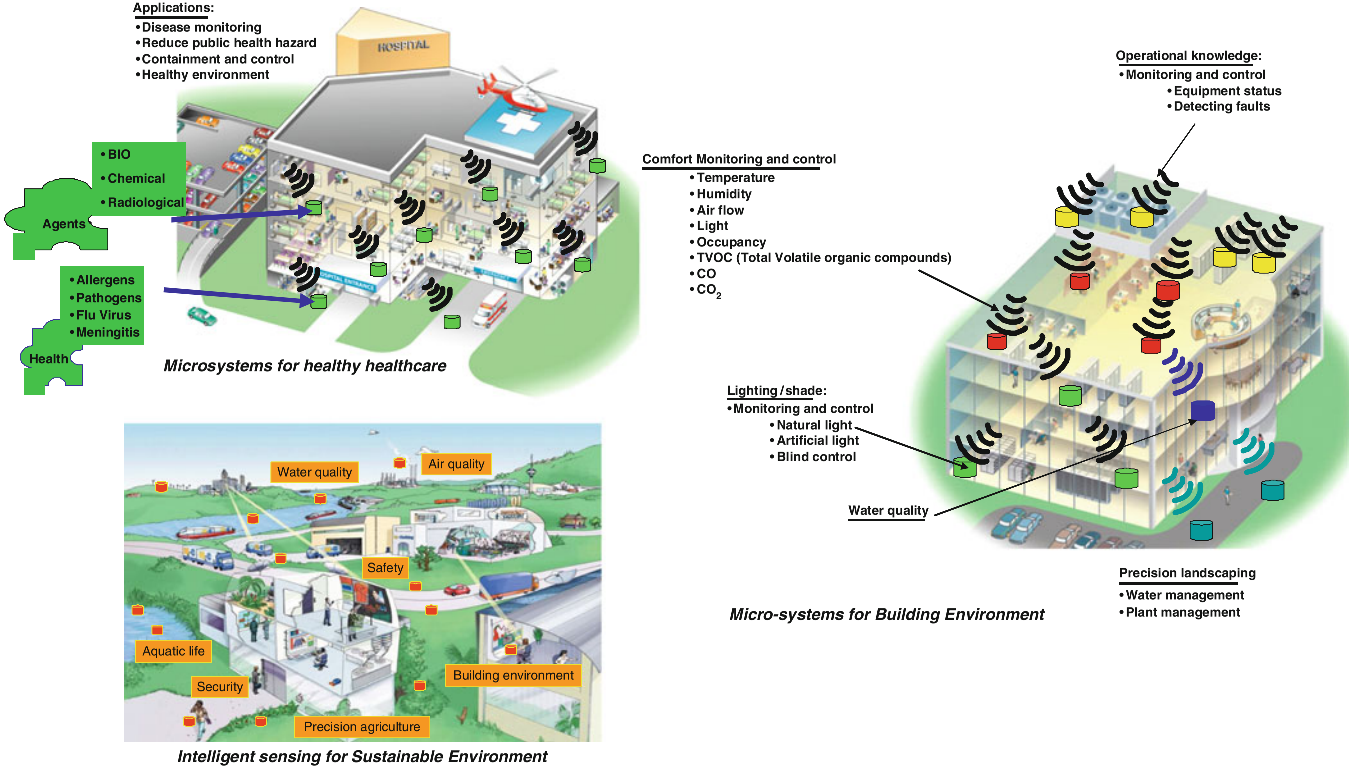

Fig. 2 Various embodiments of building microsystems environment

follows and includes both traditional domains such as comfort and energy management but new domains such as health and building that knows its occupants.

3 Sensing Need for Specific Applications

3.1 Comfort

Emphasis will be to measure comfort more routinely as compared to the present practice of measuring temperature. Sensing needs to calculate comfort shall include more variables such as relative humidity, TVOC, and CO_2. Mean radiant temperature (MRT) is also a variable that may be needed to measure in order to quantify "comfort" accurately. In some special cases, other chemicals may be needed to be measured such as CO or Ammonia (NH_3). The definition of comfort may even include light level, both natural and artificial, and sound.

3.2 Health

In certain facilities such as health care, educational, airports, train stations, etc., outbreak of air/water-borne diseases is common. In such facilities, health sensitive sensing may be needed for early detection of such viruses that may pose serious health risk to the population or even cold flu virus that may impact a company's productivity. So the sensing need for a healthy environment will become more prevalent. A future building management systems (BMSs) need to sense, monitor, analyze, and report on the overall health of the building environment.

3.3 Energy Management Applications

Sensing needs for energy management applications have seen tremendous growth in recent years. The building energy performance is a core functionality of such applications that require sensing, monitoring, and analyzing building's energy consumption and performance characteristics. For that building senses power consumptions at a main or primary power control panel but also more and more throughout the building at the equipment level such as chillers, fans, pumps, and lighting. A more granular tertiary level power monitoring is emerging and that is to measure power consumption for every electrical outlet. The level of sensing should match the overall goals of energy management applications in terms of what types of knowledge can be extracted and utilized by the applications in order to enhance overall building energy performance.

3.4 Security

Next generation buildings will require advanced security above and beyond what has been the norm today for basic property and asset and people protection such as burglary and thefts. Terrorism threat, protection of corporate intelligence, and need to safeguard people from violent criminals who are often driven by a social cause or personal grudge or revenge are driving the need for next generation building security. The scientists and technologists are working to secure a landmark building against a possible attack by a hijacked airline that closely approaches and endangers building by remotely taking over the control of such an airplane in order to avoid collision.

More incremental approach shall see wide usage of smart cameras, RFID or similar technology to track and tag people, biometrics, real-time data analytics, and extracting knowledge from video and picture streams. The overall results can then create several layers of security that are needed to protect people, asset, specific locations or zone, building, and the entire enterprise. Tracking and tagging people, without compromising privacy issue, is a key sensing requirement that can make significant improvement in overall security of company's intellectual intelligence and data by linking people to location, time of day, specific usage of a device, and activity.

3.5 Life Safety

Building life safety such as fire protection applications will continue to use core-sensing technologies such as photoelectric, ionization, CO, temperature, rise in temperature, and optical for fire detection. The applications fields in fire protection will become very interesting again because of the ability to combine sensing, processing, and communication functionalities in a single platform.

Examples are detecting or pinpointing the root cause of fire and its location or eliminating false alarms. Both goals often conflict to each other. For example, cooking smoke, excessive heat, welding smoke, fibers, dust, excessive moisture or heat, process exhaust gas all can falsely indicate fire, but at the same time smoke from cooking can also really indicate the presence of a fire. In order to make a distinction between false and real fires, real-time processing of advanced algorithms that is built into sensing is becoming more prevalent.

On top of things, life-safety sensing is going to include a building internal GPS in order to locate it. Not only that, advanced building modeling technology shall be able to create a virtual building that will provide information as what sorts of materials or processes are adjacent to the sensor. Hence, it will be possible not only to pinpoint the location of the fire but also to assess the fire hazard by knowing the surrounding environment.

The location of people and linking that information with the life-safety sensor reading and its location can create a dynamic building evacuation plan. Buildings floor like an airplane can literally light-up and instant message on mobile phone can provide direction to evacuate.

4 Building That Knows You and Your Physical Environment

A host of new applications shall emerge that will radically change the way the occupants are connected to their building environment. Using same core sensing that have been described above such as comfort, health, life safety, and security but by also sensing the location of a person and what surrounds him or her, BMSs can finally achieve the goal of knowing and serving its main clients or the occupants. The principal behind such integration between human occupant and building relies upon the fact that it is possible today to sense the surrounding, the needs of the occupant, and data that measures human comfort or health. It is possible to measure indoor environment quality, the location of a specific occupant, and also what surrounds that human occupant – carpet, building materials, exposure to any processes, equipments, external environment such as lights, sounds, etc. All these information along with the sensing can determine whether we are able to maintain the IEQ or not, and if not, what could be the main reason behind that. Could carpet be the cause based on TVOC? Or if we sense higher concentration of SO_x, then an adjacent industrial process should be investigated.

The building should have the ability to understand the behavior of its occupants and adapt to accommodate what occupants really need. Again, for example, using the basic sensing components, new applications will be able to adjust the blinds or shades in the late afternoon to provide the maximum natural light from the top portion of the window but block any direct sun on the computer screen or face by knowing the orientation of the office and seating configuration. In this example, lights need be measured – both natural and artificial and at the desk. The knowledge of occupant's preference of a cool office or warm environment in a late afternoon is also required. This knowledge can be extracted from a priori set of data that captures how occupant wanted space temperature or set comfort parameters in conjunction with the time of day and external environment conditions. The sensors, therefore, are required to measure localized external conditions. The rest will be to use advanced algorithms to map the comfort parameters that the occupant wanted and external conditions. Once such mapping is done, the algorithm then needs to optimize a solution that matches occupant's requirements but in a most cost-effective way. In our example, more natural lighting will lower the lighting cost but also increase cooling cost due to solar gain. So the BMS needs to reduce the overall energy cost but as an optimal combination of cooling and lighting energy.

5 Carbon and Sustainability Footprint

Perhaps, the most interesting areas where sensing applications will make most profound impact are related to carbon and sustainability in order to track, monitor, and manage them. A host of sensing technologies is emerging to measure carbon and green house gas (GHG) emissions. But an interesting factor that shall largely define the success of such technologies is not based on their performance but how affordably they can offer solutions in the market place. In this sense, Microsystems are already making its mark. Companies have developed low cost tiny power meters that can be embedded into an electrical outlet and at a fraction of a cost of regular meter. Such meters include wireless technologies or transmit measured power consumption at the outlet via Power line carrier or PLC. Besides electrical power, consumptions of other resources such as water, gas, and waste can also be measured at a granular level. Measurement of GHGs at the source will be possible. All these measurements will provide the ability to know and understand how, when, where, by whom, and what processes carbon is being generated within or outside (i.e., landscape) a building, and hence the chance of managing carbon and sustainability. Without a carbon and sustainability footprint infrastructure as sensing in its core, it is impossible to conceptualize a carbon-based society or economy.

6 Conclusion

The future building systems will largely depend on sensing as on of its core technologies. But the technology advancement in converging sensing with other functionalities such as communication, intelligent processing, and power management is the real key to imagine and implement a variety of applications affordably. And such applications are fundamental for a true smart or intelligent building. Microsystems and the future Nanosystems are the fundamental blocks to create applications for the future buildings.

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Requirements for Gas Sensors in Automotive Air Quality Applications

T. Tille

Abstract The implementation of gas sensors in automotive environments aims to improve the air quality for vehicle occupants. These sensors provide output signals corresponding to the gas concentration of the prevalent pollutant and the degree of odor contamination. This output signal is primarily used for the automatic recirculation control of the vehicle's Heating, Ventilation, and Air Conditioning (HVAC) system.

This paper outlines the requirements of solid state gas sensors for use in automotive air quality applications. Implementing these sensors in an automotive environment poses a number of challenges, due to the wide range of possible temperature, atmospheric pressure, humidity, and vibration profiles. Additionally, the sensors must fulfill strict cost requirements and meet high standards of reliability and quality.

Based on the example of a metal oxide semiconductor gas sensor, the technical specification, data interpretation, application criteria, and automotive suitability are demonstrated. Furthermore, a brief overview of the use of solid state gas sensors for detecting the indoor cabin air quality via odor pattern recognition is given.

Keywords Air quality, Automotive, Gas sensors, Requirements

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1 Introduction

Air quality sensors measure air quality in order to improve the comfort of a vehicle's occupants. These sensors provide an output signal corresponding to levels of pollution and smell, which is proportional to the gas concentration. To analyze the air quality outside the vehicle cabin, sensors based on the change in conductivity of metal oxide semiconductors are primarily used. These sensors have significant advantages compared to other sensors such as mass sensitive sensors or thermal conductivity sensors. The advantages of metal oxide semiconductor sensors are high sensitivity, and therefore a low detection limit for the gas to be detected, a low dependence on humidity and temperature, a long service life and relatively low product costs. However, disadvantages are a sensitivity drift with increasing life span and a limited reproducibility of the sensor properties. For this reason, metal oxide gas sensors are used to measure relative changes in gas concentration [1], for example in the detection of air quality changes for controlling vehicle air recirculation.

The operation of metal oxide gas sensors is based on the change in conductivity of a metal oxide semiconductor under the influence of reducing or oxidizing gases. In our case, these gases are the typical traffic exhaust fumes. As the temperature is an important factor influencing the behavior of the gas-sensitive metal oxide semiconductor, the metal oxide gas sensors is generally include a gas-sensitive layer with an additional heating element. The classical manufacturing of a metal oxide gas sensor uses powder metallurgy (pills or tubes form) or thick-film technology. In more advanced methods, a microstructured silicon substrate is applied to a metal oxide. Due to the limited space to be heated, and the shorter distance between heating layer and the sensitive surface layer, the necessary heating power of microstructured sensors is lower than that of conventional sensors. The design of a metal oxide gas sensor in microstructured silicon technology is illustrated in Fig. 1 [1].

As gas-sensitive materials metal oxides such as SnO_2, ZnO or WO_3 is mainly used, as well as mixed oxides of different metal oxides. The gas-sensitive metal oxide layer is contacted by a structured metallization, for example of platinum. The metallization and the gas-sensitive layer are electrically isolated from the heating layer (e.g., platinum meanders) by a passivation. Reducing gases (e.g., CO, C_xH_y)

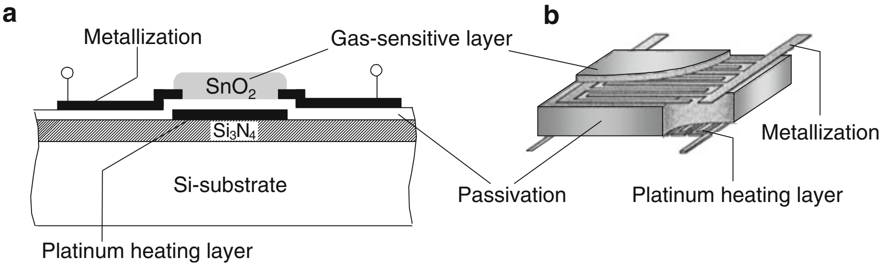

Fig. 1 Schematic illustration of a microstructured metal oxide gas sensor (**a**) Cross section, (**b**) Visualization of the metallization as interdigital structure, and the heating layer as platinum meander structure [1]

result in an increase in conductivity; oxidizing gases (e.g., O_2, NO_2) produce a reduction in the conductivity of the metal oxide, which acts electrically as an n-type semiconductor.

At the semiconductor surface (here SnO_2), oxygen is adsorbed from the ambient air. The adsorption energy level at the semiconductor surface is below the Fermi energy of the n-type semiconductor, so the electrons are absorbed by the semiconductor and negatively charged oxygen forms. With the release of electrons from the semiconductor, a depletion of electrons at the semiconductor surface is caused, resulting in a reduction of conductivity and an increase in electrical resistance R_S of the metal oxide semiconductor. If the semiconductor surface now comes into contact with molecules of a reducing gas (e.g., CO), these react with the adsorbed negatively charged oxygen to negatively charged CO_2. The negatively charged CO_2 has a higher energy level than the Fermi level, so electrons are supplied to the semiconductor, which results in an increase of conductivity. The now uncharged CO_2 desorbs from the semiconductor surface and the adsorption site can be reoccupied by new oxygen. The time available for the conductivity change is determined by desorption of CO_2 and the renewal of the adsorption sites by oxygen. In the following section, a technical specification for an air quality sensor for use in a vehicle is described.

2 Technical Specification

2.1 Functional Requirements

Table 1 gives an overview of the technical specification of a standardized automotive air quality gas sensor [2], which is explained in more detail in a follow-up.

For the detection of smell situations specific to traffic, emissions from petrol and diesel vehicles are primarily used. Representative substances in waste gases of gasoline vehicles are carbon monoxide (CO) and certain hydrocarbons (C_xH_y). For diesel vehicle exhaust emissions, nitrogen oxides (NO_x) are suitable as

Table 1 Technical specification of a standardized automotive air quality gas sensor [2]

Property	Value
Sensitivity 1st Gas (CO)	<1 ppm
Sensitivity 2nd Gas (NO_2)	<50 ppb
Sensitivity 3rd Gas (NH_3)	<50 ppb (optional)
Cross sensitivity	Low
Contamination	None
Response time t_{90}	<1 s
Ambient temperature ϑ_A	$-40°C \leq \vartheta_A \leq 85°C$
Storage temperature ϑ_S	$-40°C \leq \vartheta_S \leq 90°C$
Relative humidity H	$5\% \leq H \leq 95\%$
Operating voltage V_B	$9.0\ V \leq V_B \leq 16.5\ V$
Maximum voltage V_{Max}	18.5 V (1 h); 26.0 V (1 min)
Power consumption P_{Max}	<1 W
Interface	LIN 2.0 [3]
Plug	AMP2-967642-1
Pin connector	Terminal 1: Clamp 15, Terminal 2: Clamp 31 Terminal 3: Output
Plug frequency	$\geq 10\times$
Mounting	Bayonet socket and dovetail guide
IP protection classes	IP64 + IP67 [4]
Identification marking	Interchangeable inserts or labeling with ink/laser
Dimensions	≤ 45 mm $\times$ 35 mm $\times$ 25 mm
Weight	<20 g
Recycling	End of life vehicle (ELV) directive [5]

indicator gases, particularly nitrogen dioxide (NO_2). In order to make an appropriate evaluation of the gas concentration, the CO sensitivity of the sensor should be less than 1 ppm and the NO_2 sensitivity less than 50 ppb. Furthermore, for air recirculation control, smell situations are also of interest, which arise, for example, through agricultural conditions (manure). The detection of these situations through a multigas air quality gas sensor is optional. To identify manure smell situations, ammonia (NH_3) can be used as an indicator gas, which is detected with a sensitivity of less than 50 ppb. Other odor-specific concentrations of indicator gases or total concentrations can also be used for the detection of agricultural odors.

The multigas air quality sensor should have a constant sensitivity at high life time without the occurrence of contamination effects; the sensor signal should exhibit a low humidity and temperature dependence. The cross sensitivity to other gases should be low and well defined. In order to achieve a prompt response of the recirculation flap in the application, the response time of the air quality gas sensor should be $t_{90} < 1$ s. The ambient temperature of the sensor is in the range of $-40°C \leq \vartheta_A \leq 85°C$. The storage temperature is in the range of $-40°C \leq \vartheta_S \leq 90°C$. The sensor needs to withstand a maximum temperature of $\vartheta_{Smax} = 90°C$ for a period of 2 h (in case of vehicle repainting). The air quality sensor must be designed for a relative ambient humidity range of $5\% \leq H \leq 95\%$.

The operating voltage of the sensor is in the range of $9.0\ V \leq V_B \leq 16.5\ V$. The sensor must withstand a maximum voltage of $V_{Max1} = 18.5$ V for a period of 1 h