# An Overview of Applications and Integrated Circuit Design Techniques for Semiconductor Gas Sensors

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***Abstract*—A gas sensor as the device that detects the presence and quantitatively measures the concentration of the certain gas analyte is in pervasive use even nowadays. Nevertheless, with further technological advancement which will imply smaller form factors, lower power consumption and reduced unit prices, this sensor type is expected to become ubiquitous in the Internet of Things era. Semiconducting metal oxides are currently considered as the most promising sensing material to fulfill the foreseen agenda of gas sensor omnipresence. One of the major factors is the processing compatibility with CMOS fabrication technology which allows sensor conditioning and interface circuitry to be cointegrated onto the same chip. This paper gives a brief snippet of some semiconductor gas sensor applications which range from industrial safety and security, over use in health care and medical, all the way up to air quality and environmental monitoring, and automotive. An overview of the MOx gas sensor support circuits with an accent on integrated implementations is also scratched.**

***Index Terms*—Gas sensors, applications, signal conditioning, interface circuitry, chemiresistor, semiconducting metal oxides.**

## I. INTRODUCTION

Our society is in the midst of the so-called sensor revolution: the Internet of Things (IoT), comprising smart appliances and smart gadgets, as well as ever more powerful wearable and mobile consumer devices fuel the demand for smarter sensor solutions. Applications of gas sensors which provide information about the presence and concentration of a particular gas or gases are virtually countless. These gas sensors not only have the potential to improve the service quality in numerous existing fields, but are also anticipated to be the driving force for many novel use-cases in the near and foreseeable future.

Historically, gas sensors were built as discrete components and reserved for relatively low-volume markets. However, a prospective single-chip integrated solution with a low unit cost, slight power consumption and small form factor would lead to their omnipresence in consumer and industrial electronic devices, along with probable pervasive use in a variety of areas spanning from agriculture to automotive and from environmental to healthcare. This will probably occur in the next decade when certain types of gas sensors are expected to become just as common as humidity or temperature sensors are today.

Miniaturization of gas sensors drives the development of electronic noses in miscellaneous fields. Such noses contain an array of dozen or more sensors, which dominantly exploit gas sensors based on chemiresistive semiconducting metal oxides.

This manuscript is organized as follows: Section II elaborates on contemporary semiconductor gas sensor applications, while the following Section III gives an elementary overview of the support circuits. Finally, Section IV concludes the paper.

## II. APPLICATIONS OF SEMICONDUCTOR GAS SENSORS

The current global gas sensor market size has been roughly estimated [1], [2] to be worth somewhere in-between one and two billion euros and is anticipated to have the annual growth rate of about 5-10% in the forthcoming decade. This effective market doubling in the next ten years is partially going to be driven by regulatory initiatives in developed markets which will lead to increased demand for smart and wireless gas sensors. The major factors driving the growth besides increasing enforcement of health and safety regulations by governments and continuous development of ever cheaper and miniaturized gas sensors, is also the raised awareness of indoor and outdoor air quality control among general population.

The single most significant obstacle on the road toward more widespread use of gas sensors is their price. Cost of the majority of gas sensors on the market today is in a range of a dozen of euros. However, almost exclusively, these sensors, which are discrete components, are embedded in instruments that bring the price up to and excess of hundreds or even thousands of euros. This greatly limits their application areas.

The future gas sensor market expansion is also likely going to come through unit cost reduction which will be achieved by further sensor miniaturization and co-integration with signal drive and conditioning, as well as processing circuitry. Such solid-state gas sensors [3] integrated alongside standard low-cost manufacturing technology (like CMOS process for example) flow with price tags which will be as low as couple of euros per piece including read-out interfaces [4] would open several high-volume markets. Namely, towards the end of the next decade, gas sensors could potentially be included into many consumer electronic products such as laptops, tablets, cell phones and even smart watches. In this aspect they could follow related success stories of low-cost temperature, barometric pressure and/or humidity sensors which all incorporate the sensing element together with surrounding electronics.

Certainly, cost factor is not the only impediment to making a commercially successful sensor. Sensor characteristics are generally summarized through its “4S”: **s**ensitivity, **s**electivity, **s**tability and **s**peed of response and recovery. Besides these metrics, also of paramount importance is sensor size and power consumption, especially in mobile or wireless sensor network battery-powered applications, and other mass markets like the Internet of Things (IoT) or wearables. The last requirement is particularly challenging when one considers that for optimum performance the majority of gas sensors must be heated by a separate heating element to operating temperatures which are well-above the ambient. Notwithstanding, the intermittent gas sensor operation is the usual method to relax this concern.

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Nowadays, semiconductor gas sensors are applied and find their use cases in a wide variety of fields. As an illustrative starting example, at the beginning of the periodic table of elements sits hydrogen with the atomic number 1. It is the lightest of all elements and, since on standard pressures and temperatures hydrogen with molecular formula $H_2$ is a colorless, odorless and tasteless, it cannot be detected by human senses. Moreover it is highly combustible and flammable gas. With air the hydrogen forms explosive mixture which may be ignited in a spontaneous reaction. On the other hand hydrogen finds its direct end use cases as fuel and propellant in hydrogen powered vehicles and aerospace operations, respectively. Indirectly hydrogen observation is important in plethora of spheres ranging from everyday ones like detection of environmental pollution or indication of certain diseases up to an early sign of fire or reactors safety inside nuclear power plants. Hydrogen presence detection and concentration quantification also finds its applications in semiconductor manufacturing and revealing of impending transformer failure in electric power plants.

Therefore the detection of hydrogen leaks and measurement of its concentration is essential from production and storage, to transportation and use in both mobile and stationary applications. Hydrogen gas sensors [5] are hence necessary in each sector of the emerging hydrogen economy, in which hydrogen gas is exploited as an energy carrier and as a chemical reactant, as they monitor safety in production plants, storage tanks, refueling stations and combustors and engines themselves.

Totally different, but equally illustrative example are the so-called volatile organic compounds (VOCs), which are basically high vapor pressure organic chemicals. VOCs are both numerous and ubiquitous, and while some of them can cause harm to human health, others present a danger to the environment.

Typically harmful VOCs are not acutely toxic, but if generated inside houses may cause sick building syndrome. Some of them can have compounding long-term health effects and are even carcinogenic. On the other hand, VOCs can also be found inside the human body. Particularly, a breath contains thousands of VOCs which can either originate from within the body (endogenous VOCs) or from external sources such as diet, prescription drugs or environmental exposure (exogenous VOCs). More details on the breath biopsy will be given later, but semiconductor gas sensors that can detect total VOC (TVOC) concentrations indoor, or specific compounds during breath screening are fundamental component in both scenarios.

Apart from single dedicated gas sensors there is an increasing desire to simultaneously measure more than one gas. In other words, there exists a growing demand to have multi-gas sensing systems with roughly speaking a dozen of sensors (which may also include ambient temperature, humidity and barometric pressure). Such an array in which every individual sensor is not specific to a particular gas, but rather has different sensing pattern, is the basis for the fundamental sensing system commonly known as “electronic nose”. In combination with a pattern recognition module, the e-nose [6] is considered to be a genuine artificial olfaction structure for odor characterization.

Both, individual gas sensors and gas sensor arrays, nowadays are in pervasive use in a variety of spheres. An outlook of some application areas is given in the following subsections.

### *A. Safety and Security*

A snippet of applications of hydrogen gas sensors was given above. As seen, their main purpose is safety in various places. Hydrogen is not an exception here. There are other examples of hazardous and toxic gases that should be kept under control. As is well-known the demand and application of gas sensors in practice began with the inflammable gas alarms [7] to protect people from fatal gas hazards such as exposure to poisonous gases and gas explosions or incomplete combustion accidents. Fire alarms usually combine smoke and/or thermal detector together with a semiconductor gas sensor and are literaly found in every place where humans live, from residential buildings and hotels to schools and office space. Gas sensors are found in homes for, e.g., monitoring flammable gas level inside gas-fired boilers. There has also been an increasing demand for workplace safety in coal mines or certain industries like petrochemical, to name a few. Actually, the success story of semiconductor gas sensors can be partially explained by their high sensitivity to a broad range of inflammable and toxic gas species and their simple detection principle relying on changes of electrical conductance due to interaction with the gas.

Historically, this was actually the first use case of gas sensors that exploit semiconducting metal oxides. The pioneering work of Naoyoshi Taguchi in Japan led to electrochemical gas sensor discovery being the first commercial device [8] that was used to detect low concentrations of combustible and reducing gases. Later he founded the company Figaro Engineering Inc., which is still today the largest manufacturer of semiconductor gas sensors worldwide. The original Taguchi gas sensor (TGS) is a highly-sensitive device, rather than highly-stable, making it ideal for gas alarms and economical detection of potentially explosive concentrations of inflammable gases in general.

Even though traditionally, single gas sensor was responsible for a particular safety monitoring purpose, integrating multiple gas sensors is gaining popularity with the increased availability of affordable sensors. For example in a boiler combustion process, there is a requirement to measure hydrogen or methane, as well as carbon oxides (monoxide/dioxide) and even oxygen.

Semiconducting metal oxide gas sensors can be employed to construct multi-sensor units (marketed as FireNose) that are utilized to discover and discriminate between known and unknown gases in harsh and uncontrolled conditions [9] or mobile (rescue) robots for gas leak detection and localization [10], as well as toxic smoke real-time mapping which could serve as an aid to firefighter brigades and teams. The field of mobile robotic olfaction customarily considers gas source localization and gas distribution mapping as two of its main tasks.

Oxygen sensors are indispensable in non-air breathing gas scuba diving or other hyperbaric use cases. In every such scenario, it is essential that the constituents of the breathing gas mixture are precisely kept at the correct concentrations.

Finally, a breathalyzer (a portmanteau of breath and analyzer), i.e., a portable handheld breath alcohol checker that detect ethanol vapour in human breath for preventing drunken driving are also examples of semiconductor gas sensors used for safety purposes. Interestingly, the very same semiconductor gas sensors are not only exploited inside car ignition locking system but are also utilized inside a brewing process control.

### *B. Health Care and Medical*

While some gases are toxic and hazardous, others may be vital for life and symptomatic of health conditions. Perhaps the most dominant gas sensor overall by gas type is the oxygen one. Besides industrial applications where it is widely used in automotive, building automation for smart cities and food and beverages, it is beyond doubt the leader in health and medical equipment. In this area, the oxygen sensors are used in incubators and other hypoxic life science products, like patient and breathe monitoring systems, anesthesia monitors, lung function diagnosis systems, respirators/ventilators, and oxygen concentrators. Besides oxygen, other anesthetic and respiratory gases are regularly monitored during operations.

Detection of disease-related gases is drawing increasing attention for medical purposes. Exhaled human breath contains thousands of different volatile organic compounds (VOCs) which are usually measured in the sub-ppm level or even lower concentrations for healthy subjects. The attractiveness of VOC analysis comes from its absolutely non-invasive character and can be applied to any stage of life from early childhood to late adulthood. Even though the correlation between certain disease and some VOCs was well known for more than a century, only modern instruments based on semiconductor gas sensors can give quantitative measures necessary for strict clinical practice. Independent clinical trials [11] have shown the possibility of using breath for detecting serious illnesses, such as different types of cancer, diabetes, Alzheimer's and Parkinson's disease, multiple sclerosis, tuberculosis, chronic kidney disease, among other. An additional burst to the interest in VOCs examination and analysis for medical purposes has been provided by the development and the diffusion of solid-state gas sensors [12], therefore in the foreseeable future breath tests are expected to become just as common (if not more) as blood tests are today.

Specific breath biomarkers can not only indicate a presence of some diseases, but can also reflect general physical condition. An example of such devices are portable acetone analyzers that measure the ketone level and calculate body fat burning rate just from exhaled breath. These pocket-sized accessories that monitor fat metabolism and levels of ketosis are in a widespread use in various diet and fitness programs.

Besides being applied in healthcare, gas sensors are, along the similar path, also more and more part of the fast developing wearable biosensors market. These wearable biosensors [13] are complex miniature devices that incorporate wireless communication modules for transmitting sensor data to computing infrastructure. A variety of substances are used in such sensing devices. As an illustration, for semiconducting oxide materials this is a real challenge as it is necessary to reduce the sensor operating conditions to room temperature. One way to achieve this is through nanostructures, like graphene [14] or nanowires. Recently, even flexible and stretchable self-heating metal oxide (MOx) gas sensing platform [15] has been demonstrated.

Compared to their industrial counterparts, the development of wearable gas sensors needs to address additional challenging requirements, including lightweight and small form factor, low operating temperature, low energy consumption, and mechanical robustness upon various skin deformations.

### *C. Air Quality and Environmental Monitoring*

Pollution and urban air quality are the major environmental risks [16] to public health. Gas emissions are responsible for a variety of respiratory illnesses and environmental problems, such as acid rain and the depletion of the ozone layer. Pollutants may be released from natural sources and they can be man-made or anthropogenic. Natural sources of air pollutants are lightning, soils, fires and volcanoes while anthropogenic sources incorporate emissions from human activity — for example, exhaust gases from transportation, chemical accidents or industrial actions such as power plants and landfill sites.

Many countries express air quality in terms of the air quality index which is calculated based on concentrations of several key air pollutants [17] such as ground-level ozone, particulates, sulfur dioxide, carbon monoxide and nitrogen dioxide.

Some of these are powerful oxidizing toxic gases that have noxious effects on both vegetation and human health. Ozone, as a secondary pollutant, for example, has become of growing importance in ambient air during the last decades [18] and has been identified as the main agent responsible of heavy peaks of pollution in urban atmospheres during warm sunny periods.

Commonly, data on air quality are collected from monitoring stations, which contain a sensor for each pollutant or a gas sensor array [19], just like in electronic nose. Currently, many monitoring systems consist of a static network of air quality sensors that are distributed at key locations and can produce a spatially-resolved picture of pollution variations on the urban scale. Consequently, in order to obtain a truthful representation of the gas distribution and be able to locate gas sources, it is essential to collect spatially distributed gas concentration data.

Mobile robots equipped with gas detectors were also used in outdoor applications for pollution monitoring and source localization in public areas, surveillance of industrial facilities producing harmful gases, and monitoring of landfill sites. Portable electronic nose featuring on-demand operation [20] is particularly neat for the IoT and wireless sensor networks.

More recently, gas monitoring outdoors was also addressed using unmanned aerial vehicles (UAVs), commonly known as drones, although with far more power and size constraint [21] limitations placed upon gas sensors. In addition to air quality and environmental monitoring in general [22], an individual and a swarm of micro and nano drones [23] have also been employed for volcanic gas sampling, localization of fugitive emissions, early fire detection, precision agriculture, landfill monitoring and mine blasting, among many other use cases.

The tiny form-factor and maneuverability of UAVs allow sensing of hazardous environments inaccessible to terrestrial robots. Miniaturization of semiconductor gas sensors made possible equipping drones with olfaction capabilities which can be exploited in myriad of applications. For example, in the aftermath of an earthquake or explosion drones could navigate such scenarios much faster and sample the space in 3D.

Both indoor and outdoor air quality concerns are driving the applications not only in environmental monitoring but in commercial building automation too. Therefore, gas sensors are experiencing a high demand in Heating, Ventilation and Air Conditioning (HVAC) control systems as they facilitate intelligent ventilation control based on gas concentrations.

Furthermore, air quality sensors are usually incorporated into air cleaners, deodorizers, ionizers, purifiers and air sanitizers for energy saving purposes or just plain amenity also.

### *D. Automotive*

Modern cars include abundance of gas sensors located both inside and outside of cabin which serve either as a commodity or an essential indispensable part in the engine compartment.

It is nowadays fairly common to have the electronic control unit (ECU) of a car to automatically close and open the fresh air flaps [24], depending on the ambient gas concentration measured in the air-intake manifold under the hood of the car. Typical gases that are monitored are combustion-related compounds. Therefore, a pair of CO and $NO_2$ sensitive sensors are regularly installed into a damper system to determine the "outside air quality level". In addition, car interior could also exhibit multiple sources of disturbing gases like cigarette smoke, food odor, or bioeffluents, which are detected by sensor system directly mounted within the cabin of a passenger vehicle to define the "inside air quality level" thus requiring more sophisticated air and climate-management concepts. This means that based on interior and exterior semiconductor gas sensor readings contemporary automotive heating, ventilation, and air conditioning (HVAC) systems can decide to take no action, close the recirculation flap in case of bad outside air quality level, increase air exchange rate in case of bad inside air quality level, or start active air cleaning in addition to the flap closure in case of bad inside and outside air quality levels.

Besides external and internal air quality level monitoring, just as important are oxygen sensors, for this particular application more frequently referred to as the lambda sensor, where lambda ($\lambda$) refers to air–fuel equivalence ratio, which measure the exhaust-gas concentration of oxygen for internal combustion engines in order to calculate and dynamically adjust the air-fuel ratio so that catalytic converters can perform properly and work optimally. The lambda sensors, which are in modern cars more and more semiconductor based, make today's electronic fuel injection and emission control possible.

### *E. Industrial*

Applications of semiconductor gas sensors in industry are virtually countless and span across every industrial branch.

Mining and in particular, the underground mining exposes workers to flammable gas, asphyxiants, oxygen depletion and a range of toxic gas hazards. To keep miners safe, both fixed and portable detectors are deployed to ensure that if a dangerous condition arises, audible and visual alarms are generated so that evacuation can occur rapidly. Likewise, in gas and oil industry, whether upstream in the production process (exploration and extraction) or downstream (transportation, processing, storage) or around the distribution pipelines, many different gas detectors are used for process control as well as for staff and plant protection against explosion or the presence of toxic gases. Gas sensors are also used at rig and processing locations to monitor the concentration of the gases released into the Earth's atmosphere. Similar use cases of gas sensors for various process control and safety of the employed personnel are encountered in petrochemical industry too.

Apart from toxic and explosive gas detection for the purpose of domestic, industrial and public safety, semiconductor gas sensors are used in beverage and food industries to control the fermentation processes. A very interesting application is in intelligent food packaging [25] used to detect rotten or spoiled food using cheap gas sensors. For instance, these sensors can identify spoilage gases like ammonia in meat and fish products and can be read by smartphones. Even though the concept of food quality control [26] using gas sensors is already known for quarter of a century, it became economically feasible only recently. Eventually, these low-cost gas detectors with prices in the order of one cent might eventually replace the "use-by" date stickers, as much more reliable freshness indicator. As a consequence these sensors could partially reduce food waste, but more importantly cut the yearly number of food poisoning.

More advanced multisensor arrays inside an electronic nose have been applied to determine optimal beef aging time [27] and monitor meat quality as well as to control food in general.

### *F. Electronic nose (e-nose or eNose)*

A contemporary electronic nose system typically consists of a multisensor array, an information-processing unit such as an artificial neural network, software with digital pattern-recognition algorithms, and reference-library database of digital aroma fingerprint signatures. These systems have been designed specifically to be used in numerous application areas.

Even though different types of gas sensor are employed in e-nose systems, semiconductor-based gas sensors are preferred primarily thanks to their fast response and recovery times [28], but also because their small size, low manufacturing cost and acceptable power consumption [29] even for handheld devices.

Example use cases of electronic noses [30] practically do correspond to those of gas sensors themselves and include (in no particular order): explosive and flammable material detection for public safety and welfare as well as for passenger and personnel security in airline transportation; perfume and cologne development and choice of fragrance additives as well as personal application product enhancement and consumer appeal in cosmetics; ingredient or product consistency confirmation for brand recognition and consumer fraud prevention as well as detecting off-flavors and characterizing taste and smell to determine contamination or ripeness or spoilage inside food and beverage quality control assessment; safe food supply and corp protection, corp ripeness and preservation treatments for harvest timing and storage inside agriculture; checking product characteristics and consistency for processing controls as well as aroma and flavor uniformity across products, but also toxic gas leak detection and fire alarms for the purposes of safety, security and proper work conditions inside any manufacturing industrial sector; pathogen identification and disease detection together with patient treatment selection and prognoses as well as checking nutrition status, organ failures, disease diagnoses, metabolic disorders and general physiological conditions inside medical, healthcare and clinical sectors; biological and chemical weapons and explosive materials detection in defense and military sectors; quality control of drug purity including formulation consistency and uniformity in product mixtures for pharmaceutical industry; among many other example cases.

## III. Gas Sensor Signal Conditioning & Interfaces

Mainly, semiconductor gas sensor interface circuitry depends whether hybrid or monolithic approach has been used.

*1) Hybrid:* Traditionally, integration is realized with the so-called multi-chip approach in which the sensor and circuits are designed and fabricated on separate chips. There are multiple advantages of this two-chip solution. First, this implementation scenario enables independent adjustment and optimization of the gas sensor and the interface circuitry thus providing much more flexibility in the design and fabrication which leads to shorter development cycles. Furthermore, if there is a problem with the sensing device, the same circuitry can be reused, thus enhancing manufacturing yield. However, extra cost is incurred by the complex packaging. Also, parasitic capacitances and inductances associated with long bonding wires and interconnect are undesirable and can give rise to increased noise and signal degradation. Additionally, the hybrid approach is less robust and more expensive with respect to single-chip implementation particularly when considering high volume production.

*2) Monolithic:* A more recent and a more advanced method is the so-called monolithic approach in which both the sensor and circuitry are designed and fabricated on the same substrate. This single-chip solution enhances the gas sensor performance by reducing its overall size, power consumption and noise. It is also more cost-efficient and hence more commercially attractive in high unit volumes. The additional challenges arise from limitation of process compatible gas sensor materials and prolonged and costly development cycle. Also, a potential fault in either a sensor or the nearby circuitry will result in the complete chip failure. Thermal isolation is crucial since the main challenge is that the operating temperature of the metal oxides exceeds maximum operating temperature of the CMOS-based silicon integrated circuits. But, if a proper isolation mechanism is employed [31], only several degrees difference between the sensor circuit and the ambient temperature can be achieved.

The main operating principles of chemiresistive gas sensors, including there semiconducting metal oxide sensors, is based on the change of conductivity/resistivity of the oxide on interaction with a gas and this dependence is usually proportional to the concentration of the gas. By the rule, the gas sensor itself has a bell-shaped temperature dependent response with a maximum at elevated temperatures. Therefore, semiconductor gas sensors also incorporate integrated (micro)heaters as well.

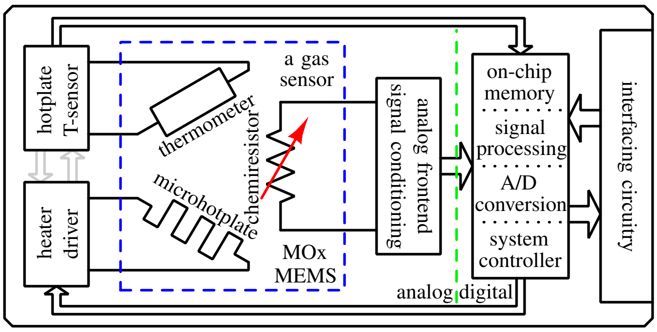

Fig. 1. A chemiresistive MOx gas sensor model and the surrounding circuitry.

### A. Heater Driving and Sensing Circuitry and the Controller

Since the gas sensor response greatly depends on the precise temperature, the heater driving and temperature control makes a crucial part of the overall gas sensor system. The temperature control circuitry becomes more challenging when it is taken into account that semiconductor metal oxide sensors can be operated either in isothermal (that is, constant temperature) or temperature-modulated regime, the latter being more complex but provides insight into distinguishing temporal response [32] pattern based on which different analytes can be discriminated.

*1) Heater Driver:* Heaters are driven either by a current or voltage source. Circuits are designed to provide a source either at a static (e.g., DC) or modulated (e.g., AC or pulsed) level. In case of a voltage drive, commonly a bandgap voltage reference and a current limiter are required to provide an accurate and stable voltage and avoid any overheating damage. In case of current drive, a current mirror is employed. In both cases it is desirable to measure the power through the heater and provide an indication [4] of temperature and general operating status.

*2) Temperature Sensor:* Since the sensing material temperature plays a vital role in improving the selectivity of almost any gas sensor, either a dedicated temperature sensor can be deployed or the change of heater resistance with temperature can be exploited to estimate the actual temperature of the heater itself. Even though separate temperature sensors bring additional circuit complexity & cost, they are often much more reliable approach especially when tied with the pulsed driving.

*3) Controller:* With the incorporation of a microheater and temperature sensor of some sort, there are several ways how to monitor and control the heater temperature. The heater can be controlled in binary on-off mode (also referred to as the “bang-bang” controller), proportional mode or proportional integral derivative (PID) mode which eliminates the steady-state error while offering rapid response time without overshoot. In case the temperature sensor readings are digitized and compared to a digital preset value, a digital controller can be designed to achieve very accurate and flexible soft-programmable control.

### B. Sensing Material Measurement and the Readout Interface

Interfacing circuitry design is one of the most challenging components mainly because it has to: (i) handle the precision and dynamic range of the gas sensing element whose baseline sheet resistance can vary from kΩ/□ all the way up to GΩ/□; and (ii) compensate for the drift in the baseline resistance of the sensing material. The simplest scheme involves resistance-to-voltage conversion either through a resistive voltage divider or a Wheatstone bridge. When seeking full integration, these techniques are not ideal as they require either a resistor bank circuit with very large value or a trimming or variable resistors to cover wide range and match the sensing material resistance.

Another approach is to use the resistance-to-frequency conversion instead, but in order to cover a very high dynamic range the parasitic capacitance associated with the sensing material has to be retrieved and isolated [33] to avoid resistance measurement contamination in the high frequency portion.

A relatively simple idea to use a logarithmic converter (utilizing exponential characteristics of a diode) to compress the large dynamic range but it inevitably compromises accuracy.

By the rule, contemporary sensors include the analog front-end circuitry which consists of amplifiers that increase sensor signal fidelity as well as analog-to-digital (A/D) converters.

Digital sensor platforms which are becoming increasingly popular [34] because they effectively co-integrate analog and digital electronics together with a microhotplate and the sensing elements onto a single die. They allow more advanced signal processing circuitry in the digital domain and also incorporate digital interface that greatly simplifies the integration into different applications, since the output signal can be directly used by customers without further processing.

## IV. CONCLUSIONS

Semiconductor gas sensors, also known as MOS sensors, that are constructed on the basis of a semiconducting metal oxide (MOx), detect gases by a chemical reaction that takes place when the gas comes in direct contact with the sensor.

Over the past several years they became pervading across many industrial sectors. One of the main reasons is cointegration with the nearby circuitry which triggered the constant improvement in performance in combination with ever lower price tags. This trend will most certainly continue in the future.

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