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Gas sensors 1. The basic technologies and applications

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This paper focuses on the technologies used for gas sensing, notably optical, electrical, mass-based and biological. Applications are summarized under the headings of healthcare, security, environment and processes, as a precursor to the more detailed consideration of gas sensor markets in Part 2, the following paper.

The survival of any system, whether living or inanimate, depends on its ability to maintain its "essential variables" within the bounds of viability. For a human being, these essential variables include such things as body temperature and heartbeat, the presence of certain chemicals in the blood, and so forth For a relatively simple system, such as a thermostat-controlled water bath or a central heating installation, there may be just one essential variable, namely the temperature of the bath or boiler.

In what is usually called a feedback loop, a sensor registers the value of the quantity to be measured within the system (the measurand) and a controller (regulator) is actuated to maintain that quantity at the required level.[1] For the thermostat-controlled water bath, this works as follows: some perturbation occurs (e.g., someone places a flask of cold water into the bath), the temperature falls, and the thermometer immersed in the water eventually registers the change

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[1] W.R. Ashby calls this "regulation by error".

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and thereby causes the appropriate device (in this example, it would be a heater) to be switched on.

For systems that have long response times such as the water bath, swifter and more precise regulation would be possible if some detector or sensor could predict the required change in advance (this is called "feed forward" control). A "smart" central heating system might include thermometers outside the building to better anticipate the likely heating requirements, and might be programmed with diurnal requirements, such as office hours, or even seasonal variations.

Living organisms have developed a host of sensors for the external world in order to warn them of danger. Whereas they alone sufficed for the survival of early man, these individual sensors are now complemented by an elaborate cultural apparatus—in other words, human culture has made survival a collective enterprise. But this in itself is often inadequate, and artificial sensors are needed—especially as our civilization has become more industrialized. Sensors for toxic gases provide warnings at concentrations well below the level of toxicity. Examples include carbon monoxide, which is a product of incomplete combustion, yet which we cannot smell. Carbon monoxide competes directly for the oxygen binding sites in the protein haemoglobin, found in abundance inside the red blood cells that carry oxygen from our lungs and distribute it throughout our body. We do not need to inhale very much carbon monoxide (the WHO recommended 8-hour exposure limit is 9 ppm, or parts per million[2]) to deprive our muscles and brain from their essential oxygen. Hydrogen sulfide is another very toxic gas, which we can smell at very low concentrations only briefly, for the nose itself is poisoned by it. In these examples, gas sensors directly enhance our own bodily capabilities. In other cases, they are carrying out tasks that a human would never be able to undertake.

In the next section of this article we shall describe the technologies of gas sensing, and in the final section we shall outline the main application areas. The applications are discussed in much more detail in the following article.[3]

The technologies of gas sensing

The basic construction of a gas sensor (or indeed any chemical sensor) is shown in Figure 1. The sensor is a transducer that typically converts the presence of certain molecules into an electrical signal. The filter ensures that the sensor only responds to the gas to be measured (sometimes called the measurand or analyte) and not to other gases or other variables. It may be a physical filter, permitting the flow of only certain molecules into the capture zone, or a more fundamental means of identifying the target gas by some unique property such as its optical absorption wavelength. Note that the output may be a single value, or a more complex, time-dependent signal, and may be electronically filtered or otherwise processed.

The most basic performance criteria of a gas sensor are shown in Figure 2. The ratio of signal-to-noise in the output is often used to characterize performance (see Yamazoe[4] and Manghani and Ramsden[5] for more discussion of performance criteria). There are of course

[2] J. Raub, *Carbon Monoxide* (Environmental Health Criteria 213), World Health Organization, Geneva, 2nd Ed, (1999).
[3] J. Hodgkinson et al., Gas sensors 2. The markets and challenges. *Nanotechnol. Perceptions* 5 (2009) 83–107.
[4] N. Yamazoe, Towards innovations of gas sensor technology. *Sensors Actuators* B 108 (2005) 2–14.
[5] S. Manghani and J.J. Ramsden, The efficiency of chemical detectors. *J. Biol. Phys. Chem.* 3 (2003) 11–17.

other important criteria, such as sensor size and power consumption, ease and cost of manufacture (and nowadays disposal), durability, lifetime etc. In this article, we shall not go into these other matters in much detail.

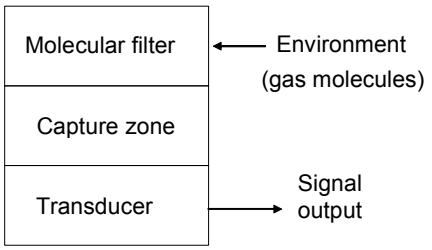

Figure 1. The basic components of a gas sensor.

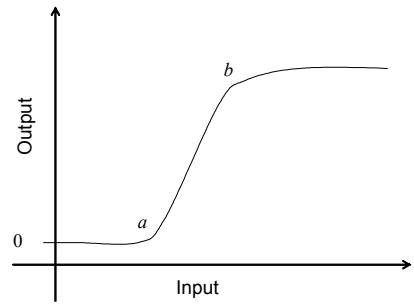

Figure 2. Sketch of a possible input-output relation for a sensor. Point *a* indicates the response threshold and point *b* indicates saturation. The ruling slope of the line connecting *a* and *b* is the responsivity, and the difference in their abscissae is the latitude. This diagram does not show more sophisticated performance criteria such as the detectivity.[5]

One of the key circumstances governing the choice of a particular technology is the background environment in which the gas to be sensed must be detected. The ability to discriminate between different gases is one of the essential features of the performance of a gas sensor. The starting point is to ask, what unique property distinguishes the gas to be detected from the rest of the environment? Once this property can be measured, the output from the sensor is compared with prototype outputs. The final result would be the identity of the gas and its concentration. The principle can readily be extended to deal with the detection of multiple gases.

The four main current and emerging technologies can be grouped into optical, electrical, mass and biological measurements. We shall deal with each of them in turn.

Optical technologies

All gases consist of one or more atoms, which in turn consist of nuclei surrounded by electrons. The electrons and any molecular bonds occupy distinct energy states, which can be excited by absorption of light—electromagnetic radiation—at characteristic wavelengths (see Table 1). This is the basis of several families of gas sensors. The capture zone (see Figure 1) is now simply a cavity containing the gas to be detected, which is illuminated by a spectrum of radiation. The example in Figure 3 shows optical absorption spectra of different gases in the so-called "fingerprint region". Here, absorption wavelengths depend on the chemical bonds between the different atoms present in the gas molecules, yielding the identities of the gases contained in the sample, and the strength of light absorption indicates gas concentration. A great deal of current research is focused on developing novel (tunable) lasers, which typically emit very

narrow bands of light whose absorption therefore can be highly discriminating between different gases (see next section). Nondispersive infrared sensing uses a narrowband filter to select an absorbing region of the spectrum, without resolving the spectral lines, and is therefore a simplified and hence a cheaper technology. Table 2 summarizes the absorption-based gas sensing techniques.

Table 1. Some gases commonly detected by optical absorption.

Spectral region	Gas species	Basis of absorption	Characteristics
Mid-infrared (IR)	CO, CO_2, CH_4, NO, SF_6, NH_3, H_2O, HCl, N_2O	molecular vibrations (fundamental)	strong absorption, many narrow lines
Near-infrared	CO, CO_2, CH_4, NO, SF_6, NH_3, H_2O, HCl, N_2O, O_2	molecular vibrations (overtone)	weak (~ 1/100) absorption, many narrow lines
Ultraviolet (UV)	O_3, H_2S, SO_2, NO, NO_2, NH_3, BTEX,[a] Cl_2	electronic transitions of energy states in bonds	strong absorption, broader lines

[a] Benzene, toluene, ethylbenzene, xylene.

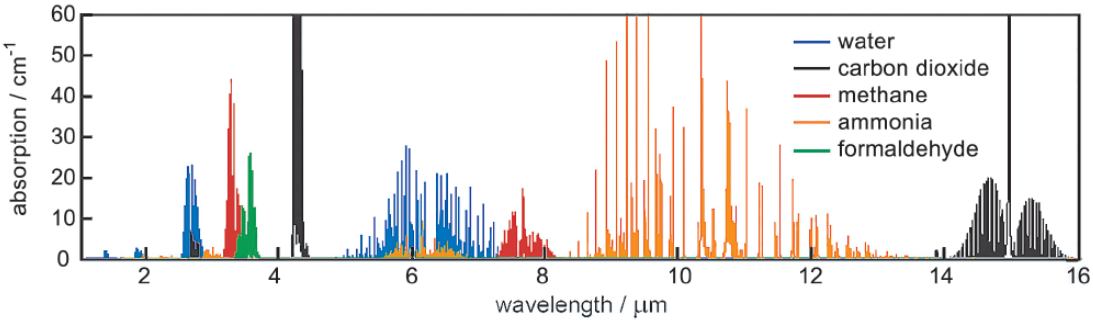

Figure 3. The infrared absorption spectra of several commonly detected gases.

Table 2. Commonly used absorption-based gas sensing techniques.

Technique	Principle of operation and comment
Nondispersive infrared, (NDIR) or ultraviolet (NDUV)	IR (or UV) light is absorbed by the target gas in the path between a broadband source and detector. The absorption waveband is selected using optical filters. A second reference beam can be used in a neighbouring (non-absorbing) waveband. Good for low cost, single component detection where there is little spectral interference from other species.
Spectrophotometry	Light from a broadband source is dispersed, for example using a grating or in a Fourier transform infrared (FTIR) interferometer. The entire spectrum is measured at a defined resolution. Good for multicomponent sensing.
Tunable diode laser absorption spectroscopy (TDLAS)	IR absorption using a tunable diode laser as the source. Resolution is very high, enabling measurement of a single gas line. High sensitivity is achieved by using multipass cells to increase the optical path length and hence the signal-to-noise ratio.
Cavity ringdown spectroscopy (CRDS)	Light is multiply reflected between two mirrors within a cell containing the gas sample. The decay time of the light is measured as it is absorbed with each pass. Effective path lengths of several km lead to high (one part in 10^{12}) sensitivity.

Sometimes the absorbed light is not merely degraded into heat, but may be re-emitted at a different wavelength (the phenomenon of fluorescence or photoluminescence). The emitted light can be detected and this forms the basis of another kind of sensor. In yet another kind of optical sensor, the sample is mixed with a reactive gas, chosen such that one of the products of the reaction is emitted light (the phenomenon of chemiluminescence), which can be detected in the same way as photoluminescence.

Light sources

Many of the most commercially important optical gas sensing techniques are based on absorption at mid-IR wavelengths (e.g. ~3–15 μm) but still use incandescent filament lamps as the light sources. These are subject to drift and cannot be modulated faster than around 10 Hz because of their high thermal mass. New developments of incandescent technology include very thin platinum plate emitters (for faster modulation) and emitters with microstructured surfaces that enable more efficient emission of plasmon-generated light at the wavelengths needed for gas IR measurement. LEDs offer much greater light efficiency, more stable output and faster (kHz) modulation, but until recently their continuous wave (CW) output has been too weak for commercial use, and a reliable commercial supply is yet to be established, especially at wavelengths longer than 2.2 μm.

Tunable lasers have long been available in the near-IR region as developments of telecoms technology in wavebands centred on 1.3 and 1.55 μm. Such tunable lasers emit in a narrow band able to resolve a single gas absorption line, providing a high degree of gas specificity with a superior signal:noise ratio. Tuning over a wider wavelength range is of interest because it could allow gas-specific multicomponent gas detection with a single instrument. At telecoms wavelengths, a driver for wider-range tuning comes from the need for single devices able to tune their emission across the International Telecommunication Union (ITU) grid of wavelengths around 1.55 μm. In the mid-IR, where gas absorption lines are strongest (see Figure 3), there is a race to develop a room temperature tunable solid-state laser with three contenders: quantum cascade lasers (QCLs), room temperature lead salt lasers and devices based on periodically poled lithium niobate.

In the case of QCLs, the wavelength is governed by the thickness of the material layers rather than the bandgap of the material itself. QCLs operating at room temperature are now available and prices are falling: volume prices are reputed to have dropped to £2–3k at the time of writing and market leaders such as Hamamatsu have recently joined the fray.

Relatively few gases are routinely detected at UV wavelengths (i.e. $\lambda \sim 200$–380 nm) and most instruments use UV sources such as xenon or mercury vapour lamps. Smaller and inexpensive UV LEDs and laser diodes are anticipated within the next few years, offering more stable output and faster modulation leading to sensitivity gains. Laboratory sources already exist, and BlueRay as well as other new DVD technologies are driving the reliability of UV lasers. Very short wavelength, intense but low-power sources are also seen as essential for the future of photoionization detectors.

Table 3 summarizes the current situation regarding lasers.

Table 3. Summary of lasers with the potential to be used in gas sensing.[a]

Laser type	Wavelength	Power	Comments
Gallium nitride (GaN)	Blue/violet to near UV (300–480 nm)	< 5 mW	-
AlGaInP	Red (630–690 nm)	10 mW	Room temp., low cost
Aluminium gallium arsenide (AlGaAs)	NIR or visible (750–1,000 nm)	10 mW	Room temp., low cost
Vertical cavity surface emitting lasers (VCSELs)	NIR or visible (650–1,680 nm)	-	Room temp., low cost, widely tunable
InGaAsP for comms	NIR (1,200–2,000 nm)	10 mW	Room temp., fibre optic
Antimonide	NIR to mid-IR (2–4 μm)	≥ 1 mW	Room temp. or cooled
Quantum cascade lasers (QCLs)	Mid-IR (4–12 μm)	pulsed: tens of W; CW: tens of mW	Falling prices, no need now for cryogenic cooling
Lead salt	Mid-IR (3–30 μm)	< 1 mW	Requires cryogenic cooling

[a] From R.W. Bogue. *Technology Roadmap: Optoelectronic Gas Sensors in the Petrochemicals, Gas and Water Industries*. Published on www.OptoCem.Net, August 2006.

Photodetectors

Improved detectors are also a topic of significant research effort and as with mid-IR sources, the key requirements for detectors within this wavelength range are room temperate operation and low cost. Photovoltaic and photoconductive detectors fabricated from compound semiconductors such as InAsSb, HgCdTe arrays on Si (Qinetiq), PbSe and InSb operating to 10 μm and for near IR to 2.2 μm with wavelength-extended InGaAs have recently been demonstrated.

Currently, low cost detectors are available as either thermopile arrays or pyroelectric arrays used for standard thermal imaging. More widespread use in gas camera requires either an improvement in sensitivity of the cheaper manufacturing technologies or a reduction in price of the higher specification arrays. High specification IR array technology is controlled mainly by North American companies, a result of long-term military funding. Recent consolidations have resulted in FLIR dominating this market.

Silicon carbide (SiC) and diamond UV detectors covering the range ~200–400 nm are currently available. But, as with the mid-IR region, novel detectors offering higher sensitivity and more wavelength specifity may be required if this spectral region is to be exploited to the full.

Microspectrometers have, as yet, only exerted a minor impact in certain process control applications. They offer limited resolution and are relatively expensive, but there is great competition and prices are falling rapidly. If these issues can be resolved they could play a role in, for example, portable multigas sensing instruments.

Nanophotonics

The development of integrated optics (also called nanophotonics, because it involves evanescent fields extending a few tens of nanometres away from the waveguide) has led to the development of new types of optical sensors. The sensing function is based on materials that can respond to the presence of a gas by changing their optical thickness—defined as the product

of their geometrical thickness and refractive index. In other words they may, for example, swell or shrink or change colour, or simply absorb a large amount of the gas. The transducer function is provided by an optical waveguide. A thin metal film in which surface plasmons can be resonantly excited at the optical frequencies can also be used. If the responsive material is applied to the surface of a planar optical waveguide, the propagation constant of the guided light will change in the presence of the gas being sensed due to the interaction between the evanescent field generated by the guided light and the material being acted upon by the analyte gas, allowing the concentration of the gas to be determined. These types of sensors are presently still being researched. Many variants exist. For example, holograms can be created using a photographic silver halide emulsion created in a responsive hydrogel,[6] or the responsive material can be applied as a film onto the end of an optical fibre. The two boundaries form a miniature Fabry-Perot cavity. The output of such an end-coated optical fibre is an interferogram, whose evolution enables the identity of the gas and its concentration to be determined.

Electrical technologies

Electrically-based gas sensors can be divided into five main types, "heated element" or pyroelectric, "semiconductor conductivity", "conducting polymer", "ion detection", and electrochemical (polarographic).

The heated element type comprises a metal wire through which the current is flowing. It is based on the fact that the electrical resistance of metals increases with temperature (this is due to the motion of the atoms becoming more violent as the temperature increases, resulting in more scattering of the electrons bearing the electrical current as they pass through the metal). In a katharometer, the current flowing through the wire is chosen such that the wire is kept hot. The gases surrounding the metal collide with it and carry off some of the heat, causing the temperature to fall, thereby decreasing the resistance and hence the voltage that must be applied to the wire to maintain the same flow of current. In a pellistor, the wire is coated with a combustion catalyst and combustible gases colliding with it generate a tiny amount of heat, which increases the temperature of the wire and hence the resistance. Any catalyst is, of course, potentially at risk of performance degradation due to "poisoning"—its irreversible reaction (rendering it noncatalytic) with some other (e.g., sulfur-containing) compound present in the environment. Katharometers are typically used for detection and process control and pellistors for fire and explosion prevention.

A precursor to the nowadays very widely used Taguchi sensor (described below) was Seiyama's replacement of the metal wire by a semiconductor (zinc oxide) thin film. Many oxides catalyse gas oxidation and the resulting temperature rise increases the conductivity of the semiconductor. The Taguchi sensor, however, operates on a different principle. The conductivity of a semiconductor may be strongly modified by the presence of defects within it and the defect concentration is in turn controlled by the concentration of germane gases surrounding it. A "germane gas" is one that is chemically comprised within the semiconductor. For example, oxygen is a germane gas for zinc oxide. The original Taguchi sensor used a thin

[6] See A. Kabilan et al., Holographic glucose sensors, *Biosensors Bioelectronics* 20 (2005) 1602–1610, for an example of this method applied to sensing analyte in a liquid.

film of tin oxide made by sintering SnO_2 particles. Typically tin oxide is an n-type semiconductor, the electron donors being oxygen vacancies. Oxygen gas adsorbs on the surface of the tin oxide particles ("grains"). This results in a three-way diminution of the free electron concentration and hence the conductivity: firstly the oxygen is chemisorbed and acquires an electron, forming O_2^- (and O^- and O^{2-} at higher temperatures); secondly the presence of this negative charge at the particle surface creates an electron depletion layer below the surface (rather like a Schottky barrier) impeding particle-particle electron flow; and thirdly the adsorbed oxygen starts filling the oxygen vacancies in the bulk of the particle thereby eliminating the electron donor levels. Reducing gases, such as carbon monoxide, have the opposite effect. In order to have a reasonable starting concentration of electrons the tin oxide is typically maintained at a temperature of several hundred degrees Celsius.

A very specialized type of sensor is the paramagnetic oxygen sensor, which relies on that particular distinguishing feature of the oxygen molecule, with applications in medicine and in process monitoring and control.

The impedance of conducting polymers (typically prepared as a thin film in which a pair of interdigitated electrodes are embedded) changes in the presence of gases, including water vapour.

The "ion detector" type causes the gas to be detected to be ionized either in a flame or by irradiating with light. The ions are swept to an electrode by a suitable electrical field and the resulting current is measured. The two main subtypes are called flame ionization detectors (FIDs) and photo-ionization detectors (PIDs).

The polarographic or electrochemical class is based on an electrode that can reduce or oxidize gases adsorbing on its surface. The current passing at a particular electrode potential depends on the ambient concentration of a particular gas. One disadvantage of this type is that for the electrochemistry to take place humidity needs to be present and to ensure reproducibility this is usually supplied by a water reservoir incorporated within the sensing device.

Technologies based on mass

This emerging family is based on miniature mass spectrometers. The molecules are introduced into the spectrometer, ionized and strongly accelerated by an electrical field towards an ion detector while being weakly deflected in a direction perpendicular to that of the strong acceleration. The numbers of ions detected for a particular combination of acceleration and deflexion is characteristic of a particular molecule. Differential ion mobility spectroscopy (DMS) and high field asymmetric waveform ion mobility spectrometry (FAIMS) are variants of this basic theme.

We might also include the use of gas chromatography (GC) in this family. GC is of course a well-known technique in analytical chemistry, involving the introduction of molecules into a long tube packed with some more or less inert porous material. The molecules are impelled along the tube by a constantly flowing inert carrier medium (e.g., helium), and the duration of their passage depends on their interaction with the porous material filling the tube. If that material is totally inert, the duration of passage will depend on the size of the molecule (large molecules diffuse more slowly than small ones, but small ones may be able to penetrate into small pores inaccessible to the larger ones, hence their effective path length will be longer). If the material has some weak *affinity* with the molecule, its passage will be retarded and this is also used to discriminate between chemically distinct molecules.

If a microcantilever made to vibrate at its resonant frequency is coated with a thin film of a material (such as a molecularly imprinted polymer) that can capture sufficient gas molecules to appreciably alter the cantilever's mass, its resonant frequency will be diminished, which can be measured and used as the sensing signal. Surface acoustic wave (SAW) devices operate on a similar principle except that the gas capture material exists between a pair of interdigitated electrodes: the extra mass of the captured gas molecules measurably decreases the propagation velocity of the surface acoustic waves created between the electrodes. If the cantilever is made really thin (i.e., a nanocantilever) the capture layer may itself contribute appreciably to the elastic properties, creating the possibility of using materials that actually become stiffer upon capturing the gas of interest. In this case the resonant frequency will increase if this effect dominates the decrease due to the increase of mass.

Biological technologies

It is said that the earliest gas sensors (used in coal mines) consisted of a singing bird such as a canary kept in a cage. When the bird ceased to chirp the reason was probably that it had been poisoned by some noxious gas (carbon monoxide), and it was time for the miners to make quick getaway. It is not a particularly selective sensor, but due to the high metabolism rate of small birds it is probably a very sensitive one. The olfactory surfaces of some animals, especially dogs, are three orders of magnitude greater than those of humans and are able to distinguish a greater number of molecules. Therefore, trained dogs are extremely useful for detecting traces of gases present at concentrations far too low for human detection by smelling. Modern artificial biosensors are based on the exquisitely selective affinity of many biological macromolecules, especially proteins, for certain gases. These technologies are particularly applicable for the detection of those gases, such as the so-called nerve gases, whose danger to a human being is essentially due to their capture by such proteins ("receptors") in the body, whereupon they can no longer carry out their normal function.

Sensor arrays

It is now known that the human olfactory system does not operate on the principle of having a huge variety of distinct receptor molecules; i.e., one for each gas molecule that can be smelled. Rather, it comprises a much smaller number of receptor molecules with broad selectivity. Exposure of this array to the gas or a mixture of gases produces a pattern of responses, which is then identified as belonging to a particular gas or mixture of gases using pattern recognition techniques. Artificial systems built on this principle are known as "electronic noses".

Fluctuation-enhanced sensing

Insofar as it also depends on pattern recognition, fluctuation-enhanced sensing is somewhat related to electronic noses. The essential point is that any sensor signal contains noise. In simple cases, the (stochastic) processes contributing to the noise can be reasonably assumed to be Gaussian, analysable via the power spectral density. In many technologically important cases (including commercial Taguchi sensors) or strong inhomogeneities engender nonGaussian stochastic components in the noise spectrum. These components contain an enormous amount

of additional information. Its analysis can very significantly enhance the information provided about the chemical environment.[7]

Applications

Gas sensors are used in a wide variety of applications in numerous niche market sectors. Note that the categorization of the sectors is not always clear-cut. The monitoring of indoor air quality, although included below under Environment, could equally well rank as a long-term health application. The automotive sector unites several sectors, and is really large enough to be considered on its own. Our designation is based on the sector in which those purchasing and using detectors are working.

Healthcare

The association of characteristic odours with certain human illnesses has been a part of medical lore for a long time, probably for millennia. On the other hand, it is only comparatively recently, with the advent of convenient and reliable analytical instrumentation for determining at least some of the principle components of these often complex odours, that their analysis has come to be considered as a valid aid to the diagnosis of illness. Indeed, if the sensors can become as compact and inexpensive as the "breathalyser" routinely used by police forces to quantify whether drivers have been drinking alcohol, they might become the primary means of diagnosing many illnesses in the general practitioner's surgery.

A specific example is the detection of ammonia, created in the stomach from the decomposition of urea by *Helicobacter pylori* in order to diminish the acidity and make its immediate environment more congenial. The presence of ammonia in exhaled breath gives a first indication of the possibility of *H. pylori* infection, a frequent cause of stomach ulcers. Of course, there is minimal indication about the extent of the infection, but at least the patient can then be referred to the gastroenterologist for an endoscopy. Note the value of instrumentation—breath must typically pass through the oral cavity, which is a rich source of a great variety of volatile components depending on what food or drink the patient has recently consumed, and which could easily mask the ammonia if the doctor were to rely on his own sense of smell.

Another example is the monitoring of NO in exhaled breath as an early indicator of asthma (higher levels of NO are produced when the airways are inflamed). CHEMFETS or even simpler carbon nanotube-based resistors whose resistance depends on the adsorption of NO on the nanotubes are in principle small enough to be incorporated in a mobile phone. This is a good example of self-diagnosis of great practical utility to the patient.

Medical diagnosis is envisaged as one of the main applications for the "electronic nose", in which many volatile components will be detected simultaneously. Building up a database through correlating the profile of the sensor array responses with an independent diagnosis of the ailment would ultimately enable the electronic nose to be transformed into an expert system for clinical diagnosis.

[7] L.B. Kish, J. Smulko, P. Heszler and C.-G. Granqvist, On the sensitivity, selectivity, sensory information and optimal size of resistive chemical sensors. *Nanotechnol. Perceptions* 3 (2007) 43–52.

Security

This constitutes a broadly ranging set of applications, some of which could equally well be placed in other categories. The pre-emptive detection of explosives (through minute traces of volatile components) in airline passenger luggage is currently very much in the public mind. Sensors for toxic gases are important in some military theatres despite the prohibition enjoined by the Geneva Convention. Civil defence organizations and private bomb shelters need to be equipped with similar sensors. There may also be forensic applications, although the fugacity of the analyte generally means that forensic work has to focus on nonvolatile, usually solid materials.

More mundanely but much more extensively applied are gas sensors assuring domestic safety, especially where combustion is taking place and ventilation might be restricted (carbon monoxide sensors) and, with a wider range of gaseous analytes, assuring industrial safety. Many countries now have health and safety legislation in place specifying minimum monitoring requirements that must be met.

The breathalyser widely used by police forces to give a reasonably quantitative indication of recent alcohol consumption by drivers involved in incidents ranks as a security application but strictly speaking is not a sensor but a dosimeter since it gives an irreversible response to exposure to a particular quantity of ethanol.

Environment

This also constitutes a rather wide-ranging set of applications. It particularly refers to indoor air quality (IAQ), meaning the interiors of homes and workplaces and the passenger cabins of aircraft, railway trains and motor-cars; and outdoor air quality (OAQ), usually meaning the quality of urban air, of which the main source of pollution nowadays is typically motor vehicle exhausts. Optical sensors are especially used for monitoring stack emissions and ventilation control as well as for monitoring indoor and outdoor air quality.

Increasing concern is being directed towards the possibly deleterious effects on human health of volatile organic contaminants (VOCs) emitted by synthetic carpets and upholstery. One difficulty is the huge variety—hundreds of different compounds—that may be responsible for adverse health effects. One solution is simply to measure carbon dioxide concentration, the rationale being that if the indoor concentration is close to the outdoor value then the room is being properly ventilated and VOCs cannot build up. In warm, humid climates, such as in Hong Kong, humidity is an important analyte. Keeping a room dry is an important preventive measure against the growth of fungi, which can themselves emit more or less toxic VOCs. Even if the compounds are nontoxic, they may be allergens for some people (the sensor detecting them could equally appropriately be considered as a healthcare application).

OAQ sensors are mainly concerned with ozone and nitrogen oxides, NO_x. Acquiring growing prominence are fine dust particles,[8] the main urban sources of which are Diesel engines and the demolition of buildings. These particles are so minute that they do not settle and hence can be handled as gases. At present, the technology for quantifying their presence is very limited.

[8] Often referred to as particulate matter (PM), subscripted with a number indicating size (most usually PM_{10} indicating particles of diameter 10 μm or less and $PM_{2.5}$ indicating particles of diameter 2.5 μm or less. Called *Feinstaub* in the German-speaking world.

Processes

The main distinguishing feature of gas sensors in the processing industry compared with those for healthcare, security and the environment is that they may have to operate at extremes of temperature and pressure. It can be anticipated that as ensuring the sustainability of economic activity becomes more and more important (not least as an essential contributor to ultimate human survival), careful monitoring of processes will significantly grow in prominence. It is a rather general rule that the more data that is obtainable about a process, the more carefully it can be controlled and maintained under optimum conditions, thereby eliminating waste. The technology of such process control, of which the gas sensors are an essential part, should pay for itself by reducing the quantity of input required to generate a given output, quite apart from the long-term benefit to the environment. An example of this kind of application is the sensors now widespread in the automotive industry, used for monitoring the operation of the four-stroke internal combustion (Otto) engines.[9] Sensors in the outlet manifold monitoring the composition of exhaust gases and whose output is fed back into the actuators controlling fuel injection into the combustion chamber operate at a temperature of several hundred degrees Celsius.

Concluding remarks

Gas sensors can greatly enhance human sensory capabilities. This brief survey has covered the main technologies in current use and the main fields of application. Part 2 will deal with the actual markets, the technical challenges that they pose and future trends.

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[9] As well as in two-stroke and Diesel engines.
[10] J. Hodgkinson, J. Saffell, J. Luff, J. Shaw, J. Ramsden, C. Huggins, R. Bogue and R. Carline, *MNT Gas Sensor Roadmap*. MNT Network, published at www.gas-sensor-roadmap.com (2006).
[11] See H. Clare, The UK microsystems and nanotechnology network. *Nanotechnol. Perceptions* 2 (2006) 213–216.
[12] SIRA went into voluntary liquidation in March 2006.