Introduction

The human nose has been used as an analytical tool in many industries to measure the quality of food, drinks, perfumes and also cosmetic and chemical products. It is commonly used for assessing quality through odour and this is carried out using sensory panels where a group of people fills out questionnaires on the smells associated with the substance being analysed. These sensory panels are extremely subjective as human smell assessment is affected by many factors. Individual variations occur and may be affected by physical and mental health as well as fatigue (Pearce et al., 2003). For this reason, gas chromatography and mass spectrometry have been employed to aid human panels to assess the quality of products through odour evaluation and identification and also to obtain more consistent results. However, these assistive techniques are not portable, they tend to be expensive and their performance is relatively slow (Nagle et al., 1998).

The solution to the shortcomings of sensory panels and the associated analytical techniques is the electronic nose (e-nose). E-nose systems utilize an array of sensors to give a fingerprint response to a given odour, and pattern recognition software then performs odour identification and discrimination. The e-nose is a cost-effective solution to the problems associated with sensory panels and with chromatographic and mass-spectrometric techniques and can accommodate real time performance in the field when implemented in portable form.

Principle of operation of e-nose systems

The e-nose attempts to emulate the mammalian nose by using an array of sensors that can simulate mammalian olfactory responses to aromas. The odour molecules are drawn into the e-nose using sampling techniques such as headspace sampling, diffusion methods, bubblers or pre-concentrators...
(Pearce et al., 2003). The odour sample is
drawn across the sensor array and induces a
reversible physical and/or chemical change in
the sensing material, which causes an associated
change in electrical properties, such as
cconductivity (Harsányi, 2000). Each “cell” in
the array can behave like a receptor by
responding to different odours to varying
degrees (Shurmer and Gardner, 1992). These
changes are transduced into electrical signals,
which are preprocessed and conditioned before
identification by a pattern recognition system as
shown in Figure 1. The e-nose system is
designed so that the overall response pattern
from the array is unique for a given odour in a
family of odours to be considered by the system.

E-nose sensor response to odorants

The response of e-nose sensors to odorants is
generally regarded as a first order time response.
The first stage in odour analysis is to flush a
reference gas through the sensor to obtain a
baseline. The sensor is exposed to the odorant,
which causes changes in its output signal until
the sensor reaches steady-state. The odorant is
finally flushed out of the sensor using the
reference gas and the sensor returns back to its
baseline as shown in Figure 2. The time during
which the sensor is exposed to the odorant is
referred to as the response time while the time
it takes the sensor to return to its baseline
resistance is called the recovery time.

The next stage in analysing the odour is
sensor response manipulation with respect to
the baseline. This process compensates for
noise, drift and also for inherently large or
small signals (Pearce et al., 2003). The three
most commonly used methods as defined by
Pearce et al. (2003) are as follows.

1) Differential: the baseline \( x_s(0) \) is subtracted
from the sensor response \( x_s(t) \) to remove
any noise or drift \( \delta_A \) present. The baseline
manipulated response \( y_s(t) \) is determined
by:

\[
y_s(t) = x_s(t) - (x_s(0) + \delta_A)
\]

2) Relative: the sensor response is divided by
the baseline. This process eliminates
multiplicative drift \( \delta_M \) and a dimensionless
response \( y_s(t) \) is obtained.

\[
y_s(t) = \frac{x_s(t)}{x_s(0)} = \frac{x_s(t)}{x_s(0)(1 + \delta_M)}
\]

3) Fractional: the baseline is subtracted from
the response \( x_s(t) \) and then divided by the
baseline \( x_s(0) \) from the sensor response
which provides a dimensionless, normalised

Figure 1 Comparison of the mammalian olfactory system and the e-nose system
response $y_s(t)$ that can compensate for inherently large or small signals.

$$y_s(t) = \frac{x_s(t) - x_s(0)}{x_s(0)}$$

The choice of baseline manipulation depends on the sensor type being used, the sensor applications and also the researchers preference. However, certain manipulation techniques have been shown to be more suitable to certain sensor types and also variations in the manipulation techniques can occur in the literature, which will be discussed later in this paper.

Sensitivity is the measure of the change in output of a sensor for a change in the input. This is the standard definition given for the sensitivity of a sensor in several texts on sensor related topics (Fraden, 1996; Gopel et al., 1989; Johnson, 1997). In the case of e-nose sensors, the sensitivity of the sensor ($S$) to the odorant is the change in the sensor output parameter ($y$), i.e. resistance for a change in the concentration of the odorant ($x$) as shown in equation (4).

$$S = \frac{\Delta y}{\Delta x}$$

However, in the literature several authors use different values to measure sensitivity, usually calculated from baseline-manipulated data.

**Sensors employed in e-nose systems**

Gas molecules interact with solid-state sensors by absorption, adsorption or chemical reactions with thin or thick films of the sensor material. The sensor device detects the physical and/or chemical changes incurred by these processes and these changes are measured as an electrical signal. The most common types of changes utilised in e-nose sensor systems are shown in Table I along with the classes of sensor devices used to detect these changes.

Some aspects of these classes of sensors, along with several examples from each class, are explored in the following sections of this review.

**Conductivity sensors**

Conducting polymer composites, intrinsically conducting polymers and metal oxides are three of the most commonly utilised classes of sensing materials in conductivity sensors. These materials work on the principle that a change in some property of the material resulting from interaction with a gas/odour leads to a change in resistance in the sensor. The mechanisms that lead to these resistance changes are different for each material type; however, the structure and layout of conductivity sensors prepared using these materials are essentially the same.

A schematic of a typical conductivity sensor design is shown in Figure 3.

The sensing material is deposited over interdigitated or two parallel electrodes, which form the electrical connections through which the relative resistance change is measured. The heater is required when metal oxides are used as the sensing material because very high temperatures are required for effective operation of metal oxide sensors.

**Conducting polymer composite sensors**

Conducting polymer composites consist of conducting particles such as polypyrrole and carbon black interspersed in an insulating polymer matrix (Albert and Lewis, 2000).

<table>
<thead>
<tr>
<th>Physical changes</th>
<th>Sensor devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity</td>
<td>Conductivity sensors</td>
</tr>
<tr>
<td>Mass</td>
<td>Piezoelectric sensors</td>
</tr>
<tr>
<td>Optical</td>
<td>Optical sensors</td>
</tr>
<tr>
<td>Work function</td>
<td>MOSFET sensors</td>
</tr>
</tbody>
</table>
On exposure to gases, these materials change resistance and this change is due to percolation effects or more complex mechanisms in the case of polypyrrole filled composites.

When the polymer composite sensor is exposed to a vapour, some of the vapour permeates into the polymer and causes the polymer film to expand. The vapour-induced expansion of the polymer composite causes an increase in the electrical resistance of the polymer composite because the polymer expansion reduces the number of conducting pathways for charge carriers (Munoz et al., 1999). This increase in resistance is consistent with percolation theory. Polypyrrole-based composites have a more complex transduction mechanism because the odour molecules can cause expansion of both the insulating polymer and the polypyrrole particles. Changes in the intrinsic conductivity of the polypyrrole particles can also occur if the odour interacts chemically with the conducting polymer backbone. Therefore, resistance changes in the polypyrrole-based composites are more difficult to predict (Albert and Lewis, 2000).

Carbon black based composites were prepared by suspending the carbon black in a solution of the insulating polymer in a suitable solvent. The overall composition of this solution is usually 80 per cent insulating polymer-20 per cent carbon black by weight. Different techniques have been used to apply the active material onto the substrate, which are shown in Table II.

The transducer device is usually a flat substrate with either two parallel electrodes or interdigitated electrodes deposited onto the substrate surface as shown in Figure 3.

However, both bulk and surface micromachining have also been used to produce wells on silicon substrates using patterned silicon nitride/oxide as insulation and gold electrodes as the metal contacts. The polymer is dropped into the well using a syringe as shown in Figure 4 (Zee and Judy, 2001).

Examples of the types of substrates and electrodes used are given in Table III along with the electrode dimensions given in the literature. Polypyrrole-based composites are usually prepared by chemically polymerizing pyrrole using phosphomolybdic acid in a solution containing the insulating polymer. A thin film coating (40-100 nm thick) is then applied across interdigitated electrodes (typical electrode gaps were 15 µm) using dip coating (Freund and Lewis, 1995).

The fractional baseline manipulation response is the most common method used to record the sensor response from conducting gas sensors (Pearce et al., 2003). This fractional baseline manipulation is referred to as the maximum relative differential resistance change, $\Delta R/R_b$. $\Delta R$ is the maximum change in the resistance of the sensor during exposure to the odorant and $R_b$ is the baseline resistance before exposure.

Response times may vary from seconds to minutes, as shown in Table IV, and, in some cases, milliseconds (Munoz et al., 1999). However, typically a set of exposure cycles is quoted for each analyte, i.e. initial reference gas, analyte and final reference gas exposure times. The response time depends on the rate of diffusion of the permeant into the polymer. The diffusion rate mainly depends on the nature of the polymer, permeant and the crosslinking, the concentration of the permeant and thickness of the film, and on the effects of fillers, plasticisers and temperature (George and Thomas, 2001). General response times for conducting polymer composites are given in Table IV.

The transport properties depend on the fractional free volume (FFV) in the polymer and on the mobility of the segments of the polymer chains. The segmental mobility of the polymer chains depends on the extent of unsaturation. Therefore, segmental mobility is significantly
reduced with increased numbers of double and triple bonds on the carbon-carbon backbone. The presence of crystalline domains can have two different effects on the permeability of a polymer. Crystallites are generally impermeable to vapours at room temperature and will reduce the diffusion coefficient. However, crystallites act as large crosslinking regions in terms of the chains entering and leaving the areas around the crystallite in which diffusion occurs (Comyn, 1985). Increased defect formation and a reduction in interlamellar links predominate and overshadow the effect of geometric impedance to such an extent that diffusivity increases despite increasing crystallinity (Vieth, 1991). For example, in PE-grafted carbon black chemiresistors, heat treatment of the composite improved the crystallinity of the matrix PE and resulted in a five-fold increase in the response of the sensor to cyclohexane vapour compared to the untreated sensor (Chen et al., 2002).

The size and shape of the penetrating molecule affects the rate of uptake of the vapour by the polymer where increased size of the molecule decreases the diffusion coefficient. Flattened or elongated molecules diffuse faster than spherical-shaped molecules (George and Thomas, 2001).

The partial pressure, i.e. the concentration, of the penetrant gas at the gas polymer interface affects the response of the sensor. The response is inversely related to the vapour pressure of the analyte at the surface. Low vapour pressure compounds can be detected in the low ppb range while high vapour pressure compounds need to be in the high ppm range to be detected. This is due to the polymer/gas partition coefficient where low vapour pressure gas molecules have a higher tendency to inhabit the polymer and thus can be detected at much lower concentrations (Munoz et al., 1999).

The equilibrium partition coefficient is essentially the solubility coefficient of the vapour in the polymer (Vieth, 1991). Sensors with constant thickness but with different surface areas have the same response when exposed to analytes with moderate partition coefficients. However, analytes with higher partition coefficients have higher affinity to sensors with smaller area. In this case, reducing the sensor area increases the sensitivity of the sensor towards particular analytes. Therefore the relationship between the partition co-efficient and the sensor geometry is an important factor in optimising polymer composite sensor response (Briglin et al., 2002).

Table II Application techniques used to deposit carbon black based composites

<table>
<thead>
<tr>
<th>Reference</th>
<th>Polymer</th>
<th>Coating thickness</th>
<th>Coating application technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matthews et al. (2002)</td>
<td>Poly(alkylacrylate)</td>
<td>Thin film 0.86 μm</td>
<td>Spray coating</td>
</tr>
<tr>
<td>Severin et al. (1998)</td>
<td>Poly(co-vinyl-acetate)</td>
<td>Thin film 1 μm</td>
<td>Spin coating</td>
</tr>
<tr>
<td>Severin et al. (2000)</td>
<td>Poly(vinyl butyral)</td>
<td>Thin film N/A</td>
<td>Dip coating</td>
</tr>
</tbody>
</table>

Figure 4 Bulk micromachined well as used by Zee and Judy (2001)

Table III Electrodes and substrates used in conducting polymer composite sensors

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Electrode material</th>
<th>Electrode dimensions (mm)</th>
<th>Electrode gap (mm)</th>
<th>Electrode thickness (nm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass microscope slides</td>
<td>Gold</td>
<td>N/A</td>
<td>5</td>
<td>50-100</td>
<td>Lonergan et al. (1996)</td>
</tr>
<tr>
<td>Glass microscope slides</td>
<td>Gold</td>
<td>10 × 10</td>
<td>5</td>
<td>50</td>
<td>Doleman et al. (1998a)</td>
</tr>
<tr>
<td>Glass microscope slides</td>
<td>Gold, Chromium</td>
<td>20 × 10</td>
<td>5</td>
<td>30, 20</td>
<td>Doleman et al. (1998a, b)</td>
</tr>
<tr>
<td>Micromachined silicon wafer</td>
<td>Gold</td>
<td>0.1 in width</td>
<td>0.5</td>
<td>N/A</td>
<td>Zee and Judy (2001)</td>
</tr>
<tr>
<td>Glass microscope slide</td>
<td>Gold, Chromium</td>
<td>1.8 in length</td>
<td>0.4</td>
<td>50, 15-30</td>
<td>Briglin et al. (2002)</td>
</tr>
</tbody>
</table>
Generally, composite polymers have operating resistances of approximately 1 to 1,000 kΩ with sensitivities of up to 100 per cent (Partridge et al., 2000). Sensitivity to hydrophobic analytes for conducting polymer composites were found to be one to two orders of magnitude higher than those recorded for intrinsically conducting polymers (Partridge et al., 2000). The polymer composites show linear responses to concentration for various analytes and also good repeatability after several exposures (Severin, 2000; Zee and Judy, 2001). From the above discussion, it can be seen that for high sensitivity, fast response and short recovery times it is essential that the sensor geometry and all the associated properties of the polymer sensing material be highly optimised.

Conducting polymer composites offer many advantages over other materials when utilised as gas sensors. High discrimination in array sensors can be easily achieved using these materials due to the wide range of polymeric materials available on the market. This is due to the fact that different polymers give different levels of response to a given odour. Conducting polymer composites are also relatively inexpensive and easy to prepare. Sensors prepared from these materials can operate in conditions of high relative humidity and also show highly linear responses for a wide range of gases (Munoz et al., 1999). No heater is required as sensors prepared from these materials operate at room temperature. This is an important advantage with portable battery powered e-nose systems, as a heater would significantly increase the power consumption of the system. The signal conditioning circuitry required for these sensors is relatively simple as only a resistance change is being measured.

The main drawbacks of using conducting polymer composites as e-nose sensors are aging, which leads to sensor drift, and also these materials are unsuitable for detecting certain gases, for example carbon-polymer composites are not sensitive to trimethylamine (TMA) for fish odour applications.

### Intrinsicly conducting polymers

Intrinsically conducting polymers (ICP) have linear backbones composed of unsaturated monomers, i.e. alternating double and single bonds along the backbone, that can be doped as semiconductors or conductors (Heeger, 2001). Yasufuku (2001) describes them as π electron conjugated polymers where the π symbol relates to the unsaturated structure of the monomer containing an unpaired carbon electron. These conducting polymers can be n-doped or p-doped depending on the doping materials used. Conducting polymers such as polypyrrole, polythiophene and polyaniline, as shown in Figure 5, are typically used for e-nose sensing. The doping of these materials generates charge carriers and also alters their band structure, which both induce increased mobility of holes or electrons in the polymer depending on the type of doping used (Albert and Lewis, 2000; Dickinson et al., 1998).

The principle of operation for ICP e-nose sensors is that the odorant is absorbed into the polymer and alters the conductivity of the polymer (Albert and Lewis, 2000; Dickinson et al., 1998). Three types of conductivity are affected in intrinsically conducting polymers. 

1. The *intrachain conductivity* in which the conductivity along the backbone is altered;
2. The *intermolecular conductivity* which is due to electron hopping to different chains because of analyte sorption (Charlesworth et al., 1997); and
3. The *ionic conductivity* which is affected by proton tunneling induced by hydrogen bond interaction at the backbone and also by ion migration through the polymer (Albert and Lewis, 2000). The physical structure of the polymer also has a major influence on the conductivity (Yasufuku, 2001). Albert and Lewis (2000) described how the conductivity of doped polyaniline was greatly increased on interaction with ethanol, caused by the hydrogen bonds.
tightening or restructuring the polymer into a more crystalline shape.

Intrinsically conducting polymers are generally deposited onto a substrate, with interdigitated electrodes, using electrochemical techniques or by chemical polymerisation, (Freund and Lewis, 1995; Yasufuku, 2001). Sensors with a more simple structure can be prepared where the polymer is deposited between two conducting electrodes (Guadarrama et al., 2000). Electrochemical polymerisation is carried out using a three-electrode electrochemical cell with the electrodes on the substrate used as the working electrodes (Gardner and Bartlett, 1995). A potential is applied across the electrode that initiates the polymerisation of the polymer onto the substrate. The polymer is initially deposited onto the electrodes and then grows between them thus producing a complete thin film across the electrode arrangement as the polymerisation reactions progress. Electrode thickness can range from 1 to 10 μm and the electrode gap is typically 10-50 μm (Albert and Lewis, 2000; Guadarrama et al., 2000). The total charge applied during the polymerisation process determines the thickness of the resultant film, while the final applied voltage determines the doping concentration.

Partridge et al. (2000) described the sensor characteristics of intrinsically conducting polymers produced by pulsing the potential during polymerisation and observed a 1-50 per cent relative differential resistance change (ΔR/Rb) for saturated gas.

The response of ICP sensors depends on the sorption of the vapour into the sensing material, causing swelling, and this affects the electron density on the polymeric chains (Albert and Lewis, 2000). The sorption properties of these materials essentially depend on the diffusion rate of the permeant into the polymer matrix as explained earlier for composite conducting polymers. Generally, the reported response times for ICPs vary considerably from seconds to minutes, e.g. 30 s (Sotzing et al., 2000), 60 s (Pearce et al., 2003) and 180-240 s (Corcoran, 1993a). Polythiophene and poly(dodecylthiophene) sensors have sensitivities from approximately 0.2 up to 1.8 (ΔR/Rb for 300 ppm gas for 10 min) for gases such as CH₄, CHCl₃ and NH₄ (Sakurai et al., 2002). Polypyrrole gas sensors were reported to have sensitivities (μV/ppm) ranging from 0.26 to 5.01 depending on the counter ions used in the polymers films (Fang et al., 2002). These response times and sensitivities are reported for an extremely vast variety of materials prepared by various techniques, sensor geometries and odour molecules, rendering direct comparisons between sensors prepared by different researchers difficult if not impractical.

Intrinsically conducting polymers have a number of advantages when used in e-nose systems. Increased discrimination when developing sensor arrays can easily be achieved with these materials as a wide range of intrinsically conducting polymers are available on the market (Albert and Lewis, 2000). ICP sensors operate at room temperature (Shurmer and Gardner, 1992), thereby simplifying the required system electronics. Conducting polymers show a good response to a wide range of analytes and have fast response and recovery times especially for polar compounds.

Problems related to intrinsically conducting polymer sensors include poorly understood signal transduction mechanisms, difficulties in...
resolving some types of analytes, high sensitivity to humidity (Albert and Lewis, 2000) and the sensor response can drift with time. The fabrication techniques for these sensors can also be difficult and time-consuming (Nagle et al., 1998), and large variations in the properties of the sensors can occur from batch to batch (Nagle et al., 1998). Finally, the lifetime of these sensors can be quite short, typically 9-18 months, due to oxidation of the polymer (Schaller et al., 1998).

**Metal oxide sensors**

The principle of operation of metal oxide sensors is based on the change in conductance of the oxide on interaction with a gas and the change is usually proportional to the concentration of the gas. There are two types of metal oxide sensors; n-type (zinc oxide, tin dioxide, titanium dioxide or iron (III) oxide) which respond to reducing gases and p-type (nickel oxide, cobalt oxide) which respond to oxidising gases (Pearce et al., 2003). The n-type sensor operates as follows: oxygen in the air reacts with the surface of the sensor and traps any free electrons on the surface or at the grain boundaries of the oxide grains. This produces large resistance in these areas due to the lack of carriers and the resulting potential barriers produced between the grains inhibit the carrier mobility. However, if the sensor is introduced to a reducing gas like H₂, CH₄, CO, C₂H₅ or H₂S the resistance drops because the gas reacts with the oxygen and releases an electron. This lowers the potential barrier and allows the electrons to flow, thereby increasing the conductivity. P-type sensors respond to oxidising gases like O₂, NO₂, and Cl₂ as these gases remove electrons and produce holes, i.e. producing charge carriers. Equations (1) and (2) describe the reactions occurring at the surface:

\[
\frac{1}{2}O_2 + e^- \rightarrow O^- (s) \quad (5)
\]

\[
R(g) + O^- (s) \rightarrow RO(g) + e \quad (6)
\]

Where e is an electron from the oxide. R(g) is the reducing gas and g and s are the surface and gas, respectively (Albert and Lewis, 2000; Pearce et al., 2003).

Thick and thin film fabrication methods have been used to produce metal oxide gas sensors. The metal oxide films are deposited using screenprinting (Schmid et al., 2003), spincoating (Hamakawa et al., 2002), RF sputtering (Tao and Tsai, 2002) or chemical vapour deposition (Dai, 1998) onto a flat or tube type substrate made of alumina, glass, silicon or some other ceramic. Gold, platinum, silver or aluminium electrodes are deposited onto the substrate using the same methods. There are various electrode designs but the interdigitated structure appears to be the most common approach. A heating element is printed onto the back of the substrate to provide the high temperatures required for metal oxides to operate as gas sensors, typically 200-500°C. Film thickness ranges from 10 to 300 μm for thick film and 6-1,000 nm for thin film, (Schaller et al., 1998). Catalytic metals are sometimes applied on top of the oxides to improve sensitivity to certain gases. The same preparative methods are used to apply the catalytic metal (Albert and Lewis, 2000; Penza et al., 2001b, c).

The sensitivity of oxide gas sensors \((\Delta R/R_b)/c(gas)\), is calculated with \(\Delta R = R - R_b\) for oxidising gases and as \(\Delta R = R_b - R\) for reducing gases where \(R_b\) is the baseline resistance and \(R\) is the resistance on exposure to the odour and \(c(gas)\) is the concentration of the gas (Steffes et al., 2001). The sensitivity of the metal oxide sensor depends on the film thickness and the temperature at which the sensor is operated, with thinner films being more sensitive to gases (Schaller et al., 1998). The sensitivity can be improved by adding a catalytic metal to the oxide; however excessive doping can reduce sensitivity. The effect of doping SnO₂ sensors with Cu, for example, demonstrated significant increases in sensitivity (Galdikas et al., 1995). The grain size of the oxide also affects the sensitivity and selectivity to particular gases as the grain boundaries act as scattering centres for the electrons (Schaller et al., 1998). The ratio of the grain size \((D)\) to the electron depletion layer thickness \((L)\), ranging below \(D/2L = 1\), i.e. the depletion region extends over the entire grain, governs the sensitivity of the sensor (Behr and Fliegel, 1995). Thin film metal oxide sensors saturate quickly, which can reduce the sensitivity range.
in which the sensor can operate. The sensitivity of metal oxide sensors is very dependent on the operating temperature, for example, the sensitivity, $\Delta R/R_b$ (per 10 ppm NO$_2$), for In$_2$O$_3$ gas sensors range from approximately 1.2 to 1.6 with the operating temperature varying from 350 to 450°C (Steffes et al., 2001). For SnO$_2$ gas sensors doped with Al$_2$O$_3$, the sensitivity per 500 ppm CH$_4$ ranges from 0.2 to 0.7 between 250 and 400°C (Saha et al., 2001).

The response times for tin oxides tend to be very fast and can reach steady-state in less than 7 s, (Doleman et al., 1998a, b). The general response times for tin oxide sensors, with gas concentrations between 0 and 400 ppm and at temperatures between 250 and 500°C, are 5 to 35 s and the recovery times vary from 15 to 70 s (Albert and Lewis, 2000). Corcoran gave values of 20 s for thick film metal oxide sensors and 12 s for thin film metal oxide sensors (Corcoran, 1993b).

The main advantages of metal oxide sensors are fast response and recovery times, which mainly depend on the temperature and the level of interaction between the sensor and gas (Penza et al., 2001c). Thin film metal oxide sensors are small, and relatively inexpensive to fabricate, have lower power consumption than thick film sensors and can be integrated directly into the measurement circuitry (Dai, 1998). However, they have many disadvantages due to their high operating temperatures, which results in increased power consumption over sensors fabricated from materials other than metal oxides. As a result, no handheld e-nose system has been fabricated utilising sensors prepared from metal oxides (Pearce et al., 2003). They also suffer from sulphur poisoning due to irreversible binding of compounds that contain sulphur to the sensor oxide (Dickinson et al., 1998) and ethanol can also blind the sensor from other volatile organic compound (VOC), gases (Schaller et al., 1998).

**Piezoelectric sensors used in e-nose arrays**

There are two types of piezoelectric sensors used in gas sensing, the surface acoustic wave (SAW) device and the quartz crystal microbalance (QCM). The SAW device produces a surface wave that travels along the surface of the sensor while the QCM produces a wave that travels through the bulk of the sensor.

Both types of devices work on the principle that a change in the mass of the piezoelectric sensor coating due to gas absorption results in a change in the resonant frequency on exposure to a vapour (Albert and Lewis, 2000).

**Surface acoustic wave sensor**

The SAW device is composed of a piezoelectric substrate with an input (transmitting) and output (receiving) interdigital transducer deposited on top of the substrate (Khlebarov et al., 1992). The sensitive membrane is placed between the transducers, Figure 6, and an ac signal is applied across the input transducer creating an acoustic two-dimensional wave that propagates along the surface of the crystal at a depth of one wavelength at operating frequencies between 100 and 400 MHz (Pearce et al., 2003). The mass of the gas sensitive membrane of the SAW device is changed on interaction with a compatible analyte and causes the frequency of the wave to be altered. The change in frequency with sorption of a vapour is given by

$$\Delta f = \Delta f_p c_v K_p / \rho_p$$

where $\Delta f_p$ is the change in frequency caused by the membrane, $c_v$ is the vapour concentration, $K_p$ is the partition coefficient, $\rho_p$ is the density of the polymer membrane used (Albert and Lewis, 2000; Nagle et al., 1998; Pearce et al., 2003).

The substrates are normally prepared from ZnO, lithium niobate or quartz, which are piezoelectric in nature (Pearce et al., 2003). The sensitive membrane is usually polymeric or...
liquid crystal, however, phospholipids and fatty acids deposited using Langmuir-Blodgett techniques have also been used (Albert and Lewis, 2000). Generally, SAW devices are produced commercially by photolithography, where airbrush techniques are often used to deposit the thin films (Nagle et al., 1998; Schaller et al., 1998) approximately 20-30 nm thick (Groves and Zellers, 2001). SAW devices have also been produced by utilising screen printing techniques (White and Turner, 1997), dip coating and spin coating.

The sensitivity of the SAW device to a particular odour depends on the type sensitive membrane and the uptake of vapours by polymers are governed by the same factors as those for composite conducting polymer sensors as detailed earlier in this paper. The sensitivity is normally quoted as differential response, i.e. $D_f$/ppm of odour (Hierlemann et al., 1995; Pearce et al., 2003). Polymer-coated SAW devices have quite low detection limits, for example tetrachloroethylene, trichloroethylene and methoxyflurane have been detected at concentrations as low as 0.7, 0.6 and 4 ppm, respectively (Albert and Lewis, 2000). Groves et al. used an array of SAW devices with polymer coatings 20-30 nm thick to detect 16 different solvents using four different polymers. Sensitivities ranging from 0.5 up to 12 Hz/mg/m^3 have been achieved with these devices (Groves et al., 2001).

Organophosphorous compounds have also been detected using these types of devices at concentrations from 10 to 100 ppm at temperatures between 25 and 50°C where a sensitivity of 27 Hz/ppm at 30°C (Dejous et al., 1995).

As can be seen above, SAW devices can detect a broad spectrum of odours due to the wide range of gas sensitive coatings available (Carey et al., 1986; Grate and Abraham, 1991) and they also offer high sensitivity and fast response times and their fabrication is compatible with current planar IC technologies (Nagle et al., 1998).

However, SAW devices suffer from poor signal to noise performance because of the high frequencies at which they operate, (Schaller et al., 1998) and the circuitry required to operate them is complex and expensive (Pearce et al., 2003). Batch to batch reproducibility is difficult to achieve and the replacement of damaged sensors was also found to be problematic (Schaller et al., 1998).

### Quartz crystal microbalance sensor

Quartz crystal microbalance (QCM) gas sensors operate on the same principle as SAW devices. When an ac voltage is applied across the piezoelectric quartz crystal the material oscillates at its resonant frequency, normally between 10 and 30 MHz (Schaller et al., 1998). The three-dimensional wave produced, travels through the entire bulk of the crystal. A membrane is deposited onto the surface of the crystal and this layer adsorbs gas when exposed to the vapour, which results in an increase in its mass. This increase in mass alters the resonant frequency of the quartz crystal and this change in resonant frequency is therefore used for the detection of the vapour (Albert and Lewis, 2000).

The sensor, shown in Figure 7, is composed of a quartz disc coated with the absorbing polymer layer and a set of gold electrodes evaporated onto either side of the polymer/quartz structure. Micromachining is used to fabricate the QCM devices, which makes the fabrication of small sensor structures possible. Coatings can be between 10 nm and 1 μm and are applied using spincoating, airbrushing, inkjet printing or dip coating, (Schaller et al., 1998).

The sensitivity of QCMs is given by

$$\frac{\Delta f}{\Delta c} = \frac{-2.3 \times 10^{-6} f^2}{A}$$

(8)

**Figure 7** Quartz crystal microbalance with polymer coating
where \( f \) is the fundamental frequency, \( c \) is the concentration and \( A \) is the area of the sensitive film (Carey and Kowalski, 1986). Higher frequencies and smaller surface areas of sensitive coatings give rise to higher sensitivity (Carey, 1987).

A quartz crystal microbalance gas sensor was developed and had a linear frequency shift on interaction with ethanol, n-heptane and acetone and showed a 16 Hz shift for 2.5 ppm of ethanol and \( \sim 1.5 \) Hz shift for 1 ppm of n-heptane, (Kim, 2002) demonstrating their high sensitivity to organic vapours. QCM devices are sensitive to a diverse range of analytes and are also very selective (Pearce et al., 2003). Polyvinylpyrrolidone modified QCMs have been used to detect various organic vapours and had sensitivities in the range of 7.5-48.2 Hz/mg/l (Mirmohseni and Oladegeagoroze, 2003).

The advantages of using QCMs are fast response times, typically 10 s (Haug et al., 1993), however, response times of 30 s to 1 min have been reported (Carey, 1987). However, QCM gas sensors have many disadvantages which include complex fabrication processes and interface circuitry, (Nagle et al., 1998), and poor signal to noise performance due to surface interferences and the size of the crystal (Nagle et al., 1998). As with SAW devices, batch-to-batch reproducibility of QCM gas sensors and the replacement of damaged sensors are difficult (Dickinson et al., 1998).

**Optical sensors used in e-nose arrays**

Optical fibre sensor arrays are yet another approach to odour identification in e-nose systems. The sides or tips of the optic fibres (thickness, 2 \( \mu \)m) are coated with a fluorescent dye encapsulated in a polymer matrix as shown in Figure 8. Polarity alterations in the fluorescent dye, on interaction with the vapour, changes the dye’s optical properties such as intensity change, spectrum change, lifetime change or wavelength shift in fluorescence, (Nagle et al., 1998; Pearce et al., 2003). These optical changes are used as the response mechanism for odour detection (Grattan and Sun, 2000; Gopel, 1992).

The sensitivity depends on the type of fluorescent dye or mixture of dyes and the type of polymer used to support the dye (Nagle et al., 1998). The nature of the polymer controls the response and the most important factors are polarity, hydrophobicity, porosity and swelling tendency (Nagle et al., 1998; Pearce et al., 2003). Adsorbants, such as alumina, can be added to the polymer to improve the response by lowering the detection limits of the sensor (Walt et al., 1998). Polyanaline-coated optical sensors have been used to detect ammonia at concentrations as low as 1 ppm and the linear dynamic range was between 180 and 18,000 ppm, (Jin, 2001). Optical gas sensors have very fast response times, less than 10 s for sampling and analysis (Walt et al., 1998).

These compact, lightweight optical gas sensors can be multiplexed on a single fibre network, immune to electromagnetic interference (EMI) and can operate in high radiation areas due to Bragg and other grating based optical sensors (Gopel, 1992; Walt et al., 1998).

However, there are several disadvantages of these types of sensors. The associated electronics and software are very complex, leading to increased cost, and the sensors have quite a short lifetime due to photobleaching (Nagle et al., 1998). However, this problem was overcome by measuring the temporal

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**Figure 8** A gas optical fibre sensor. The odorant interacts with the material and causes a shift in the wavelength of the propagating light wave.
responses because these remain consistent despite photobleaching (Walt et al., 1998).

Metal-oxide-semiconductor field-effect transistor sensor and its use in the e-nose
The metal-oxide-semiconductor field-effect transistor (MOSFET) is a transducer device used in e-nose to transform a physical/chemical change into an electrical signal. The MOSFET sensor is a metal-insulator-semiconductor (MIS) device and its structure is shown in Figure 9 (Eisele et al., 2001).

This particular sensor works on the principle that the threshold voltage of the MOSFET sensor changes on interaction of the gate material, usually a catalytic metal, with certain gases, such as hydrogen, due to corresponding changes in the work functions of the metal and the oxide layers (Pearce et al., 2003). The changes in the work functions occur due to the polarization of the surface and interface of the catalytic metal and oxide layer when the gas interacts with the catalytically active surface (Kalman et al., 2000). In order for the physical changes in the sensor to occur, the metal-insulator interface has to be accessible to the gas. Therefore, a porous gas sensitive gate material is used to facilitate diffusion of gas into the material (Eisele et al., 2001). It has been observed that the change in the threshold voltage is proportional to the concentration of the analyte and is used as the response mechanism for the gas. Changes in the drain-source current and the gate voltage have also been used as the response mechanisms for the MOSFET gas sensors as they are also affected by changes in the work function (Albert and Lewis, 2000; Nagle et al., 1998).

Gas sensing MOSFETs are produced by standard microfabrication techniques, which incorporate the deposition of gas sensitive catalytic metals onto the silicon dioxide gate layer (Nagle et al., 1998). In the case of catalytic metals, such as platinum (Pt), palladium (Pd) and iridium (Ir), the gate material is thermally evaporated onto the gate oxide surface through a mask forming 100-400 nm thick films or 3-30 nm thin films depending on the application (Albert and Lewis, 2000). Thick films have been used to detect hydrogen and hydrogen sulphide while thin films are more porous and can detect amines, alcohols and aldehydes (Kalman et al., 2000).

Polymers have also been used as the gate material for MOSFET gas sensors (Hatfield et al., 2000). Covington et al. 2001 used three polymers (poly(ethylene-co-vinyl acetate, poly(styrene-co-butadiene), poly(9-vinylcarbazole)) mixed with 20 per cent carbon black, which were deposited onto the FETs using a spray system. The polymer thickness was between 1.9 and 3.7 μm, respectively (Covington et al., 2001). These MOSFETs, which use polymers as the sensitive membrane are more commonly called PolFETs and can operate at room temperature.

Apart from the standard MOSFET gas sensor architecture, a hybrid suspended gate FET (HSGFET) gas sensor can also be fabricated by micromachining (Figure 10). The HSGFET is a metal air-gap insulator (MAIS) device. The air-gap allows easy access to both the gate material and the insulator, so diffusion is not necessary and therefore a wider choice of gas sensitive materials can be used (Eisele et al., 2001; Pearce et al., 2003).

The catalytic metal thickness and the operating temperatures of the MOSFETs in

![Figure 9 MOSFET gas sensor with gas sensitive membrane deposited on top of SiO₂](image)

![Figure 10 Hybrid suspended gate field effect transistor](image)
### Table V Characteristics of commercial e-noses

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Sensor type</th>
<th>No. of sensors</th>
<th>Applications</th>
<th>Pattern recognition/comments</th>
<th>Website/reference/university background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airsense analysis GmbH</td>
<td>MOS</td>
<td>10</td>
<td>Food evaluation; flavour and fragrance testing</td>
<td>ANN, DC, PCA Laptop</td>
<td><a href="http://www.airsense.com/">www.airsense.com/</a></td>
</tr>
<tr>
<td>Alpha MOS-Multi Organoleptic Systems</td>
<td>CP, MOS, QCM, SAW</td>
<td>6-24</td>
<td>Analysis of food types; quality control of food storage, fresh fish, and petrochemical products; packaging evaluation; analysis of dairy products, alcoholic beverages and perfumes</td>
<td>ANN, DFA, PCA Desktop</td>
<td><a href="http://www.alpha-mos.com">www.alpha-mos.com</a></td>
</tr>
<tr>
<td>Applied Sensor</td>
<td>IR, MOS, MOSFET, QCM</td>
<td>22</td>
<td>Identification of purity, process and quality control, environmental analysis, medical diagnosis</td>
<td>ANN, PCA Laptop</td>
<td><a href="http://www.appliedsensor.com">www.appliedsensor.com</a></td>
</tr>
<tr>
<td>AromaScan PLC</td>
<td>CP</td>
<td>32</td>
<td>Environmental monitoring, chemical quality control, pharmaceutical product evaluation</td>
<td>Ann</td>
<td>University of Manchester</td>
</tr>
<tr>
<td>Array Tech</td>
<td>QCM</td>
<td>8</td>
<td>Diagnosing lung cancer, food analysis</td>
<td>Desktop</td>
<td>Institute of science and technology, UK</td>
</tr>
<tr>
<td>Bloodhound sensors</td>
<td>CP</td>
<td>14</td>
<td>Food evaluation, flavour and fragrance testing microbiology, environmental monitoring, degradation detection</td>
<td>ANN, CA, PCA, DA Laptop</td>
<td>University of Leeds, UK</td>
</tr>
<tr>
<td>Cyrano Science Inc.</td>
<td>CP</td>
<td>32</td>
<td>Food quality, chemical analysis, freshness, spoilage, contamination detection, consistency in foods and beverages</td>
<td>PCA Palmtop</td>
<td>California institute of Technology, USA</td>
</tr>
<tr>
<td>Marconi Applied Technologies</td>
<td>QCM, CP, MOS, SAW</td>
<td>8-28</td>
<td>Food and beverage quality, bacteria identification, explosives and drug detection, environmental monitoring</td>
<td>SPR Desktop</td>
<td>University of Warwick</td>
</tr>
<tr>
<td>Electronic Sensor Technology Inc</td>
<td>GC, SAW</td>
<td>1</td>
<td>Food and beverage quality, bacteria identification, explosives and drug detection, environmental monitoring</td>
<td>Desktop</td>
<td><a href="http://www.estcal.com">www.estcal.com</a></td>
</tr>
<tr>
<td>Forschungszentrum Karlsruhe</td>
<td>MOS, SAW</td>
<td>40, 8</td>
<td>Environmental protection, industrial process control, air monitoring in textile mills, fire alarms. Quality control in food production. Automotive applications</td>
<td>PCA</td>
<td><a href="http://www.fzk.de/FZK2/english">www.fzk.de/FZK2/english</a></td>
</tr>
<tr>
<td>HKR-Sensorsysteme GmbH</td>
<td>QCM</td>
<td>6</td>
<td>Food and beverages, cosmetics and perfumes, organic materials, pharmaceutical industry</td>
<td>ANN, CA, DFA, PCA Desktop</td>
<td><a href="http://www.hkr-sensor.de/">www.hkr-sensor.de/</a></td>
</tr>
<tr>
<td>Illumina</td>
<td>FO</td>
<td>–</td>
<td>Life sciences, food processing, agriculture, chemical detection</td>
<td>ANN</td>
<td><a href="http://www.illumina.com">www.illumina.com</a> Tufts University, USA</td>
</tr>
</tbody>
</table>

*Continued*
### Table V

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Sensor type</th>
<th>No. of sensors</th>
<th>Applications</th>
<th>Pattern recognition/comments</th>
<th>Website/reference/university background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lennartz Electronic GmbH</td>
<td>MOS, QCM</td>
<td>16-40</td>
<td>Food and beverage processing, perfume oils, agricultural odours and chemical analysis, process control</td>
<td>ANN, PCA</td>
<td><a href="http://www.lennartz-electronic.de/PDF_documents">www.lennartz-electronic.de/PDF_documents</a> University of Tubingen</td>
</tr>
<tr>
<td>Marconi technologies Mastiff Electronic Systems Ltd.</td>
<td>CP</td>
<td>16</td>
<td>Sniffs palms for personal identification</td>
<td>Desktop</td>
<td><a href="http://www.mastiff.co.uk/">www.mastiff.co.uk/</a></td>
</tr>
<tr>
<td>Microsensor Systems</td>
<td>SAW</td>
<td>2</td>
<td>Chemical agent detection, chemical warfare (CW) agents and toxic industrial chemicals (TICs) analysis</td>
<td>Palmtop</td>
<td><a href="http://www.microsensorsystems.com/pdf/hazmatcad">www.microsensorsystems.com/pdf/hazmatcad</a></td>
</tr>
<tr>
<td>OligoSense</td>
<td>CO</td>
<td>–</td>
<td>Automotive applications, food evaluation, packaging evaluation</td>
<td></td>
<td><a href="http://www.oligosense.be">http://www.oligosense.be</a></td>
</tr>
<tr>
<td>RST Rostock Raum-fahrt und Umweltschatz GmbH</td>
<td>MOS, QCM, SAW</td>
<td>6-10</td>
<td>Early recognition of fires, warning in the event of escape of hazardous substances, leak detection, workplace monitoring</td>
<td>ANN, PCA</td>
<td>Antwerp University, Belgium <a href="http://www.rst-rostock.de/">www.rst-rostock.de/</a></td>
</tr>
<tr>
<td>Shimadzu Co.</td>
<td>MOS</td>
<td>6</td>
<td>Diagnosing tuberculosis, bowel cancers, infections in wounds and the urinary tract</td>
<td>PCA, Desktop</td>
<td><a href="http://www.nose-network.org/">www.nose-network.org/</a> Cranfield University, Bedfordshire, England</td>
</tr>
</tbody>
</table>

**Notes:** MOS – metal oxide semiconductor; CP – conducting polymer; QCM – quartz crystal monitor; SAW – surface acoustic wave; IR – infra red; MOSFET – metal oxide semiconductor field effect transistor; GC – gas chromatography; FO – fibre optic; CO – conductive oligomer; ANN – artificial neural network; DC – distance classifiers; PCA – principle component analysis; DFA – discriminant function analysis; CA – cluster analysis; DA – discriminant analysis
### Table VI Summary of the properties of each sensor type reviewed

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Measurand</th>
<th>Fabrication</th>
<th>Examples of sensitivity/detection range/detection limits (DL)</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer composites</td>
<td>Conductivity</td>
<td>Screenprinting, spincoating, dipcoating, spray coating, microfabrication</td>
<td>ppb for HVPG ppm for LVPG; 1 per cent $\Delta R/R_0$/ppm; DL $\leq$ 0.1-5 ppm</td>
<td>Operate at room temperature, cheap, diverse range of coatings</td>
<td>Sensitive to temperature and humidity</td>
<td>Munoz et al. (1999), Gardner and Dyer (1997) and Ryan et al. (1999)</td>
</tr>
<tr>
<td>Intrinsically conducting polymers</td>
<td>Conductivity</td>
<td>Electrochemical, chemical polymerisation</td>
<td>0.1-100 ppm</td>
<td>Sensitive to polar analytes, cheap, good response times, operate at room temperature</td>
<td>Sensitive to temperature and humidity, suffer from baseline drift</td>
<td>Nagle et al. (1998)</td>
</tr>
<tr>
<td>Metal oxides</td>
<td>Conductivity</td>
<td>Screenprinting, RF sputtering, thermal evaporation, microfabrication</td>
<td>5-500 ppm</td>
<td>Fast response and recovery times, cheap</td>
<td>High operating temperatures, suffer from sulphur poisoning, limited range of coatings</td>
<td>Nagle et al. (1998)</td>
</tr>
<tr>
<td>SAW</td>
<td>Piezoelectricity</td>
<td>Photolithography, airbrushing, screenprinting, dipcoating, spincoating</td>
<td>1 pg to 1 mg of vapour 1 pg mass change; DL = 2 ppm for octane and 1 ppm NO$_2$ and 1 ppm H$_2$S with polymer membranes</td>
<td>Diverse range of coatings, high sensitivity, good response times, IC integratable</td>
<td>Complex interface circuitry, difficult to reproduce</td>
<td>Nagle et al. (1998), Albert and Lewin (2000) and Penza et al. (2001a)</td>
</tr>
<tr>
<td>QCM</td>
<td>Piezoelectricity</td>
<td>Micromachining, spincoating, airbrushing, inkjet printing, dipcoating</td>
<td>1.5 Hz/ppm; 1 ng mass change</td>
<td>Diverse range of coatings, good batch to batch reproducibility</td>
<td>Poor signal-to-noise ratio, complex circuitry</td>
<td>Nagle et al. (1998) and Kim and Choi (2002)</td>
</tr>
<tr>
<td>Optical devices</td>
<td>Intensity/spectrum</td>
<td>Dipcoating</td>
<td>Low ppb; DL (NH$_3$) = 1 ppm with polyaniline coating</td>
<td>Immune to electromagnetic interference, fast response times, cheap, light weight</td>
<td>Suffer from photobleaching, complex interface circuitry, restricted light sources</td>
<td>Jin et al. (2001) and Nagle et al. (1998)</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Threshold voltage change</td>
<td>Microfabrication, thermal evaporation</td>
<td>2.8 $\mu$V/ppm for toluene; DL = (amines, Sulphides) = 0.1 ppm; Maximum response = 200 mV especially for amines</td>
<td>Small, low cost sensors, CMOS integratable and reproducible</td>
<td>Baseline drift, need controlled environment</td>
<td>Covington et al. (2001) and Kalman et al. (2000)</td>
</tr>
</tbody>
</table>

Notes: HVPG – high vapor pressure gas; LVPG – low vapor pressure gas; $\Delta R/R_0$ – relative differential resistance change
the e-nose arrays are altered to provide different selectivity patterns to different gases (Schaller et al., 1998), and operating temperatures are usually between 50 and 170°C (Kalman et al., 2000).

The factors that affect the sensitivity of FET-based devices are operating temperature, composition and structure of the catalytic metal (Lundstrom et al., 1995; Schaller et al., 1998). The temperature is increased to decrease the response and the recovery times (Dickinson et al., 1998). Typical sensitivities of ChemFET sensors with carbon black-polymer composite sensitive films was found to be approximately 2.8 µV/ppm for toluene vapour (Covington et al., 2001). The detection limit of MOSFET devices for amines and sulphides was 0.1 ppm with Pt, Ir and Pd gates and the maximum response was approximately 200 mV especially for amines (Kalman et al., 2000). Response time varies from device to device and response times from milliseconds up to 300 s have been reported in the literature (Covington et al., 2001; Eisele et al., 2001; Wingbrant et al., 2003).

MOSFET sensors have a number of advantages and disadvantages when used in e-nose arrays. Gas sensing MOSFETs are produced by microfabrication, therefore reproducibility is quite good and the sensor can be incorporated into CMOS technology resulting in small, low cost sensors (Dickinson et al., 1998; Gu et al., 1998; Nagle et al., 1998; Pearce et al., 2003; Schaller et al., 1998). The sensors can suffer from baseline drift and instability depending on the sensing material used (Nagle et al., 1998). If CMOS is used, the electronic components of the chip have to be sealed because the sensor needs a gas inlet so it can penetrate the gate (Nagle et al., 1998). The gas flows across the sensor and also the operating temperature have serious effects on the sensitivity and selectivity of the sensor, so control of the surrounding environment is important (Eklov et al., 1997; Nagle et al., 1998). This does not suit a handheld e-nose.

**Commercial e-nose systems**

Manufacturers of commercial e-nose systems have become plentiful in recent times and produce a wide range of products utilising different sensor types depending mainly on the applications. Many of these systems are reviewed in Table V.

**Conclusions**

Conducting polymer composite, intrinsically conducting polymer and metal oxide conductivity gas sensors, SAW and QCM piezoelectric gas sensors, optical gas sensors and MOSFET gas sensors have been reviewed in this paper. These systems offer excellent discrimination and lead the way for a new generation of “smart sensors” which will mould the future commercial markets for gas sensors. The principle of operation, fabrication techniques, advantages, disadvantages and applications of each sensor type in e-nose systems have been clearly outlined and a summary of this information is given in Table VI.

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