Scientific Journal of Impact Factor (SJIF): 5.71

e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 5, Issue 04, April -2018

OVERVIEW OF CONTEMPORARY GAS SENSING TECHNOLOGIES IN E-NOSE APPLICATIONS

Ashok Kanade[1] and Arvind Shaligram[2]

[1]*Assistant Professor, Department of Electronic Science, P.V.P. College, Pravaranagar, India, 413713,*
[2]*Professor and Head, Department of Electronic-Science, Savitribai Phule Pune University, Pune, India, 411007,*

Abstract: *Different types of gas sensors are utilized in electronic noses (E-noses) that have partial specificity. In this paper, the main focus is on the range of sensors used in commercial and experimental electronic nose arrays to date. This review paper outlines the construction, working principles, sensing materials, fabrication processes and application areas of each sensor type which have been utilized. It also covers the advantages and disadvantages of each sensor type for a cost-effective, low-power and portable e-nose system.*

Keywords: *Gas sensors, e-nose sensor array, MOS sensors, SAW sensors, QCM sensors, MOSFET sensors, Optical sensors.*

I. Introduction:

The sense of smell has long played a fundamental role in human development and biosocial interactions. Consequently, the olfactory sense has become a key element in the development of many commercial industries to improve product appeal, quality, and consistency. 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. A group of experts called sensory panel 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. The relatively low sensitivity and discrimination capabilities of the human nose, coupled with the common occurrence of olfactory fatigue, has led to the need for electronic instruments with sensors capable of performing repeated discriminations with high precision[1-5]. The solution to the shortcomings of sensory panels and the associated analytical techniques is the electronic nose (e-nose). Rapid advances in sensor technologies have facilitated the development of high-performance electronic noses that can detect and discriminate volatile compounds in situ [2].

The E-Nose is an intelligent chemical-array sensor system that mimics the mammalian olfactory system. The two main components of an electronic nose (E-nose) are the sensing system and the automated pattern recognition system. Aromas in general are characterized by four quantifiable qualitative dimensions: threshold, intensity, quality, and hedonic (or pleasure) assessment [3]. The sensing system can be an array of several different sensing elements or a single device or a combination of both. The odor molecules are drawn into the e-nose using sampling techniques such as headspace sampling, diffusion methods, bubblers or pre-concentrators [1-3].Each “cell” in the array can behave like a receptor by responding to different odors to varying degrees. The most common types of changes utilized in e-nose sensor systems are Conductivity, Mass, Optical and Work function etc. [10]. These changes are transduced into electrical signals, which are preprocessed and conditioned before identification by a pattern recognition system primarily assisted by appropriate algorithms and software tools. The volatile organic compounds (VOCs) presented to the sensor array produces a signature or pattern which is characteristic of the vapor. By presenting many different chemicals to the sensor array, a database of signatures can be build up. Nevertheless, the electronic nose often has the advantage of detecting certain odorless compounds that are not detectable by the human nose.

Recent applications of electronic nose technologies have come through advances in sensor design, material improvements, software innovations and progress in microchip design and systems integration. The invention of many new e-nose sensor types and arrays, based on different detection principles and mechanisms, is closely correlated with the expansion of new applications. Electronic noses have provided a plethora of benefits to a variety of commercial industries, including the agricultural, biomedical, cosmetics, environmental, food, manufacturing, military, pharmaceutical, regulatory, and various scientific research fields [1-2, 16, 19]. The selection of sensors is application specific. The choice of sensors, geometrical arrangement of the sensor array and appropriate arrangements for the sniffing and replenishing of the sensing area is critically important for good quality E-Nose.

This paper critically reviews many contemporary sensor technologies. Primarily conducting polymer composite, intrinsically conducting polymer and metal oxide conductivity gas sensors, Surface Acoustic Wave (SAW) and Quartz Crystal Microbalance (QCM) based piezoelectric gas sensors, optical and MOSFET gas sensors technologies have been reviewed. A detailed discussion on Fiber optic based distributed gas sensor arrangement is included. The principle of operation, fabrication techniques, advantages, disadvantages and applications of each sensor type in e-nose systems have been described in details.

It is noted that Intrinsically Conducting Polymers (ICP) has 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 is available in the market. ICP sensors operate at room temperature thereby simplifying the required system electronics. Thin and thick film metal oxide sensors provide advantages such as fast response and recovery times [6]. 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. However, their high operating temperatures results in increased power consumption over sensors fabricated from materials other than metal oxides. SAW and QCM devices can detect a broad spectrum of odors due to the availability of wide range of gas sensitive coatings and they also offer high sensitivity and fast response times and their fabrication is compatible with current planar IC technologies. Optical fiber sensor arrays are yet another approach to odor identification in e-nose systems. The sides or tips of the optic fibers are coated with a fluorescent dye encapsulated in a polymer matrix. Changes the dye's optical properties such as intensity, spectrum, lifetime or wavelength shift in fluorescence are used as the response mechanism for odor detection. These compact, lightweight optical gas sensors can be multiplexed on a single fiber network, immune to electromagnetic interference (EMI) and can operate in high radiation areas due to Bragg and other grating based optical sensors. MOSFET sensors have quite good reproducibility and the sensor can be incorporated into CMOS technology resulting in small, low cost sensors.

A comparative techno-commercial analysis of contemporary gas sensor technologies in variety of E-Nose applications is presented in this paper.

II. Electronic nose (E-nose) technology

"An electronic nose is an instrument which comprises an array of electronic chemical sensors with partial sensitivity and an appropriate pattern recognition system capable of recognizing simple or complex odors"[1]

The electronic nose attempts to emulate the human olfactory system [2]. This concept is emulated artificially in an electronic nose consisting of an array of sensors and a pattern recognition algorithm for odor recognition. Figure 1 shows the basic components of the human olfactory system and compares it with an electronic nose system [3].

The human olfactory system consists of three essential elements: an array of olfactory receptor cells situated in the roof of the nasal cavity, the olfactory bulb which is situated just above the nasal cavity and the brain. Olfactory receptors are a group of chemical sensors, which produce a time-dependent electrical signal in response to the odor. The cerebral cortex of the brain, which is the final stage in the human olfactory process, classifies and memorizes the odor [3].

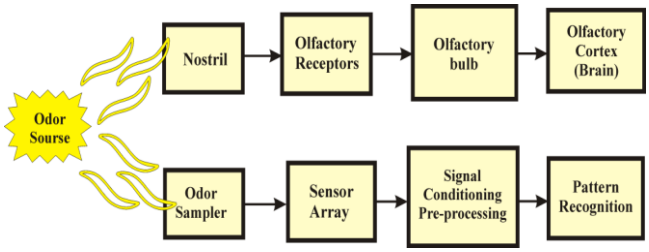

Figure 1 Analogy between biological olfaction system and electronic nose system

The electronic nose also has three main elements: the sensor array, data pre-processing and pattern recognition (PARC) engine. The sensor array of an electronic nose gives a unique overall response pattern for the volatiles [4]. The odor/vapor is then identified using data pre-processing and pattern classification techniques. The electronic nose has both large differences in sensitivity and selectivity from the human nose as the sensors used in an electronic nose respond to both odorous and odorless volatile compounds [4].The analogy between biological olfaction system and electronic nose system is shown in figure 1.

The basic principle of e-nose is that each odor results in a characteristic pattern or fingerprint of sensor array response [5]. Based on this assumption, the process begins by collecting the signal responses from each sensor, which occurs by converting the chemical reaction into an electrical signal. Many gas sensors exhibit a response profile for several analytes. The degree of selectivity and the type of odors that can be detected largely depend on the choice and number of sensors in the sensor array.

The sensors are mounted in an air tight chamber containing gas inlets and outlets to control the gas flow. The sampling system or odor delivery system (ODS) plays an important role in the design of an electronic nose system. It aids in bringing the odorant molecules to the sensing surface of the sensor array. The signals from each sensor are digitized and data is transformed by a variety of pre-processing techniques. Features are extracted for odor identification and analysis using pattern recognition.

The odor delivery system significantly contributes to the capability and reliability of an electronic nose. There are two main types of odor delivery systems, the static system and the dynamic flow system [2].The fundamental static system measures the steady-state response of a sensor to a vapor at constant concentration and at a constant temperature. In the dynamic (sample) flow system, the sensors are placed in the vapor flow. There is several sample flow systems exist such as headspace sampling, diffusion, permeation, bubbler and sampling bag methods [2].The different odor delivery systems are shown in figure 2.

The sensor arrays consists of two or more sensors with certain degree of affinity towards a specific gas but are sensitive towards a wide spectrum of gas types with partially overlapping sensitivities [6]. It is also necessary that odor interaction with sensor material is reversible, response drift is negligible, training protocols be relatively intuitive, and calibration and sensor preparation are replicable [7].

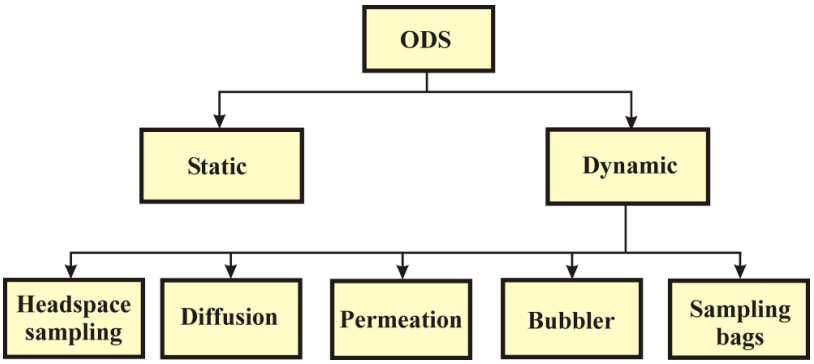

Figure 2 Odor delivery systems

There are several different types of gas sensors used in an e-nose array depending on application. Commonly used gas sensors include metal oxide semiconductor (MOS) [6], conducting polymer (CP) sensors [8], acoustic wave sensors [9], field-effect gas sensors [10], Pellistors [11] and Optical sensors [12]. Many of these sensing technologies are explored in research and have also been implemented on commercially available electronic noses [13]. Each of these sensors has certain advantages and disadvantages over their counterpart and choosing the right kind of gas sensor depend on the application.

There are various stages in the signal processing of an e-nose system in which the signals generated from an array of sensors are first pre-processed and then fed in to a pattern analyzer. In other words the n dimension vector in sensor space is transformed into feature space (a process called feature extraction) and then identified using some form of pattern classifier. The data pre-processing is the first stage after the sensor array data has been sampled. The goal of data pre-processing is to extract relevant information from the sensor responses and prepare the data for pattern analysis. The choice of data preprocessing is critical and can have a significant impact on the performance of subsequent modules in the pattern analysis [14].For a typical sensor array configuration, acquired signals are represented in terms of voltage or conductance. Although signal pre-processing is somewhat dependent on the underlying sensor technology, three general stages can be identified: baseline manipulation, compression and normalization.

The first stage of pre-processing consists of manipulating the sensor response with respect to its baseline (e.g., response to a reference analytes) for the purposes of drift compensation, contrast enhancement and scaling. Considering the dynamic response of the sensor x_s *(t)* shown in Fig. 3,

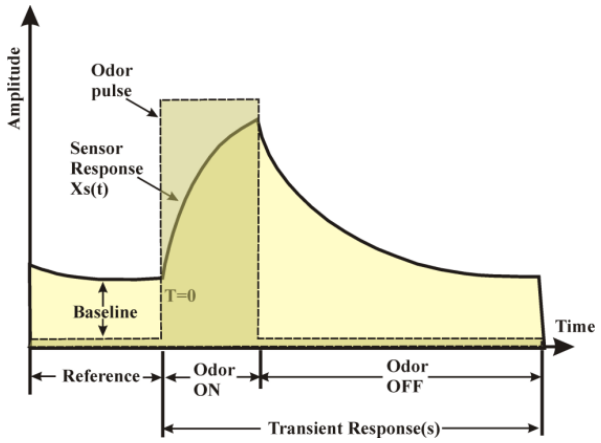

Figure 3 Gas sensor transient response to an odor pulse

The first stage in odor 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 3. 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 analyzing the odor is sensor response manipulation with respect to the baseline. This process compensates for noise, drift and also for inherently large or small signals. The three most commonly used standard preprocessing methods as defined by electronic nose designers are as listed in Table 1 [14, 15].

Table 1 Some different pre-processing algorithms used to generate static parameters xij ; Frequency (f),Resistance(R),Conductance(G),Signals(S),Baseline(0),Sensor(i),odor(j).

Sensor Type	Method	Specific Formulae
Metal oxide Resistor/Polymer Resistor	Difference	$X_{ij} = R_s - R_o$
Metal oxide Resistor/Polymer Resistor	Relative	$X_{ij} = R_s / R_o$
Metal oxide Resistor/Polymer Resistor	Fractional Change	$X_{ij} = (R_s - R_o) / R_o$
Metal oxide Resistor/Polymer Resistor	Log Parameter	$X_{ij} = \ln (R_s / R_o)$
BAW/SAW	Difference	$X_{ij} = f_s - f_o$
Metal oxide Resistor/Polymer Resistor	Difference	$X_{ij} = G_s - G_o$
Metal oxide Resistor/Polymer Resistor	Fractional Change	$X_{ij} = (G_s - G_o)/ G_o$

Pattern recognition is used in the final stage of the electronic nose for odor identification. It can be broadly classified as statistical and artificial neural network (ANN) based. There are a large number of pattern recognition techniques that have been applied to e-nose technology and reported [16]. Some of these techniques are quantitative and others qualitative as illustrated in Figure 4.A good electronic nose designer will be able to investigate a particular problem, and thus determine the optimal combination of pre-processing algorithm (e.g. relative) and pattern recognition (e.g. MLP neural network).

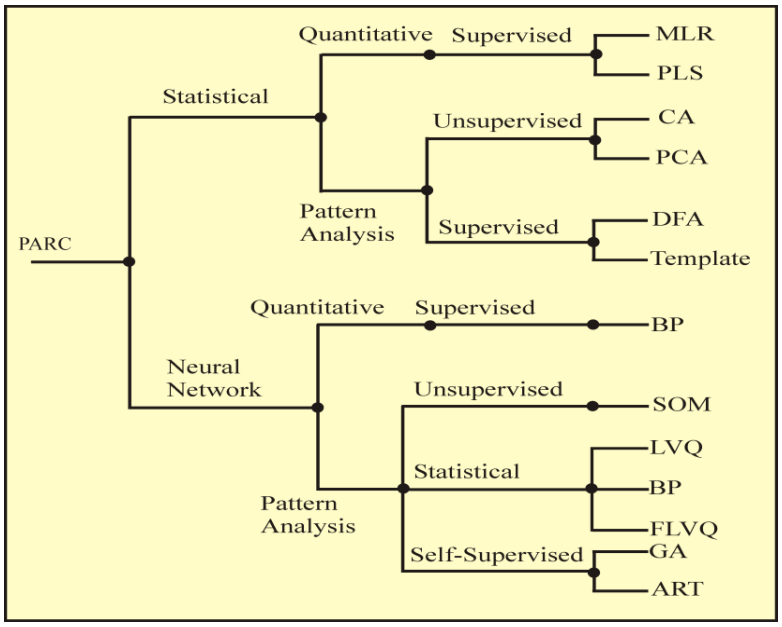

Figure 4 Pattern recognition techniques employed by electronic noses

III. Sensors used in e-nose array

Selection of sensor technology relies on many factors, such as the nature of the analyte to be identified, the nature of the sample evaluation, the principle and the condition of the analysis. The ideal sensors to be added in an electronic nose (E-nose) should attain the following properties: High sensitivity to chemical compounds, i.e. similar to the human nose near 10^{-12} g/mL, Low sensitivity towards humidity and temperature, Medium selectivity, i.e., respond to special compounds present in the sample, High stability, High reproducibility and reliability, Short response and recovery time, Dynamic and long lasting, Easy to calibrate, Easily processable data output, Small size [17].

There are many types of gas sensors available; their use depends on type of application and surrounding environment. The sensors which are used to detect the molecules of chemicals are based on the measurement principles such as electrical, thermal, optical, and mass changes. Figure 5 shows the different types of sensors used in e-nose array.

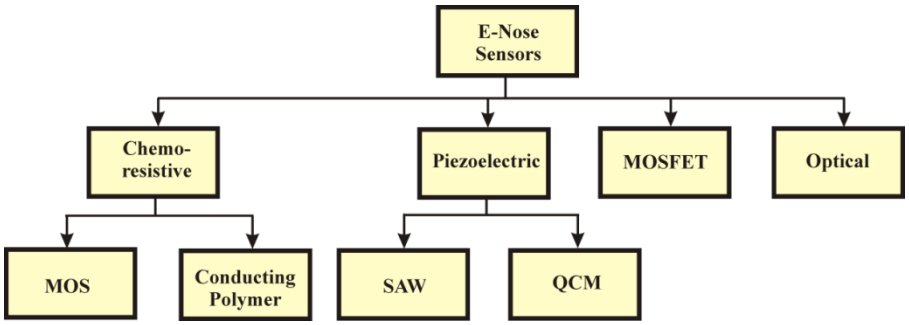

Figure 5 Different types of sensors used in e-nose array

3.1 Conductivity/Chemo-resistive sensors

The electrical resistance of a chemically sensitive layer changes drastically when exposed to the molecules of analyzing gas. The mechanisms of changing resistance are different for each material type but the structure and layout of chemo-resistive sensors prepared using these materials are essentially the same [18].There are two most commonly used chemo-resistive sensors i) Conducting polymer and ii)Metal oxides semiconductor. A constructional diagram of chemo-resistive sensor design is shown in Figure 6. The active gas sensitive material is deposited over two parallel electrodes, which serves as electrical connector through which change in resistance of the film is observed. When metal oxide semiconductors are used as sensing material then the heater is required because they operates at very high temperature [18].

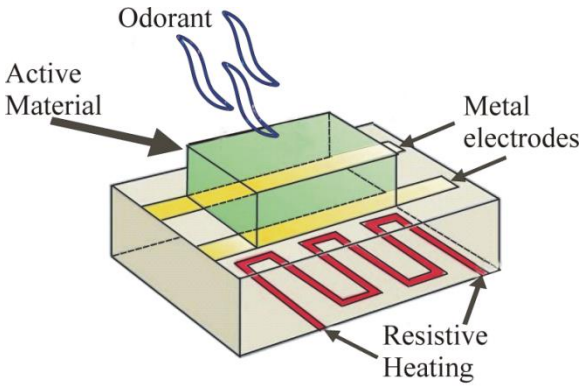

Figure 6 Typical structure of conductivity/chemo-resistive sensor

3.1.1 Conducting Polymer sensors

Chemo-resistors made from organic CPs also exhibit a change in conductance when they are exposed to reducible or oxidizable gases. Organic CPs show reversible changes in conductivity when chemical substances (e.g. methanol, ethanol, and ethylacetate) adsorb and desorbs from the polymer [19].

As soon as the polymer composite sensor is exposed to a vapor of chemical/gases, some of the vapor permeates into the polymer and causes the polymer film to expand. The vapor-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 [20] .The typical schematic of conducting polymer gas sensors is shown in fig. 7.

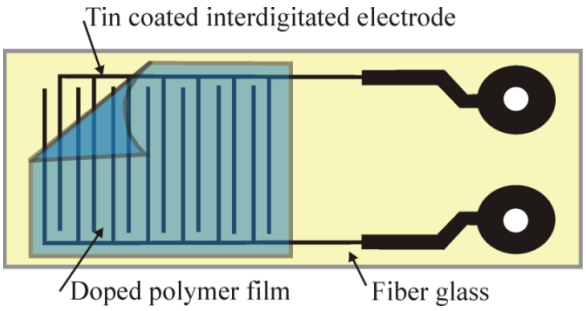

Figure 7 Schematic of conducting polymer

There are a large number of different electronically conducting polymers. Polypyrrole was first prepared electrochemically in 1968 [21] and has been most extensively studied so far. Typical polymers are constructed from monomers such as pyrrole, aniline, thiophene, indoles or furans. The most commonly used CPs for gas-sensing applications are polypyrrole, polyaniline, polythiophene, and polyacetylene [22] and their derivatives such as Polyterthiophenes, ployfluorines, poly-3-alkylthiophenes, polytetrathiafulvalenes, polynapthalenes, polyphenylene sulfide, poly-phenylenevinylenes, poly-3, 4 thylenedioxythiophene, polyparaphenylene, polyazulene, polyparaphenylene

sulfide, polycarbazole, and polydiaminonaphthalene have been used as the active layers of gas sensors since early 1980s by various researchers[17-20]].

The synthesizing processes of CP are comparatively easy and their structure can be modifiable conveniently by copolymerization or structural derivations. They has high sensitivities and short response time at room temperature.

Conducting polymers exhibits both metallic and semiconductor characteristics combinely which differs them from any other known material. The conjugated double bonds along the backbone of polymer are the key interesting property. The bonds between the carbon atoms are alternately single and double. For example, the structure of Polyacetylene is shown in Fig. 8.

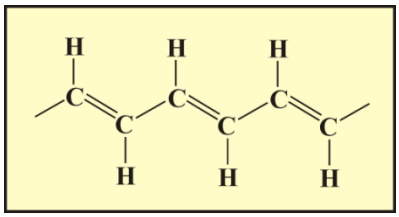

Figure 8 Polyacetylene chain

The molecular interaction capabilities of a polymer can be selectively modified by changing doping concentration during polymer preparation or by attaching functional groups to the polymer backbone [19].Chemoresistors using organic CPs respond to a wide range of polar molecules at temperatures as low as room temperature (RT) and high sensitivity near to 0.1 ppm is possible.

The conductivity of CP film changes when it is exposed with reactive gases and the bonding takes place with the polymer backbone. The bonding may be ionic or covalent. The bonding affects the transfer of electrons along the polymer chain that means conductivity changes when interaction between polymer chain and reactive species of gas takes place.

A given compound's affinity for a polymer and its effects on the polymer's conductivity are strongly influenced by the counter-ions and functional groups attached to the polymer backbone [19]. The use of conducting polymer nano composites/nano particles could greatly improve diffusion since they have much greater exposed surface area and as a result of this the basic characteristics of a biosensor like low detection limit get enhanced[17-22].

Different techniques have been developed to prepare conducting CP films, in order to adapt to different sensing materials and different types of sensor configurations. The methods includes electromechanical deposition[23-24],Dip-coating[25-28],Spin-coating [29-30], Langmuir-Blodgett (LB) technique , Layer-by-layer (LBL) self-assembly technique[31-32], Thermal evaporation[33], Vapor deposition polymerization[34], Drop-coating[35-36], inkjet-print film[37]

The chemo-resistive sensors based on conducting polymers and their composites for detection of several gas analytes are listed in table 2.

The organic CP is a potentially useful material for gas sensing applications .These materials have many good feature like i) wide range of materials can be simply prepared ;ii)
relatively low cost materials; iii) high sensitivity towards many kinds of organic vapors; iv) gas sensors using organic CPs operate at low temperatures [38].

Table 2 Conducting polymer and their composites based sensors for different gas analytes

Analyte	Sensing material	Detect limit	Ref.
NH3	PAni /SWNT	50 ppb	[39]
	PPy /PET	<20 ppm	[40]
	PTh /CuPc	4.3 ppm	[41]
	PAni/In_2O_3	<0.5 ppm	[42]
HCl	PAni /FeAl	0.2 ppm	[43]
H2S	PAni/heavy metal salts	<10 ppm	[44]
CO	PAni /FeAl	10 ppm	[45]
	PAni/In_2O_3	<60 ppm	[42]
Water	PAni	< 25 ppm	[46]
Methanol	PAni/Pd	<1 ppm	[47]
Methane halide	Poly(3-methylthiophene)/MWNT	Several ppm	[48]
	PAni/Cu	<10 ppm	[49]
Acetone	PTh copolymer	200~ 300 ppm	[50]
Toluene	PTh copolymer	20 ppm	[50]
Butylamine	Poly(anilineboronic acid)	10 ppb	[51]

3.1.2 Metal oxide semiconductor (MOS)

Metal oxide semiconductor sensors resistance varies when they are in vicinity of reducing gases. The change of resistance is proportional to the concentration of the gas. This type of sensors are most popular because they have lot of advantages like relatively inexpensive, stable in time, high sensitivity from 0.1 ppb to 500 ppm [52-54] , high chemical

resistance and are easy to operate.[55-56]. Basically, these sensors comprise a ceramic support containing a platinum heater spiral onto which metal oxide semiconducting film is coated onto the external side of the ceramic support [57-58]. Figure 9 and 10 shows the basic construction of the sintering-type and thin-film type of gas sensors.

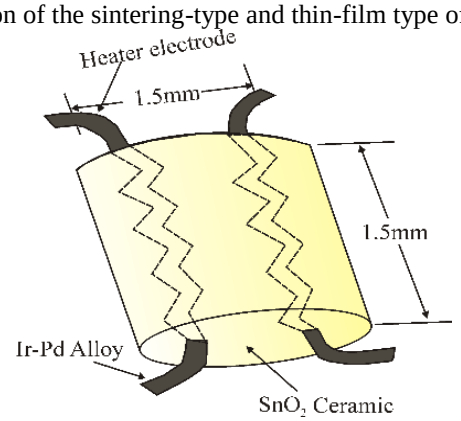

Figure 9 Sintering-type MOS sensor

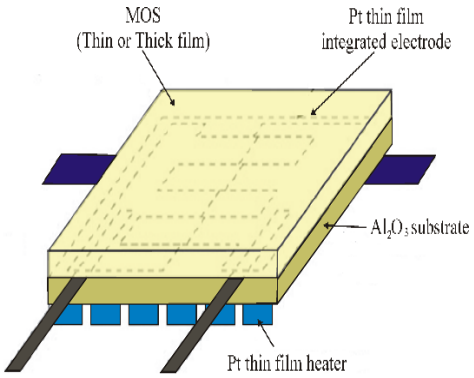

Figure 10 Thin-film type MOS sensor

In Fig. 9 and 10, sensors consists of a sensitive layer, an insulating layer, two electrodes, and a heating layer. At temperature level of 250–450^{0}C, the semiconducting layer oxidizes the sample compound. Therefore, the semiconducting substance adsorbs the free electrons and its conductivity changes. As a result, the change of resistance in the electrical circuit is registered.

There are two types of metal oxide coatings may be either p-type or n-type semiconductor. Metal oxides such as SnO_2, ZnO, TiO_2, Fe_2O_3, and WO_3 are intrinsically n-type semiconductors. At temperatures of 200–500 ^{O}C, these responds to reducible gases such as H_2,CH_4, CO, C_2H_5, or H_2S and increase their conductivity.[59].The p-type semiconductors such as CuO, NiO, and CoO respond to oxidizable gases such as O_2, NO_2, and Cl_2 [60].

When sensor is heated to a high temperature, e.g. 400°C, without the presence of oxygen, free electrons flow easily through the grain boundaries of the tin dioxide (SnO_{2-X}) particles. When sensor is present in clear air, oxygen atoms that traps free electrons by its electron affinity, is adsorbed on to the tin dioxide particle surface forming a potential barrier in the grain boundaries. This potential barrier (eVs in air) restricts the flow of electrons, causing the electric resistance to increase (Fig. 11).When the sensor is exposed to an atmosphere containing reducing gases, e.g. combustible gases, CO, etc, the tin dioxide surface adsorbs these gas molecules and causes oxidation. This lowers the potential barrier, allowing electrons to flow more easily, thereby reducing the electrical resistance (Fig.12).

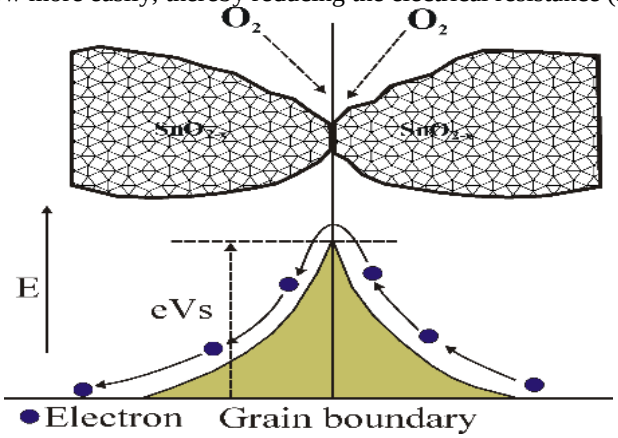

Figure 11 Potential barrier in the absence of reducing gas

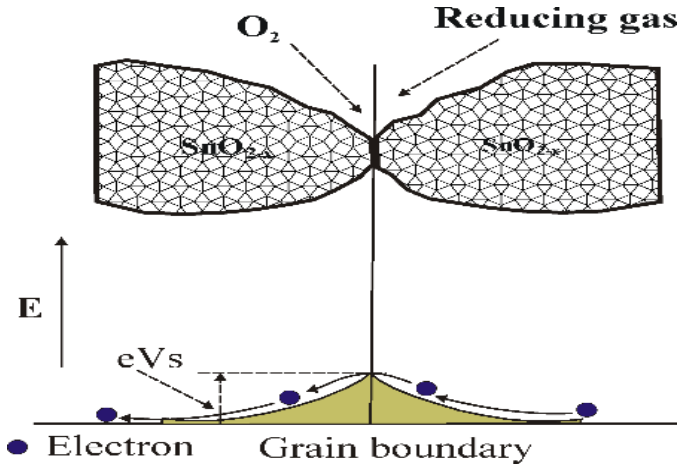

Figure 12) Potential barrier in the presence of gases

The relationship between sensor resistance and the concentration of deoxidizing gas can be expressed by the following equation over a certain range of gas concentration:

$$Rs = A[C] - \alpha \quad (1)$$

Where:
Rs = electrical resistance of the sensor
A = constant
[C] = gas concentration
α = slope of Rs curve

The mechanism of the increase in carrier concentration by reacting with the reducible gases can be explained by following reactions:

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

$$R(g) + O(s)^- \rightarrow RO(g) + e \quad (3)$$

Where e is conduction band electron of metal oxide (g) is reducible gas, and s and g is surface and gas respectively. Equation (2) indicates that oxygen in air is adsorbed on to lattice vacancies in metal oxide surface or grain boundaries of the oxide grain. This increases the resistance of the area due to lack of carriers and the resulting potential barriers produced between the grains inhibit the carrier mobility, means conductivity is lowered.

When reducing gas like H_2, CH_4, CO, C_2H_5 or H_2S is in contact with the metal oxide surface then it reacts with oxygen atoms present at surface and free electron generates as explained in equation (3), this lowers the potential barrier and allows the electrons to flow, thereby increasing the conductivity. The reaction rate between reducing gases and surface oxygen are depending on the operating temperature of the sensor and the activity of sensor materials.

The MOS sensors are usually doped with little amounts of catalytic metal or metal oxide additives such as Pt, Pd, Cu and Au [61]. The humidity and temperature dependency is diminished by the doping and also to increase the sensitivity and the selectivity of the sensor [62-63]. The care should be taken that excessive doping may be reducing sensitivity [57].

Metal oxide semiconductor gas sensors have been produced by thick and thin fabrication methods. Deposition techniques include physical or chemical vapor deposition [64], thermal evaporation [65], spraying [66], spincoating (67), sol-gel processes [68]. RF sputtering (69) for thin films (6–1,000 nm).A screen printing and painting for thick films (10–300 μm) [70].The films deposited onto flat or tube type substrate made of alumina, glass, silicon or ceramic [64-70]. The electrodes for electrical contacts are deposited onto the substrate using the same methods and materials may be Gold, platinum, silver or aluminum. The interdigitated structure of electrode is most preferred. The heater is printed back of the substrate to provide adequate temperature requirement typically 200-500^{O}C.

The thickness of the sensing film decides the response time (faster for thin films), sensitivity (higher for thin films), reproducibility (higher for thick films), cost (lower for thick films) [57-58]

These types of sensors are works in temperature range of 300-500^{O}C, which shows the humidity dependency effect on analysis result and decreasing the response and recovery time [64].To overcome this additional heater is required for sensor. The old edge electronic nose instruments were bulky and require high electrical energy due to heater. For this reason, consuming less energy sensors with a thin layer of metal oxides were utilized [57].Nowadays, these type of sensors are small and despite of high operating temperature, their power consumption is relatively low (tens of mW), making them useful for portable instruments [61, 72]

The type of sensor materials with relative operating temperatures and detectable gases of typical gas sensors using MOSs that have been reported so far are listed in Table 3.

Table 3 Typical sensor material with operating temperature and detecting gases

Materials (Dopants)	n-type or p-type	T_{op} (^oC)	Detecting gases	Ref.
ZnO(Al)	n	250	C_2H_5OH	[73]
ZnO(Al)	n	350	NH_3	[74]
ZnO(Al,In,Ga)	n	400	TMA	[75]
ZnO(Cu)	n	150-400	CO	[76]
ZnO(Al_2O_3)	n	250-450	H_2	[77]
SnO_2	n	200-500	NO_2,SO_2,C_2H_5OH,NH_3	[78]
WO_3(Pt)	n	250-400	N_2H_4, NH_3, H_2S,H2	[79]
WO_3	n	500	CO, CH_4, SO	[80]
TiO_2(Ru)	n	560	NH_3	[80]
□-Fe_2O_3	n	400	H_2, CH_4	[81]
□-Fe_2O_3	n	420	H_2, CH_4, $C_3H_8C_4H_{10}$, C_2H_5OH	[81]
$CdIn_2O_3$	n	300	CO	[80]
$CuTa_2O_6$	n	400	H_2, CO	[80]
CuO/ZnO	p/n	250	H_2, CO	[82]
Co_3O_4	p	200-500	CO, H_2, NO_X	[83]
Cr-TiO_2	p	350-400	NO_2,O_2	[84]
In_2O_3	n	300	CH_4,H_2,NO,CO,C_3H_6	[85]
$BaSnO_3$	n	300-500	H_2, CO, CH_4, H_2S, SO_2	[80]
$Bi_2Sn_2O_7$	p	500	H_2, CO, C_2H_4, NH	[80]
$Bi_6Fe_2Nb_6O_{30}$	n/p	500	C_3H_8, Cl_2, NO_2, SO_2, H_2S	[80]

Gas sensors based on MOS are commercially available. They have been more widely used to make e-nose arrays for odor measurement than any other class of gas sensors [86].Table 4 lists some of the commercially available gas sensors of SnO_2 and ZnO that are manufactured by Figaro Engineering Inc. (Japan) [6], HANWEI ELETRONICS CO.,LTD [87]

Table 4 Commercially available metal oxide semiconductor sensors

Manufacturer	Model	Target Gas Sensitivity	Typical detection range
FIGARO ENG	TGS2600	Air contaminants (hydrogen, ethanol, etc.	1 - 30ppm
	TGS2602	Air contaminants (VOCs, ammonia, H2S, etc.)	1 - 30ppm
	TGS2603	Air contaminants (Trimethylamine, methyl mercaptan, etc.)	1 - 10ppm
	TGS8100	Air contaminants (hydrogen, ethanol, etc.)	1 - 30ppm
	TGS826	Ammonia	30-300ppm
	TGS2444	Ammonia	10 ~ 300ppm
	TGS3870	Methane, Carbon Monoxide	CH_4 - 500-12500 ppm, CO - 50-1000ppm
	TGS821	Hydrogen	30-1,000ppm)
	TGS823	Alcohol, Solvent vapors	50-5,000ppm
	TGS2620	Alcohol, Solvent vapors	50 - 5,000 ppm
	TGS823	Alcohol, Solvent vapors	50-5,000ppm
	TGS2620	Alcohol, Solvent vapors	50 - 5,000 ppm
	TGS816	Methane, Butane, Propane	500 - 0,000ppm
	TGS2610-C00	Butane, Propane	100-10000ppm
	TGS2610-D00	Butane, Propane	100-10000ppm
	TGS2612	Methane, Propane, Butane	100-10000ppm
	TGS6810-D00	Methane, Propane, Butane	100-10000ppm
	TGS6812-D00	Hydrogen, Methane, Butane, Propane	100-25000ppm
	TGS832-A00	Halocarbon gas	10 - 1,000ppm
	TGS832-F01	Halocarbon gas	1,000 -10,000ppm
	TGS816	Methane, Butane, Propane	500 - 10,000ppm
	TGS2611-C00	Methane	100-10000ppm
	TGS2611-E00	Methane	100-10000ppm

	TGS816	Methane, Butane, Propane	500 - 10,000ppm
HANWEI LTD.	MQ-2	General combustible gas	200-10000ppm
	MQ-3	Alcohol Vapor	0.05mg/L—10mg/L
	MQ-4	Natural gas, Methane	200-10000ppm
	MQ-5	LPG, Natural gas, Coal gas	300-10000ppm
	MQ-6	LPG, Propane	200-10000ppm
	MQ-7	Carbon Monoxide (CO)	20ppm-2000ppm
	MQ-8	Hydrogen	100-10000ppm
	MQ-9	CO and Combustible gas	10-1000ppmCO; 100-10000PPm Gas
	MQ131	Ozone O3	10-1000ppm
	MQ135	Air Quality Control (NH3,Benzene,Alcohol,smoke)	10-10000ppm
	MQ136	Sulfur dioxide SO_2	1-200ppm
	MQ137	Ammonia (NH3)	5-500ppm
	MQ138	VOC (Mellow, Benzene, Aldehyde, Ketone, Ester)	5-500ppm
	MQ216	Natural gas\Coal gas	500ppm-10000ppm
	MQ303A	Alcohol	20-1000ppm
	MQ306A	LPG, Propane	100-10000ppm
	MQ309A	Carbon Monoxide (CO), Flammable Gas	300-10000ppm

MOS-based electronic noses are find applications in much diversified fields like Food industry, quality control, monitoring process, aging, geographical origin, adulteration, contamination and spoilage detection etc.

During several years back electronic noses based on MOS sensors have been developed for the classification and recognition of different variety of foods products[88-89], fruits [90-91] ,coffees [92], meats [93-95], fishes [96-98],oils[99], cheese [100], spirits [101] , wines [102-104],dairy products [105-106],environment [107], Eggs [108-109],Grains[110] etc.

3.2 Piezoelectric sensors

Piezoelectric odor sensors uses acoustic wave devices that works on the principle that a change in the mass of the piezoelectric sensor coating due to odor molecule absorption results in a varying the resonant frequency [18].This group consists of two types of sensors, the surface acoustic wave (SAW) device and the quartz crystal microbalance (QCM) or bulk acoustic wave (BAW). In both types, the basic device consists of a piezoelectric substrate, such as quartz, lithium niobate and ZnO, coated with a suitable sorbent membrane [111].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 [59].These devices uses the ultrasound band of frequencies from 1 to 500 MHz.

3.2.1 SAW

Recently SAW-based gas sensor has gained increasing attentions due to its high sensitivity, quick response time and easy reproducibility [111].The SAW device is made of a piezoelectric substrate with interdigitated electrodes deposited on top of the substrate to excite the oscillation of the surface wave. The sensitive film which is selective to volatile compounds is placed between the input and output electrodes as shown in Figure 13.The sensing film often made from polymers, lipids, Langmuir-Blodgett films or self-assembled monolayers [112].When an ac signal is applied across the input electrode, then a two dimensional wave is created that travels along the surface of the crystal. When compatible odor molecules gets interacts with the gas sensitive membrane film, then mass of the gas sensitive membrane of the SAW device is changed and causes the frequency of the wave to be altered. The change in frequency due to absorption of a VOC vapor is expressed by

$$\Delta f = \Delta f_p \, c_v K_p / \rho_p \tag{4}$$

WhereΔf_p is the change in frequency caused by the membrane, c_v is the vapor concentration, K_p is the partition coefficient,ρ_p is the density of the polymer membrane used (112-113).

SAW sensors can produce different types of waves such as Rayleigh waves, surface transverse waves, Bleustein-Gulyaev wave and Lamb and Love waves which depend on the geometry of the acoustic structure and on the frequency scaling [62].

The substrate generally made of materials having piezoelectric properties such materials are zinc oxide (ZnO), lithium niobate (LiNbO3), lithium tantalite (LiTaO3) or quartz [18,59].SAW devices sensitive membrane film is usually polymeric or liquid crystal, however, phospholipids and fatty acids produced by variety of techniques such as photolithographic method in which 20-30nm thick films were deposited using airbrush techniques [113,62],Langmuir-Blodgett [61], screen printing techniques[114],dip coating and spin coating[115], spray coating[116].

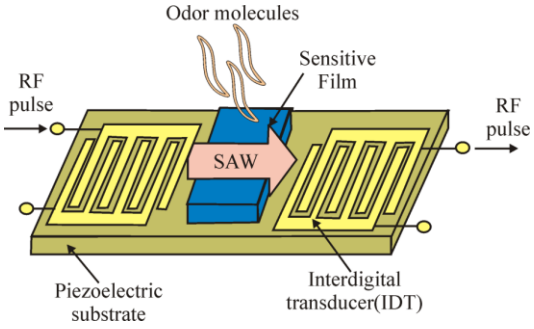

Figure 13 SAW sensor

The gas sensing properties and applications of SAW devices reported on the measurement of inorganic gases such as NO_2, H_2, H_2S, and SO_2 and organic gases such as CH_4, C_6H_6, and C_2H_5OH. This type of sensor using polymer materials as a sensing membrane can be chemically modified to obtain a higher degree of specificity, because the choice of chemically sensitive membrane determines the selectivity of the sensor [117].The SAW odor sensors are works at much higher frequencies in order of GHz. The main problems with SAW odor sensor are a relatively poor long-term stability and a high sensitivity to humidity. A good review of acoustic sensors is available [118].

3.2.2 QCM

Quartz crystal microbalance (QCM) sensors are also commonly referred bulk acoustic wave devices (BAW) or thickness shear mode (TSM) devices. These devices are working on the same principles as SAW. In e-nose application a QCM odor sensor comprises of a crystal of quartz disc coated with the odor absorbing polymer layer. The polymer films such as propylene-butyl, polycarbonate, and acrylic resin for sensitive towards toluene, acetaldehyde, and ammonia gas, respectively, deposited on the QCM surface [59]. The coatings are semi-selective thus allowing for reversibility of the sensors. The two thin film gold electrodes are evaporated onto opposite surfaces of quartz disc coated with sensing film, typically around 1 cm in diameter as shown in figure 14. Small structures fabrications are possible using micromachining technique. Coatings of 10nm to 1mm are applied using spincoating, airbrushing, inkjet printing or dip coating [119].If QCM devices are excited by suitable AC voltage across the two electrodes, the device can oscillate at its characteristic resonant frequency between 10 and 30MHz [119]

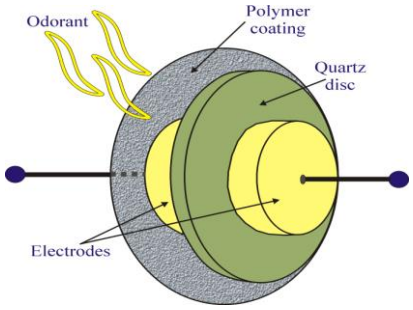

Figure 14 QCM sensor

When surface of the quartz crystal coated with sensing membrane is exposed to odor molecules, the surface absorbs gas, which results in an increase of its mass. This increase in mass causes the change in resonant frequency of the quartz crystal. This change in resonant frequency is proportional to the absorbed gas concentration and hence used to detect the odors [18].The sensitivity of QCMs is given by

$$\frac{\Delta f}{\Delta c} = \frac{(-2.3X10^{-6})f^2}{A} \quad (5)$$

Where f is stands for fundamental frequency, c for concentration and A is the area of the sensitive film. Higher sensitivity can be obtained by using higher frequencies and smaller surface areas of sensitive membrane coatings [120].

The polymer-film-coated QCM odor sensor with adequate selectivity and high sensitivity for harmful gases such as toluene, xylene, ammonia, and acetaldehyde was worked out [121].

The response times for polymer-coated BAW devices are determined by the diffusion of the vapor into the polymer film, typically ranging from 10 to 100 secs, which cannot be considered as very fast. On the other hand, their common disadvantage is the sensitivity to changes of temperature, humidity and flow conditions.

The research on gas applications using QCM odor sensors are reported by various researchers as spirits, perfumes and odors [122-123], Ethanol[124], VOCs such as aromatics, chlororganics, ketones, and alcohols[125], Alcohols, esters, acids, and Aldehyde[126], Methane[127], NO[128], NO_2[129], NH_3[130], Olive oils [131]

3.3 MOSFET

It is a gas sensing device used in electronic nose to convert a physical or chemical change into an electrical signal. The micro chemosensor uses the MOSFET structure in which gas sensitive metal such as Palladium gate was first reported by Lundstrom in 1975 for H_2 sensing [132]. The catalytic metals or metal alloys such as platinum (Pt), palladium (Pd), iridium (Ir) and alloys may be used to fabricate the gate. The gas sensitive metal gate material must be in porous nature to facilitate diffusion of gas into the material and easily reach towards the metal-insulator interface [133].The gate is left open to facilate interaction with gas vapors. When compatible reacting gas adsorbed on to the surface of gas sensitive metal gate then the surface-charge density of metal gate alters and thus sensor exhibited a threshold voltage shift. The voltage shift depended on the gas concentration, particularly sensitive to hydrogen minimum to the ppm level with maximum threshold voltage shift of about 0.5 V. It has been observed that the change in the threshold voltage is proportional to the concentration of the analyte gas.

MOSFET sensors can be fabricated by using standard micro-electronic techniques, incorporating the deposition of gas sensitive catalytic metals onto the silicon dioxide gate layer, die sizes of 1.5 mm by 1.5mm that can operates lower temperatures around 150^0C than standard MOS sensors [134].Variants of the MOSFET structure exist, including ISFET (Ion Sensitive), OGFET (Open Gate), and SGFET (Suspended Gate).However MOSFET structure is more commonly adapted for electronic nose applications. Both n and p channel structures are used for gas sensing. Figure 15 shows a schematic of an n-channel MOSFET consists of a metal gate on top of an oxide layer, typically SiO_2, a p-type silicon substrate with two n-doped channels on either side of the gate [62]

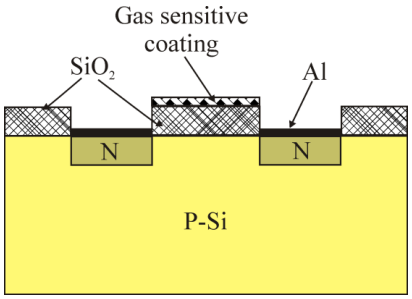

Figure 15 Schematic of MOSFET gas sensor

The MOSFET sensor sensitivity and selectivity towards particular gases can be achieved using optimum choice of the operational temperature, appropriate choice of type and thickness of catalytic metal used for gate and the microstructure of the metal. The small and inexpensive MOSFET sensors are available due modern production techniques [135] allowing a high repeatability of results. In spite of the high sensitivity and selectivity, their surrounding operating conditions must be under constant control, which restricts their use in portable instruments [135-136] also they are not capable of detecting to full range of substances of interest, which is the deciding factor against their use in commercial e-nose systems [113].

The MOSFET sensors find applications in food cooking, fermenting, wine-making processes, ethylene measurement during fruit ripening process. These sensors provide reasonable selectivity to gases such as H_2, NH_3, H_2S, and ethanol by use of metal gate materials such as Pt and Ir [135].

3.4. Optical Sensors

Optical fiber sensors are another approach to odor identification in electronic nose systems. Fluorescent type odor sensors consists of glass fibers with a diameter as small as 2µm and the sides or tips of it coated with chemically active material containing a fluorescent dye encapsulated in polymer matrix as shown in fig.16 [137].The sensor response is depended on the properties of polymer supporting fluorescent dye, i.e., polarity, hydrophobicity, porosity, and a tendency to expand [59,138].

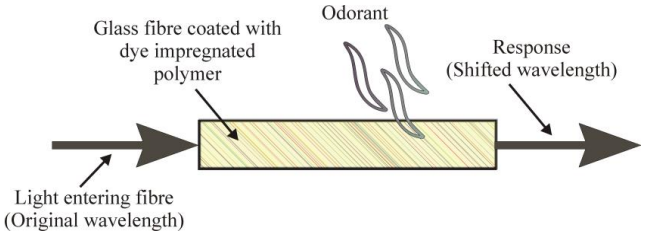

Figure 16 Fluorescent type optical odor Sensors

The optical sensing element is normally consists of a reagent phase immobilized at the fiber end or tip by either physical entrapment or chemical binding. This reagent phase contains a chemical indicator that experiences some change in optical properties on interaction with analyte gases. Polarity alterations takes place in fluorescent dye during interaction with the analyte odor vapors and optical properties of the dye's changes such as intensity change, spectrum

change, lifetime change or wavelength shift in fluorescence[113].These optical changes are proportional to the analyte gas type and concentration hence used as the response mechanism for odor detection. The optical change depends upon the nature of the analyte vapor and the concentration of its interaction with different polymer systems used. The response of sensor can be increased by adding absorbent such as alumina to the polymer by lowering the detection limits of the sensor. They have fast response times (less than 10 s) for sampling and analysis [139]

Fluorescent gas sensors finds in many application reported earlier such as Fire detector, simple gases detect such as O_2, CO_2, CH_4, HCL, and HF, Detection of pathogens, medical diagnosis based on protein or cell concentration, Real-time detection of DNA hybridization [139].

In spite of the high sensitivity, ability to identifications of individual compounds in mixtures, capabilities of finding multi parameter, however, there are several disadvantages of these types of sensors. The related hardware and software are very complex cause to increased cost; the sensors have complex sensor-array systems, having short lifetime due to photo bleaching and low portability due to delicate optics and electrical components [139].

IV. Summary of the properties of sensor type reviewed

The principle of operation, sensitivity, advantages, disadvantages and ref. of each sensor type in e-nose systems is summarized in Table 5.

Sensor Type	Principle	sensitivity	Advantage	Disadvantage	Ref.
M.O.S.	Conductivity	5-500 ppm	Micro fabricated low cost, high sensitivity, short recovery time, good resistance to corrosive gases and humidity, fast response.	High operating temperatures, suffer from sulphur poisoning, limited range of coatings	[113]
CP	Conductivity	1-100ppm	Operate at room temperature, good response times, Sensitive to polar analytes, Micro-fabricated, low cost.	Sensitive to temperature and humidity, suffer from baseline drift	[113]
SAW	Piezoelectricity	1 pg to 1 mg of vapor 1 pg mass change	High sensitivity, good response time, diverse sensor coatings, small, inexpensive, sensitive to virtually all gases, IC integratable.	Complex interface circuitry, specificity to analyte groups affected by polymeric-film sensor coating, temperature sensitive.	[113]
QCM	Piezoelectricity	1.5 Hz/ppm; 1.0 ng mass change	Good precision, diverse range of sensor coatings, high sensitivity, good batch to batch reproducibility	Poor signal-to-noise ratio, complex circuitry, sensitive to humidity and temperature.	[140]
MOSFET	Capacitive charge coupling	2.8 µV/ppm for toluene; DL = (amines, Sulphides) =0.1ppm;Maximum response =200 mV especially for amines	Small sensor size, inexpensive operating costs, integrated with electronic interface circuit	Requires environmental control, baseline drift, Odorant reaction product must penetrate gate.	[141]
Optical	Fluorescence, Chemo-luminescence	low ppb, DL (NH3)=1 ppm with polyaniline coating	Very high sensitivity, capable of identifications of individual compounds in mixtures, High electrical noise immunity.	Complex sensor array systems, Restricted availability of light sources, high cost.	[142]

Table 5 Summary of the properties of each sensor type reviewed

V. Commercial e-nose system characteristics

Commercially there are lots of manufacturers who produce a wide range of applications oriented e-nose products using different sensor technologies. Upto2015 there were at least 23 companies manufacturing and selling electronic nose instruments of various types and these companies are summarized in Table 6 together with the sensor technology employed and application(s). Key to sensor technologies: MOS – metal oxide sensor, CP –conducting polymer, SAW–

surface acoustic wave; QMB – quartz crystal microbalance, FET – field effect transistor, key to analytical instruments: MS – mass spectrometry, GC – gas chromatography, IMS – ion mobility spectroscopy.

Table 6 Commercial companies that manufactured e-noses and related instruments in up to 2018

Model	Make	Sensor array	Application	Ref.
PEN3	Airsense Analytics, Germany	10 different MOS	Food evaluation; flavor and fragrance testing	http://www.airsense.com/
Olfo Sense	Airsense Analytics, Germany	PID, EC, 4 MOS	Odor leakage monitoring , Urban air monitoring	http://www.airsense.com
GDA-FR	Airsense Analytics, Germany	IMS,PID ,EC Cell, 2MOS Sensors	Toxic Industrial Compounds (TICs) and Chemical Warfare Agents	http://www.airsense.com/
GDA-X	Airsense Analytics, Germany	Hybrid Sensor Array: IMS, PID, EC, 2 MOS	Chemical substances and dangerous gaseous compounds and many explosives.	http://www.airsense.com
GDA-F	Airsense Analytics, Germany	Hybrid Sensor Array	Fumigation gases, non-conforming chemicals or other gases due to evaporation from goods, hazardous chemicals like chlorine gas, phosphine or hydrogen cyanide, chloropicrin or benzene.	http://www.airsense.com
GDA-P	Airsense Analytics, Germany	IMS, PID, EC, 2 MOX sensors	Chemical warfare agents, chemical hazardous gases and toxic industrial compounds within seconds.	http://www.airsense.com
GDA-S	Airsense Analytics, Germany	Hybrid Sensor Array: (IMS, PID, EC, MOS)	Hazardous gases and chemical warfare agents within seconds.	http://www.airsense.com
Aerotracer	Airsense Analytics and Lufthansa Technik	Hybrid sensor array	volatile compounds used in connection with aircraft, Hydraulic liquids, heat transfer fluids, glues, de-icer compounds, kerosene etc.	http://www.airsense.com
LS-ID	Airsense Analytics	Raman spectrometer	Narcotics (e.g. white powders) and explosives.	http://www.airsense.com
EDU3	Airsense Analytics	MOS single thick film sensors array	odorants in natural gas, Proof of solvents in the workplace, pharmaceutical aerosols	http://www.airsense.com
FOX 2000	Alpha MOS	6 MOS sensors (or QMB/CP)	Application for product development and quality control analysis, VOC detection, Analysis of food types; quality control of food storage, fresh fish, and petrochemical products; packaging evaluation; analysis of dairy products, alcoholic beverages and perfumes	http://www.alpha-mos.com
FOX 3000	Alpha MOS	12 MOS sensors (or QMB/CP)		
FOX 4000	Alpha MOS	18 MOS sensors (or QMB/CP)		
Gemini	Alpha MOS	6 MOS		
Kronos	Alpha MOS	Quadruple fingerprint mass spectrometry	Analysis of aromas, flavors, taste additives, volatile organics in general.	http://www.alpha-mos.com,
Heracles	Alpha MOS	2 capillary columns (1-3 m) and 2 FIDs	Pet food ingredients detection, Detection and quantification of diacetyl in orange juice, off-odors in rinsing water.	http://www.alpha-mos.com

RQ Box	Alpha MOS	EC, PID, MOS sensors	Continuous monitoring of olfactory nuisance and gas emissions, Senses Odors,VOC,H_2S,NH_3,Mercaptans	http://www.alpha-mos.com
Prometheus	Alpha MOS	MS and 18 MOS sensors	Raw materials and final products olfactive shelf-life, stability, conformity and measurement of fragrance concentration	http://www.alpha-mos.com
ULYS e-nose	Alpha MOS	2 detectors: one (FID) and (FPD)	Food quality, chemical analysis, freshness, spoilage	http://www.alpha-mos.com
OdorVector	AltraSens	6 MOS gas sensor array	Odor filters monitoring, Monitoring odor emissions from a sewage canal.	http://www.altrasens.com/
Cybernose	CSIRO	Receptor-based array, optical sensors	food and beverage match the taste and aroma of foods to their specifications, authenticity of foods and beverages, Detecting toxins or contaminants in food, Detect the telltale smell of insect contamination in grain, Detection of other pests, weeds or diseases in commodities	http://www.csiro.au/
OMD 98	Dr. Fodisch	2x6 sensors	Odor pollutions from industry, agriculture and recycling of waste.	http://ankersmid.ro/
OMD 1.10	Dr. Fodisch	2x5 MOS sensors		
Multi-IMS	Drager	Open Loop (IMS)	Chemical warfare agents and toxic industrial compounds.	http://www.keison.co.uk/
MSI150 Pro2i	Drager	ECs	flue gas concentrations and combustion, environmental protection, etc.	http://www.draeger-msi.de
zNose4200	Estcal	GC and SAW Quartz microbalance	Detection of organic, biological and chemical compounds in real time	http://www.estcal.com
zNose4300				
zNose4600				
zNose7011				
M90-D1-C	Environics, USA	Open Loop IMS	Chemical Warfare Agent Detector	http://www.environics.fi/
ChemPro 100	Environics, USA	1 IMS, 3 MOS, FE sensor,	chemical warfare agents and toxic industrial compounds/materials	http://www.epicos.com/
ChemProDM	Environics, USA	Open-loop IMS)	Chemical Warfare Agents (CWA) and selected Toxic Industrial Chemicals (TIC).	http://www.environics.fi/
ChemProFXi	Environics, USA	Open-loop IMS sensor	Chemical Warfare Agents (CWA) & selected toxic industrial chemicals (TIC), Industrial chemical vapor monitoring.	http://www.environics.fi/
ENVI BioScout	Environics, USA	UV fluorescence ,Elastic scattering	Bioaerosol Detector, harmful airborne biological particles.	http://www.environics.fi/
ENVI-AirPro	Environics,USA	IMS	hazardous gases in ambient air	http://www.environics.fi/
ENVI-AMS200, ENVI-Cal	Environics,USA	GC, MS, and IMS.	Industrial gas monitoring system	http://www.environics.fi/
ENVI-Stack Pro DMS-AIMS2	Environics,USA	IMS	Continuous emission monitoring systems for Chlorine	http://www.environics.fi/
ENVI-AMC	Environics, USA	DMS-AIMS2	Ammonia and Acids, airborne molecular contamination (AMC) in semiconductor processing.	http://www.environics.fi/

SAGAS	Forschungszentnm Karlsruhe	8 SAW	Detection of variety of gaseous organic analytes.	http://ieeexplore.ieee.org/
QCS	GERSTEL	MOS	VOC emissions from beverage cans	http://www.gerstel.com/
MOSES II	GSG Mess- und Analysengerate,	Modular gas sensor array	unknown VOC gases and gas mixtures	http://www.gsg-analytical.com/
VOC-iDent	GSG Mess- und Analysengerate,	Modular gas sensor array	Identification of unknown VOC gases and gas mixtures	http://www.gsg-analytical.com/
oNose	Illumina Inc	fluorescence sensors bead array	Identification of gases and gas mixtures	http://www.5z.com/
HAZMATCAD	Microsensor Systems Inc.,	SAW microsensor array	Portable instrument for detection of chemical warfare agents	http://www.tradewaysusa.com/
HAZMATCAD Plus	Microsensor Systems Inc.,	SAW array and EC	Detect chemical vapor threats such as chemical warfare agents and selected TIC's (Toxic Industrial Chemicals).	http://s7d9.scene7.com/
Fuel sniper	Microsensor Systems Inc.,	SAW	Fuel Dilution Measurement	http://microsensorsystems.com/
CW Sentry 3G	Microsensor Systems Inc., MSA Inc USA	SAW array and EC sensor array	Chemical warfare agents detection,Toxic industrial chemical detection	http://www.tradewaysusa.com/
SAW MiniCAD mk II Detector	MSA Inc.USA	2 SAW sensor array	Chemical warfare agent detector for simultaneous detection of trace levels of nerve (G) and blister (H) agents.	http://media.msanet.com/
VaporLab	Microsensor Systems, Inc	SAW	Environmental, food and beverage, fragrance and cosmetics, safety exposure and personal monitoring, and medical and dental.	http://saba.kntu.ac.ir/
Spectro FDM Q600	Spectro Inc.	SAW	Fuel Dilution measurement in crankcase Oils	http://www.spectro.cz/
Lonestar	OWLSTONE	Field asymmetric IMS	Fermentation and bioreactor off-gas analysis, Food freshness and odors, Gas purity, Material verification, Glove box monitoring, Cleaning verification, Leaks and Ingress.	http://www.owlstonenanotech.com/lonestar
AP2C, AP4C, AP4C-F, AP4C-V, TIMs detector	Proengin	Flame spectrophotometer	Chemical warfare agent or in toxic industrial materials detection:	http://www.proengin.com/
ChemRAE	RaeSystemes	IMS	Wireless, portable multi-gas and multi-threat monitors	http://www.raesystems.com/
UltraRAE 3000	RaeSystemes	Separation tube and PID	Measurement of benzene from 50 ppb to 200 ppm and other VOCs up to 10,000 ppm, Confined Space Entry Environmental Cleanups/ Remediation Exploration Hazmat Response Leak Detection Plant Shutdown & Turn-Around	http://www.raesystems.com/
MultiRAE IR	RaeSystemes	PID,IR, EC cell	For indoor air quality, food industry, hospitalsand respirable air testing.	http://www.equipcoservices.com/
ToxiRAE Pro PID	RaeSystemes	PID	Detection of harmful VOCs and toxic industrial chemicals (TICs)	http://www.raesystems.com/
QRAE II	RaeSystemes	Catalytic bead for combustibles	Detects hydrogen sulfide, carbon monoxide, combustibles, and monitors oxygen ,	http://www.raesystems.com/

		Oxygen: SPE O_2Toxic: EC for H_2S or CO		
AreaRAE Steel	RaeSystemes	PID,LEL	VOCs, combustibles, toxics, and oxygen	http://www.raesystems.com/l
IAQRAE	RaeSystemes	PID, NIRD CO2, EC,	VOC of Carpets, Fabrics, Finishes, Furniture, and Building Materials, Office Equipment: copiers, printers, Microbial Contamination (mold, fungus, etc.),Human Occupancy (exhalation and perfume)	http://www.raesystems.com/
FF2	RST-Rostock	6 MOX, *T*, humidity	Fire detection, propane and methane emissions	http://www.rst-rostock.com/
EOS Ambiente	SACMI	MOS	VOC detection in landfills, urban solid waste selection and treatment plants, biogas production plants, composting plants , WDF production plants, incinerators and waste to energy plants, civil and industrial waste water treatment plants, livestock farming, rendering plants, distilleries, refineries ,chemical plants	http://www.sacmi.com/
EOS835	SACMI	MOS	Continuous monitoring of environmental odors.	http://www.sacmi.com
EOS Aroma	SACMI	6 tipo MOS	Food industry, coffee, chocolate, olive oil, milk and milk derivatives, fruit and fruit juices, mineral water and soft drinks, bakery products, meat, fish, salami, etc. Agro-industrial fodder, forages, pet food, seeds.	http://www.sacmi.com/
Bloodhound ST214	Scensive Technologies Ltd	14 conducting polymers	Detection of Mycobacterium volatiles	http://www.scensive.com/
Cyranose 320	Sensigent	Array of 32 Nanocomposite gas sensors	petrochemical, chemical, food and beverage, packaging materials, plastics, pet food, pulp and paper, medical research etc.	http://www.sensigent.com/

Conclusions:

Wide variety of gas sensors utilized in e-noses were reviewed in this paper including conducting polymer , metal oxide semiconductor , SAW and QCM piezoelectric gas sensors, MOSFET, optical type gas sensors. The review also focused on some commercial companies that manufactured e-noses and related instruments in up to 2018 listed in table 6.These listed various e-nose systems offer excellent discrimination and wide the way for a new generation of "smart sensors" which will increase the future commercial markets for gas sensors. The review paper also clearly gives the outline of sensors principle of operation, fabrication methods, cost, advantages and disadvantages, applications areas etc. The summary of this information is given in Table V.

Acknowledgement

The author A.K. acknowledges the financial support of UGC, New Delhi, India for granting two year faculty improvement program fellowship to pursue Ph.D and conduct research.

References

1] J. Gardner and P. Bartlett, "A brief history of electronic noses", *Sensors and Actuators B*, vol. 18, pp. 132-189, 1994.
2] T. C. Pearce, S. S. Schiffman, H. T. Nagle and J. W. Gardner, "Handbook of machine Olfaction", Wiley-VCH, pp. 399-417, 2003.
3] M. A. Craven, J. W. Gardner and P. N. Bartlett, "Electronic noses development and future prospects", *Trends in Analytical Chemistry*, vol. 15, pp. 486-493, 1996.
4] J. E. Haugen and K. Kvaal, "Electronic nose and artificial neural network", *MeatScience*, vol. 49 (1), pp. 273-286, 1998.
5] P. N. Bartlett, J. M. Elliott and J. W. Gardner, "Electronic noses and their applications in the food industry", *Food Technology*, vol. 51(12), pp. 44-48, 1997.
6] http://www.figaro.co.jp/en/product/index.php?mode=search&kbn=1.
7] M. Griffin, "Electronic Noses: Multi-Sensor Arrays," Davidson Coll. NC, vol. 28036, 2003.
8] S. Fiorillo, S. Di Bortolomeo, C. Nannini and D. De'Rossi, "Thin layers grown onto copper salt replica for sensor array fabrication", Sensors and Actuators-B, Chemical, vol. 7, pp. 399–403, 1992.
9] J. Grate, S. Martin and R. White, "Acoustic wave microsensors: part I", Anal. Chemistry, vol. 64, pp. 940–948, 1993.
10] J. Gardner and P. Bartlett, "Sensors and sensory systems for an electronic nose", Kluwer, Dordrecht, vol. 212, pp. 303–319, 1992.
11] E. Jones, "The Pellistors catalytic gas detector". In P Moseley, J. Morris, and D.Williams, editors, "Techniques and mechanism in gas sensing", Bristol, pp. 17–31, 1991.
12] W. Seitz, "Chemical sensors based on fiber optics", Anal. Chemistry, vol. 56, pp, 16–34, 1984.
13] Alpha MOS Multi Organoleptic Systems, Toulouse (France), http://www.alphamos.com.
14] J. Gardner, "Detection of vapors and odors from a multi sensor array using pattern recognition Part 2: Artificial neural networks", Sensors and Actuators B, Chemical, vol. 9, pp. 9-15, 1991.
15] Julian W. Gardner and JehudaYinon "Electronic Noses & Sensors for the Detection of Explosives" NATO science series, Dordrecht: Kluwer Academic Publishers.Vol-159,pp. 01-28,2004
16] J. Gardner and P. N. Bartlett. "Electronic noses. Principles and applications." Measurement Science and Technology ,Vol.11(7),pp.1087,2000)
17] Himanshu K.Patel, "The Electronic Nose: Artificial Olfaction Technology", Springer India, 2014, (eBook)
18] K. Arshak, E. Moore , "A review of gas sensors employed in electronic nose applications", Sensor Review, Vol. 24-2, pp. 181–198,2004
19] Hua Bai and Gaoquan Shi , "Gas Sensors Based on Conducting Polymers", Sensors, Vol. 7, pp.267-307, 2007
20] B.C. Munoz, G. Steinthal, S. Sunshine, "Conductive polymer-carbon black composites-based sensor arrays for use in an electronic nose", Sens. Rev. Vol.19(4), pp.300–305,1999
21] U. Paramo-Garcia, J. G. Ibanez , N. Batina, "Electrochemical Modulation of the Thickness of Polypyrrole Films by Using Different Anionic Dopants", Int. J. Electrochem. Sci., Vol.6 pp.5172 – 5188, 2011
22] Gerard Bidan, "Electroconducting conjugated polymers: New sensitive matrices to build up chemical or electrochemical sensors. A review", Sensors and. Actuators B, Vol.6, pp.45–56, 1992
23] Gewu Lu, Liangti Qu, "Gaoquan Shi, Electrochemical fabrication of neuron-type networks based on crystalline oligopyrene nanosheets", Electrochim. Acta, Vol.51, 340-346,2005
24] Jens Reemts, Jurgen Parisi, Derck Schlettwein, " Electrochemical growth of gas-sensitive polyaniline thin films across an insulating gap", Thin Solid Films, Vol.466, pp.320-325, 2004
25] Scott T. McGovern, Geoffrey M. Spinks, Gordon G. Wallace, "Micro-humidity sensors based on a processable polyaniline blend", Sens. Actuators B, Vol. 107, pp.657-665, 2005.
26] Jae-Hyun Cho, Joon-Boo Yu, Jung-Suk Kim, Sung-Ok Sohn, Duk-Dong Lee, Jeung-Soo Huh, "Sensing behaviors of polypyrrole sensor under humidity condition", Sens. Actuators B,Vol. 108,pp. 389-392, 2005
27] S. Brady, K.T. Lau, W. Megill, G.G. Wallace, D. Diamond, " The development and characterization of conducting polymeric-based sensing devices", Synth. Met.,Vol.154,pp. 25-28, 2005
28] Michael S. Silverstein, Huiwen Tai, Anatoly Sergienko, Yulia Lumelsky, Svet Pavlovsky, "PolyHIPE: IPNs, hybrids, nanoscale porosity, silica monoliths and ICP-based sensors", Polymer, Vol.46, pp.6682-6694, 2005
29] G.K. Prasad, T.P.Radhakrishnan, D.Sravan Kumar, M.Ghanashyam Krishna," Ammonia sensing characteristics of thin film based on polyelectrolyte templated polyaniline", Sens. Actuators B, Vol.106,pp. 626-631,2005
30] Rungnapa Tongpool, Sorachon Yoriya, "Kinetics of nitrogen dioxide exposure in lead phthalocyanine sensors", Thin Solid Films, Vol. 477,pp. 148-152, 2005
31] Manoj Kumar Ram, ,Ozlem Yavuz, Vitawat Lahsangah,Matt Aldissi, " CO gas sensing from ultrathin nano-composite conducting polymer film", Sensors and. Actuators B ,Vol. 106, pp.750-757, 2005
32] Razat Nohria, Rajneek K. Khillan,Yi Su, Rohit Dikshit, Yuri Lvov, Kody Varahramyan, " Humidity sensor based on ultrathin polyaniline film deposited using layer-by-layer nano-assembly",. Sensors and Actuators B, Vol. 114, pp.218-222, 2006
33] N.E. Agbor, M.C. Petty, A.P. Monkman, " Polyaniline Thin-Films for Gas-Sensing", Sensors and Actuators B, Vol.28, pp.173-179, 1995

34] Elisa Stussi, Sara Cella, Giorgio Serra,Giusto Stoppato Venier, " Fabrication of conducting polymer patterns for gas sensing by a dry technique", Mater. Sci. Eng. C-Biomimetic Mater. Sens. Syst.,Vol. 4,pp. 27-33, 1996
35] Ladawan Ruangchuay, Anuvat Sirivat , Johannes Schwank, "Selective conductivity response of polypyrrole-based sensor on flammable chemicals", React. Funct. Polym. Vol.61, pp.11-22, 2004
36] H.G.O. Sandberg ,Tomas G. Backlund , "Applications of an all-polymer solution-processed high-performance, transistor", Synth. Met.,Vol. 155,pp.662-665, 2005,
37] M.F. Mabrook, C. Pearson, M.C. Petty, "Inkjet-printed polypyrrole thin films for vapor sensing", Sens. Actuators B, Vol.115, pp.547-551, 2006
38] Hua Bai and Gaoquan Shi, "Gas Sensors Based on Conducting Polymers", Sensors,Vol. 7, pp.267-307, 2007
39] Ting Zhang, Megan B. Nix, Bong-Young Yoo, Marc A. Deshusses, Nosang V. Myung, "Electrochemically functionalized single-walled carbon nanotube gas sensor", Electroanalysis, Vol.18, pp.1153-1158, 2006
40] Dan Xie, Yadong Jiang, Wei Pan, Dan Li, Zhiming Wu, Yanrong Li , " Fabrication and characterization of polyaniline-based gas sensor by ultra-thin film technology", Sens. Actuators B, vol.81, pp.158-164, 2002
41] A.Chyla, A. Lewandowska, J. Soloducho, A. Gorecka-Drzazga, M. Szablewski, "4-t-butyl-CuPc-PODT molecular composite material for an effective gas sensor", IEEE Trns. Dielectr.Electr. Insul.,Vol. 8, pp.559-565, 2001
42] A Z Sadek, W Wlodarski, K Shin, R B Kaner and K Kalantar-zadeh, "A layered surface acoustic wave gas sensor based on a polyaniline/In2O3 nanofibre composite", Nanotechnology, vol.17,pp.4488-4492, 2006
43] S.C.K. Misra, Prafull Mathur , Maneesha Yadav, M.K. Tiwari, S.C. Garg,P. Tripathi, "Preparation and characterization of vacuum deposited semiconducting nanocrystalline polymeric thin film sensors for detection of HCl", Polymer,Vol.45,pp.8623-8628, 2004
44] S Virji, JD Fowler, CO Baker, J Huang, RB Kaner, B.H.Weiller, "Polyaniline manofiber composites with metal salts: Chemical sensors for hydrogen sulfide", Small, Vol.1, pp.624-627,2005
45] V Dixit, SCK Misra, BS Sharma," Carbon monoxide sensitivity of vacuum deposited polyaniline semiconducting thin films", Sens. Actuators B,Vol.104,pp.90-93, 2005
46] G Li, C Martinez, S Semancik, "Controlled electrophoretic patterning of polyaniline from a colloidal suspension", J. Am. Chem. Soc.,Vol. 127, pp. 4903-4909, 2005
47] AA Athawale, SV Bhagwat, PP Katre , "Nanocomposite of Pd-polyaniline as a selective methanol sensor", Sens. Actuators B,Vol. 114,pp. 263-267, 2006
48] KSV Santhanam, R Sangoi, L Fuller , "A chemical sensor for chloromethanes using a nanocomposite of multiwalled carbon nanotubes with poly(3-methylthiophene)", Sens. Actuators B, Vol.106, pp.766-771.128, 2005
49] S. Sharma, C. Nirkhe, S. Pethkar, AA Athawale, "Chloroform vapor sensor based on copper/polyaniline nanocomposite", Sens. Actuators B,Vol. 85, pp.131-136, 2002
50] B. Li, G. Sauve, MC Iovu, M Jeffries-El, R Zhang , "Volatile organic compound detection using nanostructured copolymers", Nano Lett., Vol. 6, pp.1598-1602, 2006
51] JT English, BA Deore, MS Freund , "Biogenic amine vapor detection using poly(anilineboronic acid) films", Sens. Actuators B,Vol. 115,pp. 666-671, 2006
52] David James, Simon M. Scott, Zulfiqur Ali, and William T. O'Hare, "Chemical Sensors for Electronic Nose Systems", Microchim. Acta,Vol. 149,pp. 1-17,2005
53] V. Emelin and I. N. Nikolaev, "Sensitivity of MOS sensors to hydrogen, hydrogen- sulfide, and nitrogen dioxide indifferent gas atmospheres, Meas. Tech.,Vol. 49(5), pp.524,2006
54] V. Emelin and I. N. Nikolaev, "Sensitivity of MOS sensors towards chlorine", Meas. Tech.,Vol. 49, pp.839,2006
55] M. Egashira and Y. Shimizu, " Odor sensing by semiconductor metal oxides", Sens. Actuators B ,Vol.13, pp.443 ,1993
56] H. K. Hong, H. W. Shin, D. H. Yun, S. R. Kim, C. H. Kwon, K. Lee, and T. Moriizumi, " Electronic nose system with micro gas sensor array", Sens. Actuators B,Vol. 36,p. 338-341, 1996
57] Isolde Simona, ,Nicolae Barsan, Michael Bauer, Udo Weimar, "Micromachined metal oxide gas sensors: opportunities to improve sensor performance", Sensors and Actuators B,Vol. 73,pp. 1-26,2001
58] A. Berna, "Metal Oxide Sensors for Electronic Noses and Their Application to Food Analysis", Sensors ,Vol.10(4), pp.3882-3910,2010
59] T.C.Pears, S.S.Schiffman, H.T.Nagale, J.W.Gardner, "Handbook of Machine Olfaction", WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2003
60] Joseph R. Stetter, "A surface chemical view of gas detection", J. Colloid Int. Soc.,Vol. 65(3),pp.432–443, 1978
61] Albert, K.J. and Lewis, N.S., "Cross reactive chemical sensor arrays", Chem. Rev., Vol. 100, pp. 2595-2626., 2000
62] T. M. Dymerski, T. M. Chmiel, and W. Wardencki, "Invited Review Article: An odor-sensing system—powerful technique for foodstuff studies", Review of Scientific Instruments, Vol. 82(11),2011
63] D. L. Garcia-Gonzalez and R. Aparicio, "Sensors: from Biosensors to the electronic nose", Grasas Y Aceites ,Vol.53, pp.96-114,2002
64] Ying Liu, Erik Koep, and Meilin Liu, "A Highly Sensitive and Fast-Responding SnO2 Sensor Fabricated by Combustion Chemical Vapor Deposition", Chem. Mater., Vol.17, pp.3997-4000, 2005

65] V.R. Kattia, A.K. Debnatha, K.P. Muthea, Manmeet Kaura, A.K. Duab, S.C. Gadkari , "Mechanism of drifts in H2S sensing properties of SnO2:CuO composite thin film sensors prepared by thermal evaporation", Sensors and Actuators B,Vol. 96 ,pp.245–252, 2003
66] Dainius Perednis, Ludwig J. Gauckler ,"Thin Film Deposition Using Spray Pyrolysis", Journal of Electroceramics, Vol.14(2), pp 103-111, 2005
67] F. Gu, S. F. Wang, M. K. Lu, X. F. Cheng, S. W. Liu, G. J. Zhou, D. Xu, and D. R. Yuan, "Luminescence of SnO2 thin films prepared by spin-coating method," J. Cryst. Growth, vol. 262, no. 1, pp. 182–185, 2004.
68] C. Terrier, J.P. Chatelon, J.A. Roger," Electrical and optical properties of Sb:SnO2 thin films obtained by the sol-gel method", Thin Solid films ,Vol. 295,pp. 95-100, 1997
69] N. Miyata, K. Miyake, K. Koga and T. Fukushima, "Transparent Conducting Cadmium-Tin Oxide Films Deposited by RF Sputtering from a CdO - SnO2 Target", J. Electrochem. Soc.,Vol. 127,no. 4, 1980
70] G. Ansari, S. W Gosavi, S. A Gangal , R. N. Karekar, R.C. Aiyar,"Characterization of SnO2-based H2 gas sensors fabricated by different deposition techniques", Journal of Materials Science: Materials in Electronics ,Vol.8,no. 1,pp 23-27, 1997
71] 64 S. Otles, Handbook of food analysis instruments. CRC Press, 2008.
72] 41 H. Nanto, Y. Yokoi, T. Mukai, J. Fijioka, E. Kusano, A. Kinbara, Y. Douguchi , "Novel gas sensor using polymer-film-coated quartz resonator for environmental monitoring", Mater.Sci. Eng., Vol.12,pp. 43–48,2000
73] Shih Min Chou , Lay Gaik Teoh , Wei Hao Lai 1, Yen Hsun Su and Min Hsiung Hon, "ZnO:Al Thin Film Gas Sensor for Detection of Ethanol Vapor", Sensors,Vol. 6, pp.1420-1427,2006
74] Hidehito Nanto, Tadatsugu Minami and Shinzo Takata, "Zinc oxide thin film ammonia gas sensors with high sensitivity and excellent selectivity", J. Appl. Phys., Vol. 60, pp.482,1986
75] H. Nanto, H. Sokooshi, T. Kawai, T. Usuda ,"Zinc oxide thin-film Trimethylamine sensor with high sensitivity and excellent selectivity", Journal of Materials Science Letters ,Vol.11,no.4, pp 235-237, 1992
76] H. Gonga, J.Q. Hua, J.H. Wanga, C.H. Onga, F.R. Zhub, "Nano-crystalline Cu-doped ZnO thin film gas sensor for CO", Sensors and Actuators B,Vol. 115,pp. 247–251, 2006
77] N. Jayadev Dayan, S. R. Sainkar, A. A. Belkehar, R. N. Karekar, and R. C. Aiyer, "On the highly selective ZnO: Al2O3 based thick film hydrogen sensors," J. Mater. Sci. Lett., vol. 16, no. 23, pp. 1952–1954, 1997.
78] J. Kaur, S. C. Roy, and M. C. Bhatnagar, "Highly sensitive SnO 2 thin film NO 2 gas sensor operating at low temperature," Sensors Actuators B Chem., vol. 123, no. 2, pp. 1090–1095, 2007.
79] L. F. Zhu, J. C. She, J. Y. Luo, S. Z. Deng, J. Chen, and N. S. Xu, "Study of physical and chemical processes of H2 sensing of Pt-coated WO3 nanowire films," J. Phys. Chem. C, vol. 114, no. 36, pp. 15504–15509, 2010.
80] B. Karunagaran, P. Uthirakumar, S. J. Chung, S. Velumani, and E.-K. Suh, "TiO2 thin film gas sensor for monitoring ammonia," Mater. Charact. vol. 58, no. 8, pp. 680–684, 2007.
81] H. Cui, Y. Liu, and W. Ren, "Structure switch between a-Fe2O3, c-Fe2O3 and Fe3O4 during the large scale and low temperature sol–gel synthesis of nearly monodispersed iron oxide nanoparticles," Adv Powder Technol, vol. 24, no. 1, pp. 93–97, 2013.
82] Y. Ushio, M. Miyayama, and H. Yanagida, "Effects of interface states on gas-sensing properties of a CuO/ZnO thin-film heterojunction," Sensors Actuators B Chem., vol. 17, no. 3, pp. 221–226, 1994.
83] M. Ando, T. Kobayashi, S. Iijima, and M. Haruta, "Optical recognition of CO and H2 by use of gas-sensitiveAu–Co3O4 composite films," J. Mater. Chem., vol. 7, no. 9, pp. 1779–1783, 1997.
84] Y. Li, W. Wlodarski, K. Galatsis, S. H. Moslih, J. Cole, S. Russo, and N. Rockelmann, "Gas sensing properties of p-type semiconducting Cr-doped TiO 2 thin films," Sensors Actuators B Chem., vol. 83, no. 1, pp. 160–163, 2002.
85] H. Yamaura, T. Jinkawa, J. Tamaki, K. Moriya, N. Miura, and N. Yamazoe, "Indium oxide-based gas sensor for selective detection of CO," Sensors Actuators B Chem., vol. 36, no. 1, pp. 325–332, 1996.
86] E. Schaller, J. O. Bosset, and F. Escher, "'Electronic noses' and their application to food," LWT-Food Sci. Technol., vol. 31, no. 4, pp. 305–316, 1998.
87] http://www.hwsensor.com/
88] A. Berna, "Metal oxide sensors for electronic noses and their application to food analysis," Sensors, vol. 10, no. 4, pp. 3882–3910, 2010.
89] C. Di Natale, A. Macagnano, F. Davide, A. D'Amico, R. Paolesse, T. Boschi, M. Faccio, and G. Ferri, "An electronic nose for food analysis," Sensors Actuators B Chem., vol. 44, no. 1, pp. 521–526, 1997.
90] 119].K. Shimizu, M. Suzuki, K. Yoshida, T. Muto, A. Fujita, N. Tomita, and N. Watanabe, "Maturity discrimination of snake fruit (Salacca edulis Reinw.) cv. Pondoh based on volatiles analysis using an electronic nose device equipped with a sensor array and fingerprint mass spectrometry," FlavourFragr. J., vol. 19, no. 1, pp. 44–50, 2004.
91] A. H. Gomez, J. Wang, G. Hu, and A. G. Pereira, "Discrimination of storage shelf-life for mandarin by electronic nose technique," LWT-Food Sci. Technol., vol. 40, no. 4, pp. 681–689, 2007.
92] J. W. Gardner, H. V Shurmer, and T. T. Tan, "Application of an electronic nose to the discrimination of coffees," Sensors Actuators B Chem., vol. 6, no. 1, pp. 71–75, 1992.
93] F. Winquist, E. G. Hornsten, H. Sundgren, and I. Lundstrom, "Performance of an electronic nose for quality estimation of ground meat," Meas. Sci. Technol., vol. 4, no. 12, p. 1493, 1993.

94] S. Balasubramanian, S. Panigrahi, C. M. Logue, C. Doetkott, M. Marchello, and J. S. Sherwood, "Independent component analysis-processed electronic nose data for predicting Salmonella typhimurium populations in contaminated beef," Food Control, vol. 19, no. 3, pp. 236–246, 2008.
95] B. Bourrounet, T. Talou, and A. Gaset, "Application of a multi-gas-sensor device in the meat industry for boar-taint detection," Sensors actuators B Chem., vol. 27, no. 1, pp. 250–254, 1995.
96] G. Olafsdottir, E. Chanie, F. Westad, R. Jonsdottir, C. R. Thalmann, S. Bazzo, S. Labreche, P. Marcq, F. Lundby, and J. E. Haugen, "Prediction of microbial and sensory quality of cold smoked Atlantic salmon (Salmo salar) by electronic nose," J. Food Sci., vol. 70, no. 9, pp. S563–S574, 2005.
97] J. E. Haugen, E. Chanie, F. Westad, R. Jonsdottir, S. Bazzo, S. Labreche, P. Marcq, F. Lundby, and G. Olafsdottir, "Rapid control of smoked Atlantic salmon (Salmo salar) quality by electronic nose: Correlation with classical evaluation methods," Sensors Actuators B Chem., vol. 116, no. 1, pp. 72–77, 2006.
98] N. El Barbri, A. Amari, M. Vinaixa, B. Bouchikhi, X. Correig, and E. Llobet, "Building of a metal oxide gas sensor-based electronic nose to assess the freshness of sardines under cold storage," Sensors Actuators B Chem., vol. 128, no. 1, pp. 235–244, 2007.
99] Y. G. Martın, M. C. C. Oliveros, J. L. P. Pavón, C. G. Pinto, and B. M. Cordero, "Electronic nose based on metal oxide semiconductor sensors and pattern recognition techniques: characterisation of vegetable oils," Anal. Chim. Acta, vol. 449, no. 1, pp. 69–80, 2001.
100] F. Winquist, H. Sundgren, I. Lundstro¨m, "A practical use of electronic noses: quality estimation of cod fillet bought over the counter", Technical Digest of the 8th Int. Conf. on Solid State Sensors and Actuators (IEEE) (Transducers 95), Stockholm, Sweden, 25–29 June, 1995,
101] T. Nakamoto, K. Fukunishi, and T. Moriizumi, "Identification capability of odor sensor using quartz-resonator array and neural-network pattern recognition," Sensors Actuators B Chem., vol. 1, no. 1, pp. 473–476, 1990.
102] R. C. McKellar, H. P. Vasantha Rupasinghe, X. Lu, and K. P. Knight, "The electronic nose as a tool for the classification of fruit and grape wines from different Ontario wineries," J. Sci. Food Agric., vol. 85, no. 14, pp. 2391–2396, 2005.
103] J. P. Santos, T. Arroyo, M. Aleixandre, J. Lozano, I. Sayago, M. Garcıa, M. J. Fernandez, L. Ares, J. Gutierrez, and J. M. Cabellos, "A comparative study of sensor array and GC–MS: application to Madrid wines characterization," Sensors Actuators B Chem., vol. 102, no. 2, pp. 299–307, 2004.
104] J. A. Ragazzo-Sanchez, P. Chalier, D. Chevalier, and C. Ghommidh, "Electronic nose discrimination of aroma compounds in alcoholised solutions," Sensors Actuators B Chem., vol. 114, no. 2, pp. 665–673, 2006.
105] H. C. Yu, J. Wang, and Y. Xu, "Identification of adulterated milk using electronic nose," Sensors Mater., vol. 19, no. 5, pp. 275–285, 2007.
106] S. Benedetti, S. Iametti, F. Bonomi, and S. Mannino, "Head space sensor array for the detection of aflatoxin M1 in raw ewe's milk," J. Food Prot., vol. 68, no. 5, pp. 1089–1092, 2005.
107] A. D. Wilson, "Review of electronic-nose technologies and algorithms to detect hazardous chemicals in the environment," Procedia Technol., vol. 1, pp. 453–463, 2012.
108] W. Yongwei, J. Wang, B. Zhou, and Q. Lu, "Monitoring storage time and quality attribute of egg based on electronic nose," Anal. Chim. Acta, vol. 650, no. 2, pp. 183–188, 2009.
109] R. Dutta, E. L. Hines, J. W. Gardner, D. D. Udrea, and P. Boilot, "Non-destructive egg freshness determination: an electronic nose based approach," Meas. Sci. Technol., vol. 14, no. 2, p. 190, 2003.
110] J. Olsson, T. Borjesson, T. Lundstedt, and J. Schnurer, "Detection and quantification of ochratoxin A and deoxynivalenol in barley grains by GC-MS and electronic nose," Int. J. Food Microbiol., vol. 72, no. 3, pp. 203–214, 2002.
111] C. Lim, W. Wang, S. Yang, and K. Lee, "Development of SAW-based multi-gas sensor for simultaneous detection of CO 2 and NO 2," Sensors Actuators B Chem., vol. 154, no. 1, pp. 9–16, 2011.
112] K. J. Albert, N. S. Lewis, C. L. Schauer, G. A. Sotzing, S. E. Stitzel, T. P. Vaid, and D. R. Walt, "Cross-reactive chemical sensor arrays," Chem. Rev., vol. 100, no. 7, pp. 2595–2626, 2000.
113] H. T. Nagle, R. Gutierrez-Osuna, and S. S. Schiffman, "The how and why of electronic noses," Spectrum, IEEE, vol. 35, no. 9, pp. 22–31, 1998.
114] N. M. White and J. D. Turner, "Thick-film sensors: past, present and future," Meas. Sci. Technol., vol. 8, no. 1, p. 1, 1997.
115] M. Penza and G. Cassano, "Application of principal component analysis and artificial neural networks to recognize the individual VOCs of methanol/2-propanol in a binary mixture by SAW multi-sensor array," Sensors Actuators B Chem., vol. 89, no. 3, pp. 269–284, 2003.
116] I. Nicolae, C. Viespe, and C. Grigoriu, "Nanocomposite sensitive polymeric films for SAW sensors deposited by the MAPLE direct write technique," Sensors Actuators B Chem., vol. 158, no. 1, pp. 418–422, 2011.
117] C. G. Fox and J. F. Alder, "Surface acoustic wave sensors for atmospheric gas monitoring. A review," Analyst, vol. 114, no. 9, pp. 997–1004, 1989.
118] D. S. Ballantine Jr, R. M. White, S. J. Martin, A. J. Ricco, E. T. Zellers, G. C. Frye, and H. Wohltjen, Acoustic Wave Sensors: Theory, Design, & Physico-Chemical Applications. Academic press, 1996.
119] W. P. Carey and B. R. Kowalski, "Chemical piezoelectric sensor and sensor array characterization," Anal. Chem., vol. 58, no. 14, pp. 3077–3084, 1986.

120] W. P. Carey, K. R. Beebe, and B. R. Kowalski, "Multicomponent analysis using an array of piezoelectric crystal sensors," Anal. Chem., vol. 59, no. 11, pp. 1529–1534, 1987.
121] H. Nanto, N. Dougami, T. Mukai, M. Habara, E. Kusano, A. Kinbara, T. Ogawa, and T. Oyabu, "A smart gas sensor using polymer-film-coated quartz resonator microbalance," Sensors Actuators B Chem., vol. 66, no. 1, pp. 16–18, 2000.
122] T. Nakamoto, A. Fukuda, and T. Moriizumi, "Perfume and flavour identification by odor-sensing system using quartz-resonator sensor array and neural-network pattern recognition," Sensors Actuators B Chem., vol. 10, no. 2, pp. 85–90, 1993.
123] S. K. Vashist and P. Vashist, "Recent advances in quartz crystal microbalance-based sensors," J. Sensors, vol. 2011, 2011.
124] A. Bello, F. Bianchi, M. Careri, M. Giannetto, V. Mastria, G. Mori, and M. Musci, "Potentialities of a modified QCM sensor for the detection of analytes interacting via H-bonding and application to the determination of ethanol in bread," Sensors Actuators B Chem., vol. 125, no. 1, pp. 321–325, 2007.
125] I. A. Koshets, Z. I. Kazantseva, Y. M. Shirshov, S. A. Cherenok, and V. I. Kalchenko, "Calixarene films as sensitive coatings for QCM-based gas sensors," Sensors Actuators B Chem., vol. 106, no. 1, pp. 177–181, 2005.
126] B. Wyszynski, P. Somboon, and T. Nakamoto, "Chemisorbed PEGylated lipopolymers as sensing film supports for QCM odor sensors," Sensors Actuators B Chem., vol. 130, no. 2, pp. 857–863, 2008.
127] P. Sun, Y. Jiang, G. Xie, X. Du, and J. Hu, "A room temperature supramolecular-based quartz crystal microbalance (QCM) methane gas sensor," Sensors Actuators B Chem., vol. 141, no. 1, pp. 104–108, 2009.
128] A. Palaniappan, S. Moochhala, F. E. H. Tay, X. Su, and N. C. L. Phua, "Phthalocyanine/silica hybrid films on QCM for enhanced nitric oxide sensing," Sensors Actuators B Chem., vol. 129, no. 1, pp. 184–187, 2008.
129] M. Matsuguchi, Y. Kadowaki, and M. Tanaka, "A QCM-based NO 2 gas detector using morpholine-functional cross-linked copolymer coatings," Sensors Actuators B Chem., vol. 108, no. 1, pp. 572–575, 2005.
130] N. Van Quy, V. A. Minh, N. Van Luan, V. N. Hung, and N. Van Hieu, "Gas sensing properties at room temperature of a quartz crystal microbalance coated with ZnO nanorods," Sensors and Actuators B, vol. 153, pp. 188–93, 2011.
131] M. E. Escuderos, S. Sanchez, and A. Jim ´ enez, "Quartz Crystal ´ Microbalance (QCM) sensor arrays selection for olive oil sensory evaluation," Food Chemistry, vol. 124, no. 3, pp. 857– 862, 2011.
132] I Lundstrom, S Shivaraman, C Svensson, L. Lundkvist , "A hydrogen− sensitive MOS field− effect transistor", Applied Physics Letters, Vol. 26(2),pp.55-57,1975
133] I Eisele, T Doll, M Burgmair "Low power gas detection with FET sensors", Sensors and Actuators B: Chemical, Vol. 78 No. 1-3, pp. 19-25, 2001
134] NJP Paulsson, F Winquist, "Analysis of breath alcohol with a multisensor array: instrumental setup, characterization and evaluation", Forensic Science International, Vol.105, pp.95–114, 1999
135] I. Lundstrom, E. Hedborg, A. Spetz, H. Sundgren, F. Winquist. "Sensors and Sensory Systems for an E-nose", Eds. J. W. Gardner and P. N. Bartlett, NATOASI, Vol.212, pp.303–319, 1992
136] A. Spetz, F. Winquist, H. Sundgren, and I. Lundstrom, "Field effect gas sensors in Gas Sensors", Kluwer/Academic, Dordrecht, pp. 219–280, 1992
137] David R. Walt, Todd Dickinson, Joel White , John Kauer , Stephen Johnson , Heidi Engelhardt , Jon Sutter , Peter Jurs, "Optical sensor arrays for odor recognition", Biosensors & Bioelectronics,Vol. 13 ,pp.697–699, 1998
138] Neal A. Rakow & Kenneth S. Suslick, "A colorimetric sensor array for odor visualization, Nature (London), Vol.-406, p.710, 2000.
139] Walt, D.R., Dickinson, T., White, J., Kauer, J., Johnson, S., Engelhardt, H., Sutter, J. and Jurs, P. "Optical sensor arrays for odor recognition", Biosensors and Bioelectronics, Vol. 13 (6), pp. 697-9, 1998.
140] Kim, Y.H. and Choi, K.J., "Fabrication and application of an activated carbon coated quartz crystal sensor", Sensors and Actuators B, Vol. 87, pp. 196-200,2002
141] Covington, J.A., Gardner, J.W., Briand, D. and de Rooij, N.F., "A polymer gate fet sensor array for detecting organic vapours", Sensors and Actuators B: Chemical,Vol. 77 No. 1-2, pp. 155-62,2001
142] Jin, Z., Su, Y. and Duan, Y. (2001), "Development of a polyaniline-based optical ammonia sensor", Sensors and Actuators B: Chemical, Vol. 72 No. 1, pp. 75-9,2001

