An Introduction to Gas Sensors

A brief introduction about gas sensors and their different type of classification is included in this chapter. The advantage of using semiconductor metal oxide as chemiresistive gas sensor, various metal oxides used for gas sensing, the basic characteristics of gas sensor, the detection principle for metal oxide gas sensing, the role of additives in gas sensing and the effect of nanoparticle in gas sensing are reviewed.

1.1 Sensors

Sensor is a device that produces a measurable response to a change in a physical condition, such as temperature, pressure etc.. Sensors are particularly useful for making in-situ measurements such as in industrial process control. They are the critical components in all measurement and control application, responsible for converting some type of physical phenomenon into a quantity measurable by a data acquisition (DAQ) system. A sensor does not function by itself; it is always a part of larger system that may incorporate many other detectors, signal conditioners, signal processors, memory devices, data recorders and actuators.

‘Sensor’, the term started to gain currency during the 1970s [1]. This development was caused by technological developments which are part of a technical revolution that continues to this day. Rapid advances in microelectronics made available technical intelligence. Machines became more intelligent and more autonomous. There arose a demand for artificial sensing organs that would enable machines to orient themselves independently
in the environment. A generation ago, the word sensor was not widely used. Today, however, sensors are becoming ubiquitous in our daily lives. Our world is changing rapidly and sensors play an important role in this process. Broad agreements about attributes of sensors are:

- Be in direct contact with the investigated subject
- Transform non-electric information into electric signals
- Respond quickly
- Operate continuously or at least in repeated cycles
- Be small

The most important characteristics of a sensor are

- Sensitivity
- Stability
- Repeatability

Normally, a sensor is only useful if all the three components are tightly specified for a given range of measurand values and time of operation. A highly sensitive device is not useful if its output drifts greatly during the measurement time and the data obtained may not be reliable if the measurement is not repeatable. Other sensor characteristics, such as selectivity and linearity can often be compensated for by using additional, independent sensors or by signal conditioning circuits.

Sensor classification schemes range from very simple to the complex. One good way to look at a sensor is to consider all of its properties, such as stimulus, specifications, physical phenomenon, conversion mechanism, material and application field. Generally sensors can be classified based on stimulus applied as acoustic electric, magnetic, optical and thermal.
1.2 Chemical Sensor

Chemical sensors, as a special variety of sensors analyze our environment, i.e. they detect which substances are present and in what concentration. With our senses we can not only see, hear and feel but also smell and taste. The latter sensations are the results of some kind of chemical analysis of our environment, either of the surrounding air or of liquids and solids in contact with us. Consequently, chemical sensors can be considered as artificial noses or artificial tongues.

![Diagram of biological and technical systems](image)

**Fig. 1.1 Similarities between biological and technical systems**

Figure 1.1 illustrates the similarities between biological and technical systems. As in a living organism, we find a receptor which is a part of the technical system. The receptor responds to environmental parameters by changing some of its inherent properties. In the adjacent transducer, primary information is transformed into electrical signals. Modern sensor systems
contain additional parts for signal amplification or conditioning. At the end of the chain is a microcomputer, working like the central nervous system in a living organism.

The definition of chemical sensor as given by IUPAC in 1991 is: A chemical sensor is a device that transforms chemical information, ranging from concentration of a specific sample component to total composition analysis, into an analytically useful signal [2]. The chemical information, mentioned above, may originate from a chemical reaction of the analyte or from a physical property of the system investigated. Many authors have provided more general or specific definitions for this sort of sensors. According to Wolfbeis: chemical sensors are small-sized devices comprising a recognition element, and a signal processor capable of continuously and reversibly reporting a chemical concentration [3]. Reversibility means that the sensor signals should not ‘freeze’ but respond dynamically to changes in sample concentration in the course of measurement. According to Göpel and Schierbaum [4] chemical Sensors are devices which convert a chemical state into an electric signal. Chemical sensors are just the primary link of the measuring chain, in other words, an interface between the chemical world and the electronics.

Some typical properties associated with chemical sensors, according to Stetter and Penrose [5] is:

- Sensitive layer is in chemical contact with the analyte
- A change in the chemistry of the sensitive layer (a reaction) is produced after the exposure to the analyte.
- The sensitive layer is on a platform that allows transduction of the change to electric signals.
- They are physically small
They operate in real time.

They do not necessarily measure a signal or simple physical or chemical property

They are typically less expensive and more convenient than an equivalent instrument for the same chemical measurements.

A chemical sensor is an essential component of an analyzer. In addition to the sensor, the analyzer may contain devices that perform the following functions: sampling, sample transport, signal processing, data processing. An analyzer may be an essential part of an automated system. The analyzer, working according to a sampling plan as a function of time, acts as a monitor. Chemical sensors contain two basic functional units: a receptor part and a transducer part. Some sensors may include a separator which is, for example, a membrane. In the receptor part of a sensor which is a chemical interface, the analyte interacts chemically with a surface, producing a change in physical/chemical properties. The chemical information is transformed into a form of energy which may be measured by the transducer. The transducer part is a device capable of transforming the energy carrying the chemical information about the sample into a useful analytical signal. The transducer as such does not show selectivity.

The receptor part of chemical sensors may be based upon various principles:

- Physical, where no chemical reaction takes place. Typical examples are those based upon measurement of absorbance, refractive index, conductivity, temperature or mass change.
- Chemical, in which a chemical reaction with participation of the analyte gives rise to the analytical signal.
Biochemical, in which a biochemical process is the source of the analytical signal. Typical examples are microbial potentiometric sensors or immuno sensors. They may be regarded as a subgroup of the chemical ones. Such sensors are called biosensors.

In some cases it is not possible to decide unequivocally whether a sensor operates on a chemical or on a physical principle. This is, for example, the case when the signal is due to an adsorption process.

Classification of chemical sensors is accomplished in different ways. As per IUPAC [2] chemical sensors may be classified according to the operating principle of the transducer. The table 1.1 shows the various sensor classification based on the transduction principle.

This classification represents one of the possible alternatives. Sensors have, for example, been classified not according to the primary effect but to the method used for measuring the effect. As an example the so-called catalytic devices in which the heat effect evolved in the primary process are measured by the change in the resistance of a thermistor. Also, the electrical devices are often put into one category together with the electrochemical devices.

Sensors have also been classified according to the application to detect or determine given analyte. Examples are sensors for pH, for metal ions or for determining oxygen or other gases. Another basis for the classification of chemical sensors may be according to the mode of application, for example sensors intended for use in vivo, or sensors for process monitoring and so on. It is, of course, possible to use various classifications as long as they are based on clearly defined and logically arranged principles.
An Introduction to gas sensors

The biosensors are not presented as a special class because the process on which they are based is, in general, common to chemical sensors. They may be also differentiated according to the biological elements used in the receptor. Those may be: organisms, tissues, cells, organelles, membranes, enzymes, antibodies, etc. The biosensors may have several enzymatic systems coupled which serve for amplification of the signal.

Table 1.1 Classification of Sensors based on Transduction Principles

<table>
<thead>
<tr>
<th>Sensor Classification</th>
<th>Transduction Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>Absorbance, reflectance, luminescence, fluorescence, refractive index, optothermal effect and light scattering.</td>
</tr>
<tr>
<td>Electrochemical</td>
<td>Voltammetric and potentiometric devices, chemically sensitized field effect transistor (CHEMFET) and potentiometric solid electrolyte gas sensors.</td>
</tr>
<tr>
<td>Electrical</td>
<td>Metal oxide and organic semiconductors, electrolytic conductivity and electric permittivity.</td>
</tr>
<tr>
<td>Mass sensitive</td>
<td>Piezoelectric and surface acoustic waves.</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Paramagnetic gas properties</td>
</tr>
<tr>
<td>Thermometric</td>
<td>The measurement of the heat effect of a specific chemical reaction or adsorption which involves the analyte.</td>
</tr>
<tr>
<td>Others</td>
<td>Emission or absorption of radiation</td>
</tr>
</tbody>
</table>

1.3 Gas Sensors

The problems related to air quality monitoring are important issues of the current research activity. The living standards of human race in the past few decades have grown at a remarkable pace owing to industrial revolution. Technological developments in the recent decades have brought along with it several environmental problems and human safety issues. Growing industrialization and ever increasing pollutants from vehicular exhaust has resulted into increased air pollution. Industrialization demands the specific
gas detection and monitoring for the benefit of the society. Detection of pollutant, toxic, refining, combustible and process gases is important for system and process control, safety monitoring and environmental protection. A key component in many process controls, product development, environmental monitoring etc. is the measurement of concentration of one or the other gaseous component of the ambient. In such situations suitable sensors can provide the necessary interface between the ambient and the back up electronic instrumentation to detect the target gas. Hence, sensors which detect toxic and inflammable chemicals quickly are necessary.

Gas sensors which from a sub-class of chemical sensors have found extensive applications in process control industries and environmental monitoring. In recent years, the number of gaseous species to be covered with gas sensors has increased dramatically. Toxic or bad smelling gases frequently encountered in living circumstances such as H2S and NH3 as well as hazardous gases used for industrial processes have long been the targets of gas sensors. The detection of the various volatile gases or smells generated from foods or food materials has become increasingly important in food industries. These gaseous components are often present at very low levels and mixed with several disturbing gases. The recent global issues of energy and environment are increasing the necessity of those sensors which can detect air-pollutants in environments such as SOX, COX and NOX or can be applied for the control systems of combustion exhausts from stationary facilities and automobiles. Various gas sensors should be developed for such new target gases. In addition, different sensors may be needed even for the same gas depending on the conditions of sensor operation. Thus there is a need of gas sensors to measure the pollution level in the atmosphere so that appropriate steps can be followed to control the pollution. In addition, the flammable gases also need to be monitored to protect against the unwanted
incidence of fire or explosion. Thus there is huge demand for the monitoring of useful as well as flammable / hazardous gases. It may be seen most of these gases must be detected at parts per million (ppm) levels in the ambient. While other gases (for example \( \text{H}_2 \)) are not toxic at ppm levels but they are combustible and form explosive mixtures when their concentration in air exceeds a threshold value. Table 1.2 shows threshold limit value (TLV) data for some of the common toxic gases and table 1.3 shows the lower explosive limit (LEL) and ignition temperature of some typical combustible gases/vapors [6-8].

Table 1.2 Long and short term exposure limits of some typical toxic gases/ vapors

<table>
<thead>
<tr>
<th>Gas/vapor</th>
<th>Long term exposure limit, 8hr (ppm)</th>
<th>Long term exposure limit, 10min (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2\text{S} )</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>CO</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>( \text{NO}_x )</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>( \text{SO}_2 )</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>( \text{CH}_3\text{OH} )</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>( \text{Cl}_2 )</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>( \text{NH}_3 )</td>
<td>25</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 1.3 Lower explosive limit and ignition temperature of some typical combustible gases/vapors

<table>
<thead>
<tr>
<th>Gas/vapor</th>
<th>Long term explosive limit (%v/v)</th>
<th>Ignition Temp ((^{\circ})C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2 )</td>
<td>4</td>
<td>560</td>
</tr>
<tr>
<td>CO</td>
<td>12.5</td>
<td>605</td>
</tr>
<tr>
<td>( \text{CH}_4 )</td>
<td>5</td>
<td>595</td>
</tr>
<tr>
<td>( \text{CS}_2 )</td>
<td>1</td>
<td>102</td>
</tr>
<tr>
<td>( \text{C}_4\text{H}_10 )</td>
<td>1.5</td>
<td>365</td>
</tr>
<tr>
<td>( \text{CH}_3\text{OH} )</td>
<td>6.7</td>
<td>455</td>
</tr>
<tr>
<td>Kerosine</td>
<td>0.7</td>
<td>210</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_6 )</td>
<td>3</td>
<td>515</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_2 )</td>
<td>1.5</td>
<td>305</td>
</tr>
</tbody>
</table>
In order to meet such a need for various gas sensors, one has to have a concept of gas sensor design. Generally speaking, a gas sensor should possess two basic functions, a function to recognize a particular gas species (receptor function) and another to transduce the gas recognition into a sensing signal (transducer function). In many cases, the gas recognition is carried out through gas solid interactions such as adsorption, chemical reactions and electrochemical reactions. On the other hand, the way of transduction is heavily dependent on the materials utilized for the gas recognition. The gas recognition by semi conducting oxides is conventionally transduced into a sensing signal through the electrical resistance changes of the sensor elements, while capacitance can be used for the elements using dielectric materials. Electromotive force, resonant frequency, optical absorption or emission etc can also be utilized as sensing signals for other types of sensor material.

1.4 Various Technologies in Gas sensing application

The most commonly used gas sensors can be divided into three major groups depending on the technology applied in their development.

- Optic
- Spectroscopic
- Solid

Optical sensors measure absorption spectra after the target gas has been stimulated by light. They require a complex measurement system: a monochromatic excitation source and an optical sensor to analyse the absorbed spectra. Expensive analytical techniques (such as infrared spectroscopy, ultraviolet fluorescence, chromatography, etc.) are used to analyse gases.
Spectroscopic systems make a direct analysis of the molecular mass or vibrational spectrum of the target gas. They can quantitatively measure the composition of the different gases with good precision. Gas chromatography and mass spectrometry are the most important spectroscopic gas sensor systems. The gas chromatograph (GC) is very often combined with a mass spectrometer (GC-MS) for separating and identifying compounds. Through mass spectroscopy, the molecular mass and typical fragmentation of an unknown volatile can be obtained and compared with reference libraries. Infrared spectroscopy using fourier transform methods can also be combined with a gas chromatograph (GC-FTIR). Due to its ability to differentiate between isomers, it can complement GC-MS [9]. To detect odours, the gas chromatographic separation of volatiles can be combined with sensory analysis of individual peaks, using a split gas-stream GC-technique [10]. All these techniques are very precise, sophisticated and require a technician with a lot of experience to work with the equipment in order to obtain better result.

While spectroscopic and optic systems are too expensive for domestic use and sometimes difficult to implement in reduced spaces such as car engines, the so-called solid state sensors have great advantages due to their fast sensing response, simple implementation and low prices [11-13]. They are small, so they can be portable, they are low-power consuming, they are inexpensive because of the considerable production of semiconductor materials and they can be used in complex systems such as sensor arrays. Furthermore, these sensors are capable to work on-line without need of specially trained operators.

1.5 Solid State Gas Sensors

Solid state gas sensors, based on a variety of principles and materials, are the best candidates to the development of commercial gas sensors for a...)
wide range of such applications [14-18]. The great interest of industrial and scientific world on solid state gas sensors comes from their numerous advantages, like small sizes, high sensitivities in detecting very low concentrations (at level of ppm or even ppb) of a wide range of gaseous chemical compounds, possibility of on-line operation and, due to possible batch production and low cost. On the contrary, traditional analytical instruments such as mass spectrometer, NMR and chromatography are expensive, complex and large in size. In addition, most analysis requires sample preparation, so that real-time analysis is difficult. Solid-state chemical sensors have been widely used, but they also suffer from limited measurement accuracy and problems of long-time stability. However, recent advances in nanotechnology, i.e. in the cluster of technologies related to the synthesis of materials with new properties by means of the controlled manipulation of their microstructure on a nanometer scale, produce novel classes of nanostructured materials with enhanced gas sensing properties.

Several physical effects are used to achieve the detection of gases in solid state gas sensors. This is tabulated in table 1.4. In contrast to optical processes, which employ infra-red absorption of gases, chemical processes, which detect the gas by means of a selective chemical reaction with a reagent, mainly utilize solid-state chemical detection principles. A characteristic of solid state gas sensors is the reversible interaction of the gas with the surface of a solid-state material. In addition to the conductivity change of gas-sensing material, the detection of this reaction can be performed by measuring the change of capacitance, work function, mass, optical characteristics or reaction energy released by the gas/solid interaction.
Organic or inorganic (as semiconducting metal oxides) materials, deposited in the form of thick or thin films, are used as active layers in such gas sensing devices. The read-out of the measured value is performed via electrodes, diode arrangements, transistors, surface wave components, thickness-mode transducers or optical arrangements. Indeed, although the

<table>
<thead>
<tr>
<th>Type of sensor</th>
<th>Gas sensor</th>
<th>Detection Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid State Sensors</td>
<td>Chemiresistive</td>
<td>A change in conductivity of semiconductor is measured when it interacts with the analyzing gas</td>
</tr>
<tr>
<td></td>
<td>Chemical field effect transistors(ChemFET)</td>
<td>Current-Voltage (I-V) curves of a field effect transistor(FET) are sensitive to a gas when it interacts with gate</td>
</tr>
<tr>
<td></td>
<td>Calorimetric</td>
<td>The concentration of combustible gas is measured by detecting the temperature rise resulting from the oxidation process on a catalytic element.</td>
</tr>
<tr>
<td></td>
<td>Potentiometric</td>
<td>The signal is measured as the potential difference (voltage) between the working electrode and the reference electrode. The working electrode’s potential must depend on the concentration of the analyte in the gas phase.</td>
</tr>
<tr>
<td></td>
<td>Amperometric</td>
<td>Diffusion limited current of an ionic conductor is proportional to the gas concentration</td>
</tr>
</tbody>
</table>
basic principles behind solid state gas sensors are similar for all the devices, a multitude of different technologies have been developed. Hence, nowadays the number of different solid state based gas sensors is really very large. Due to the large variety of sensors, a rich fabric of interdisciplinary science ranging from solid state physics, chemistry, electronics, biology, etc., governs the modern gas-sensing devices. Solid state sensors depend strongly on the development of technologies with applications in other areas. A steering technology is that of micromachining which for chemical sensors has led to the development of gas sensor devices with small power consumption and short time constants, greater portability and easy integration with electronics.

Semiconductor based chemiresistor sensors are most investigated and widely used for detection of combustible and toxic gases owing to their low cost and relative simplicity. Chemiresistors or conductometric gas sensors mainly operate on the base of surface reactions. The chemiresistive gas sensors work on the principle of a change in electrical resistance due to an interaction between the semiconductor and the gas [19-23]. These sensors have excellent sensitivity, very short response time, low cost, and very good suitability for design of portable instruments, which compensate their disadvantages and open great possibilities for those sensors application in alarm systems, portable instruments and electronic nose.

1.6 Chemiresistive Gas Sensors

Semiconductor gas sensors (SGS), known also as chemiresistive gas sensors, are typically based on metal oxides. Atoms and molecules interact with semiconductor metal oxide surfaces, and influence such surface properties as conductivity and surface potential. The effect of the ambient atmosphere upon the electrical conductance of semiconductors was
described earlier [24, 25]. Later on in 1962, Seiyama et al demonstrated for
the first time that the conductivity of ZnO films, heated to 300°C, was
sensitive to the presence of traces of reactive gases present in air [26]. In the
year 1970 Taguchi reported similar properties for SnO₂, with an additional
advantage of a greater stability [27]. Since then, semiconductor gas sensors
have been widely used as domestic and industrial gas detectors for gas-leak
alarm, process control, pollution control, etc. Compared to the organic (such
as phenethrene, polybenzimidole) and elemental (such as Si, Ge,
GaAs,GaP) semiconductors, semiconductor oxides have been more
successfully employed as sensing materials for the detection of different
gases, such as CO, CO₂, H₂, alcohol, H₂O, NH₃, O₂, NOₓ, etc. Both n-type
and p-type semiconductor oxides can be used as gas sensor materials. There
is a vast amount of literature devoted to the development and study of solid
state gas sensor [28-31]. Various semi conducting metal oxides (SnO₂, ZnO,
WO₃, In₂O₃) [32-35], catalytic oxides (V₂O₅, MoO₃, CuO, NiO) [36-39] and
mixed oxides (LaFeO₃, ZnFe₂O₄, BaTiO₃ and Cd₂Sb₂O₆.₈) [40-44] have been
studied for gas sensing properties and many more new oxides are currently
being explored. However, most of the gas-sensing studies are based on
empirical methods, though there have been some good scientific publications
dedicated to the understanding of the gas sensing mechanisms [45, 46].
Nevertheless, metal oxides based gas sensors are a commercial success and,
for a host of gases, are easily available in the market for last 25 years.
Nowadays, there are many companies offering metal oxide based gas
sensors, such as Figaro, FIS, MICS, UST, CityTech, Applied-sensors,
NewCosmos, etc… A summary of literature survey of chemiresistive gas
sensors using different oxides and analysed gases are tabulated in table 1.5.
Table 1.5 Various Chemiresistive materials, additives and the analyzing gas

<table>
<thead>
<tr>
<th>Chemiresistive material</th>
<th>Base Material</th>
<th>Additives</th>
<th>Analysing gas</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-Oxides</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Al, SiO&lt;sub&gt;2&lt;/sub&gt;/Si</td>
<td>Humidity, Methane, Ammonia</td>
<td>47-50</td>
<td></td>
</tr>
<tr>
<td>Bi&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Sb&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Smoke, Carbon monoxide, Nitric Oxide</td>
<td>51-53</td>
<td></td>
</tr>
<tr>
<td>CdO</td>
<td>ZnFe&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Ethanol</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>CeO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Oxygen, Hydrogen Sulphide</td>
<td>55-57</td>
<td></td>
</tr>
<tr>
<td>Cr&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Nitrogen dioxide, Oxygen, Ammonia, Humidity</td>
<td>58-60</td>
<td></td>
</tr>
<tr>
<td>Co&lt;sub&gt;3&lt;/sub&gt;O&lt;sub&gt;4&lt;/sub&gt;</td>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Ammonia, Carbon monoxide, Methane, Propane, Hydrogen, Nitrogen dioxide, Chlorine</td>
<td>61-63</td>
<td></td>
</tr>
<tr>
<td>CuO</td>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Carbon monoxide, Ethanol, Hydrogen Sulphide</td>
<td>66-67</td>
<td></td>
</tr>
<tr>
<td>Fe&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Au, Zn (Pt, Pd, RuO&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>Methane, Propane, Benzene, Toluene, Carbon monoxide, Nitrogen dioxide, Methanol, Acetone.</td>
<td>68-72</td>
<td></td>
</tr>
<tr>
<td>Ga&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;, Pd, Ta&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;, WO&lt;sub&gt;3&lt;/sub&gt;, NiO</td>
<td>Oxygen, Carbon monoxide, Methane, Nitric Oxide, Ammonia.</td>
<td>73-77</td>
<td></td>
</tr>
<tr>
<td>In&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>MoO&lt;sub&gt;2&lt;/sub&gt;, Au, Al, SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Ozone, Nitrogen dioxide, Hydrogen, Carbon monoxide, Propane, Hydrogen Sulphide, Chlorine, Carbon dioxide, Sulphur dioxide, Ammonia, Ethanol, Acetone</td>
<td>78-87</td>
<td></td>
</tr>
<tr>
<td>MoO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Ti</td>
<td>Ammonia, Carbon monoxide, Nitrogen dioxide</td>
<td>88-91</td>
<td></td>
</tr>
<tr>
<td>Nb&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Ammonia, Carbon monoxide, Ethanol, Hydrogen</td>
<td>92-94</td>
<td></td>
</tr>
<tr>
<td>NiO</td>
<td>Li, TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Hydrogen, Formaldehyde, Methane, Acetic acid, Carbon monoxide, Nitrogen dioxide</td>
<td>95-98</td>
<td></td>
</tr>
<tr>
<td>Ta&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>-</td>
<td>Humidity</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Pt, Ag, Pd, Os, Fe, Au, In, Ru, Bi&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;, CeO&lt;sub&gt;2&lt;/sub&gt;, CuO</td>
<td>Carbon monoxide, Methane, Sulphur dioxide, Nitrous Oxide, Carbon dioxide, Nitrogen dioxide, Propane, Methanol, Ethanol, Hydrogen, LPG, Hydrogen Sulphide, Ammonia, C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;13&lt;/sub&gt;, Toluene</td>
<td>6, 100-121</td>
<td></td>
</tr>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>La, Pt, Cr&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;, WO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Methanol, Ethanol, Propyl Alcohol, Nitrogen dioxide, Oxygen, Hydrogen, Ammonia</td>
<td>122-133</td>
<td></td>
</tr>
<tr>
<td>WO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Mg, Zn, Mo, Re, Au, Pd</td>
<td>Nitrogen dioxide, Ammonia, Hydrogen Sulphide, Ozone</td>
<td>134-147</td>
<td></td>
</tr>
<tr>
<td>V&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>Fe&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;, SnO&lt;sub&gt;2&lt;/sub&gt;, TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Nitrogen dioxide, Ammonia, Ethanol, Butyl amines, Propanol, Toluene</td>
<td>148-150</td>
<td></td>
</tr>
<tr>
<td>ZnO</td>
<td>Al, Sn, Cu, Pd, Fe&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Ammonia, Hydrogen, LPG, Methane, Carbon monoxide, Hydrogen Sulphide, Nitrogen dioxide, Methanol, Propyl Alcohol, Ethanol</td>
<td>151-160</td>
<td></td>
</tr>
</tbody>
</table>
An oxide semiconductor gas sensor detects an inflammable gas from a change in electric resistance of a polycrystalline element. It is unanimously agreed that the resistance change on exposure to the gas arises through a surface phenomenon of the oxide semiconductor used [161-163], but this is only a part of the whole gas-sensing processes taking place in the element. Generally speaking, a chemical sensor consists of two functions, i.e., receptor function which recognizes or identifies a chemical substance, and transducer function which transduces the chemical signal into an output signal. For the basic understanding of the semiconductor gas sensor, therefore, one needs to differentiate these two functions. Figure 1.2 shows schematically how a semiconductor sensor element generates sensing signals upon contact with an inflammable gas. Apparently, the receptor function is provided with the surface of each semiconductor particle. The obtained chemical signal is then transduced through the microstructure of coagulating particles into the resistance of the polycrystalline element.

![Fig. 1.2 Receptor and transducer functions of the semiconductor gas sensor](image)

The gas/semiconductor surface interaction is based on the gas-sensing mechanism of SGS occurring at the grain boundaries of the polycrystalline oxide film. They generally include reduction/oxidation processes of the semiconductor, adsorption of the chemical species directly on the semiconductor and/or adsorption by reaction with surface states associated with pre-adsorbed ambient oxygen, electronic transfer of delocalized conduction-band electrons to...
localized surface states and vice versa, catalytic effects and in general complex surface chemical reactions between the different adsorbed chemical species. The effect of these surface phenomena is a reversible and significant change in electrical resistance. This resistance variation can be easily observed and used to detect chemical species in the ambient.

The working temperature, at which these devices work, varies depending on the specific target gas in the ambient and on the selected sensor material in conjunction with its properties in every case. As this working temperature ranges usually from 200 to 400 °C, it is necessary to implement a heating element in sensor device. A simple SGS is thus basically composed of a substrate in alumina, glass, quartz or silicon (on which the sensing layer is deposited), the electrodes (to measure the resistance changes of the sensing film) and the heater (commonly a Pt resistive type heater) to reach the optimum sensing temperature. Semiconductor gas sensors offer low cost, high sensitivity and a real simplicity in function, advantages that should work in their favour as new applications emerge. Moreover, the possibility of easily combining in the same device the functions of a sensitive element and signal converter and control electronics markedly simplifies the design of a sensor and constitutes the main advantage of chemiresistive-type sensors over biochemical, optical, acoustic, and other gas sensing devices. In spite of the numerous advantages of resistive-type gas sensors, they show different disadvantages as poor reproducibility, long-time instability due to aging, cross sensitivity to other gases, selectivity, sensitivity to water vapour etc...

1.7 Basic Characteristics

The electrical resistance of a chemiresistive sensor changes drastically (increase or decrease) when exposed to the molecules of analyzing gas.
Increase or decrease in resistance depends on the nature of sensor material (n-type or p-type) and the gas (reducing or oxidizing). A typical response curve, that is, variation of resistance of sensor with time on exposure and withdrawal of analyzing gas, is schematically depicted in Figure 1.3.

![Fig. 1.3 Schematic response-curve of a chemiresistive gas sensor](image)

The response curve of a sensor is characterised by following five parameters:

- a) Sensitivity
- b) Selectivity
- c) Stability
- d) Response time
- e) Recovery time

These parameters are discussed below.
1.7.1 Sensitivity

This is the device characteristic to percept a variation in physical and/or chemical properties of the sensing material under gas exposure. The sensitivity is generally defined as the ratio of the resistance of the sensing element in the target gas to that in air. The sensitivity is highly dependent on film porosity, film thickness, operating temperature, presence of additives and crystallite size. In order to improve it, it will be of great interest to work with the most appropriate sensing material in every case and reach its optimum detecting temperature. As suggested by several authors [164-165] working with nanostructure materials will give a higher surface area in front of gas. Taking into account that sensing reactions take place mainly on sensor layer surface, the control of semiconductor particle size will be one of the first requirements for enhancing the sensitivity of the sensor.

1.7.2 Selectivity

This characteristic is related to the discrimination capacity of a sensor towards a mixture of gases. Selectivity plays a major role in gas identification. Generally, a ‘fingerprinting’ method relies on a unique signature of the target gas signal. However, gases often produce very similar sensor responses (except when comparing reducing to oxidizing gases). For example, gases such as ethanol, carbon monoxide, and methane have appreciable cross-sensitivity that hinders the development of a domestic gas sensor that can distinguish these species [166]. Common techniques of improving the selectivity of gas sensors include controlling the sensor operating temperature, selective gas filters used in series with gas sampling, and using additives. Different operating temperatures allow the control of the sensitivity toward a particular gas when there is a unique $T_{crit}$ (critical temperature / optimum temperature with maximum sensor response) for each
gas; thus allowing the sensor to produce distinguishable signals for two gases at a selected temperature. The film morphology and sensor architecture can also play a key role in selectivity [167]. Distinguishing poorly reactive gases from reactive gases can be facilitated by placing electrodes further inside the bulk of the sensing material to allow reactive materials to be filtered by the sensing material near the surface of the sensor. Another technique uses catalysts, which generally reduce the operating temperature of a gas sensor for a particular gas species and thus allow the target gas to be distinguished from other gases due to the differences in sensitivity. In other words, addition of catalysts can maximize the sensitivity of target gases to produce a distinct signal

1.7.3 Stability

It is a characteristic that takes into account the repeatability of device measurements after a long use. The success of the sensor will be limited if the sensor performance is not demonstrated as repeatable and stable over long-term testing. Problems of stability, as outlined by Park and Akbar [167] may be attributed to three primary areas of concern. The first is that a surface conductive sensor can suffer from surface contamination. Second, changes in the sensor characteristics (such as intergranular connectivity) can occur due to thermal expansion coefficient mismatch and/or interfacial reactions at the metal electrode/ceramic interface. Last the film morphology may change over time due to the relatively high operating temperatures of the sensor, which may change over time due to the relatively high operating temperatures of the sensor, which may also cause migration of additives.

To avoid the effects of non-repeatability after repeated use, the sensor materials are submitted to a thermal pre-treatment, which would decrease posterior material instabilities. During these treatments samples are
submitted to high calcinations temperatures (from 400 to 1000°C during 1 to 8 hours) to avoid instabilities during their working life, continuously heated at 200-400°C. Most often the sensor element gets covered with decomposition products like carbon, CO₂, and H₂O causing a gradual decrease in the sensitivity at the operating temperature. A periodic change in sensor temperature removes all the adsorbed species and unburnt organic contaminants from the surface.

1.7.4 Response Time

The response time is the time interval over which resistance attains a fixed percentage (usually 90%) of final value when the sensor is exposed to full scale concentration of the gas. Time response is especially dependent on the sensor characteristics such as crystallite size, additives, electrode geometry, electrode position, diffusion rates, etc... A small value of response time is indicative of a good sensor.

1.7.5 Recovery Time

This is the time interval over which the sensor resistance reduces to 10% of the saturation value when the sensor is exposed to full scale concentration of the gas and then placed in clean air. A good sensor should have a small recovery time so that sensor can be used over and over again.

1.8 Detection Principle

Unlike other semiconductors which, under long-term or cycled heating in air, undergo irreversible chemical transformations by forming stable oxide layers, metal oxides bind oxygen on their surface in a reversible way. The principle detection process is the change of oxygen concentration at the surface of these metal oxides, caused by adsorption and heterogeneous
An Introduction to gas sensors

catalytic reaction of oxidizing and reducing gaseous species. The electrical conductivity depends on the gas atmosphere and on the temperature of the sensing material exposed to the test gas.

According to Williams and Moseley [168], most target gases are detected due to their influence on the oxygen stoichiometry of the surface. Studies have revealed that the key reaction involves modulation of the concentration of surface oxygen ions. The conductivity changes are caused by the formation of a space charge region induced by either gas adsorption or by the formation of oxygen vacancies on the surface.

Many studies have been devoted to identify the surface oxygen species. The form of adsorbed oxygen (either molecular or atomic) depends on the temperature of the sensor where $O_2^-$ species have been observed at lower temperatures (below 175°C) and $O^+$ and $O_2^-$ species have been observed at higher temperatures (above 175°C) occurs [169-171].

In an n-type semiconductor the sensor conductivity increases in the presence of a reducing gas (such as CO) and decreases in the presence of an oxidizing gas (such as $O_2$). In most of the metal oxide based gas sensor the sensor response is due to the surface interactions between the sensor and the surrounding gases. The general steps involved in sensor response upon exposure to air and to a reducing gas, R, are shown in figure 1.4. As shown in the left of column in figure 1.4, oxygen from the air is adsorbed on to the surface of the metal oxide. Electrons from the surface region of the sensor are transferred to the adsorbed oxygen, leading to the formation of an electron depleted region near the surface of the sensor. The electron depleted region, also called the space-charge layer, is an area of high resistance and the core region of the particle, where electron densities are high, is an area of relatively low resistance.
Chapter - 1

Fig 1.4. Schematics indicating the mechanisms leading to n-type semiconducting metal oxide sensor response to oxidizing and reducing gases.

As shown in right hand column of figure 1.4, when exposed to a reducing gas like CO, surface reactions such as,

\[ CO + O^{-}_{\text{ads}} \rightarrow CO_2 + e^- \]
\[ 2CO + O^{-}_{2,\text{ads}} \rightarrow 2CO_2 + e^- \]

release electrons back to the metal oxide and lead to a decrease in the resistance of the space charge layer hence an increase in conductivity. The n-
type metal oxide semiconductor materials have relatively few adsorption sites available due to the development of potential barriers on the particle surface [172]. In addition the fraction of surface sites occupied is low in comparison with the sites available on the surface of metal oxide [167]. Consequently incorporating species that have a comparably high number of adsorption sites with high fractional occupancy in the metal oxide sensing material can have significant impact on the sensor performance. Improved efficiency and sensing selectivity of these devices require detailed understanding of the surface and interfacial processes at the atomic level, and their relationship with materials properties and device performance.

1.9 Catalytic Additives on Metal Oxide Semiconductor Sensors

Almost all metal oxides suffer from the problem of poor selectivity. Attempts have been made in literature to improve the selectivity of metal oxides using different means. The addition of an appropriate amount of metal additives has been shown to improve the detection of various kinds of gases via the enhancement of the sensor response and a decrease of the temperature of maximum sensor response. A decrease in response time and a better selectivity are also claimed to be achievable by using these additives. Table 1.4 shows the various metal additives used in metal oxide semiconductor gas sensor for achieving selectivity.

The addition of metal additives can lead to two different sensitisation mechanisms: Chemical sensitisation (spill over mechanism) and electronic sensitisation (Fermi level mechanism) [173]. Figure 1.5 shows the schematic representation of mechanism of sensitization by metal or metal oxide additive. In the first case, the promoting effect is due to the ability of noble metals to activate inflammable gases by enhancing their spill-over, so that
they react with oxygen adsorbates more easily. The promoter in this case activates a test gas to facilitate its catalytic oxidation on the semiconductor surface. In other words, the promoter does not affect the resistance of the element directly, leaving the gas-sensing mechanism essentially the same as in the case without it. In this type of sensitization, an inflammable gas eg., H₂ is activated by the metal additive and the activated fragments (H) of the gas are spilt-over to the semiconductor surface to react with the adsorbed oxygen. The metal additive thus facilitates chemical reaction of the gas on the semiconductor [16]. The promoter increases the gas sensitivity as it increases the rate of the chemical processes leading to a decrease in concentration of the negatively charged adsorbed oxygen. This is why the effect is called chemical sensitization [172]. In this way, the additives exert a sort of remote control on the catalytic and sensing properties of the metal oxide.

![Fig. 1.5 Mechanism of sensitization by metal or metal oxide additive](image)

On the other hand, the electronic sensitisation is associated with oxidised metal additives. Electronic sensitization comes out through a direct electronic interaction between the promoter and the semiconductor surface. When the oxidation state of the promoter changes with the surrounding atmosphere, the electronic state of the semiconductor will also change accordingly. The addition of fine particles of some metals to n-type metal
oxides usually results in a rise of the base resistance of semiconductor metal oxide in air. There is a decrease in the electron concentration in the oxide surface layer, which corresponds to an increase of the space charge depth as a result of the electron transfer from the metal oxide to the metal loaded on to its surface. When the metal surface is covered with oxygen adsorbates at elevated temperatures in air (i.e. the metal is oxidised), the oxygen adsorbates extract electrons from the metal, which in turn extracts electrons from the metal oxide, leading to a further increase in the space-charge depth. More specifically these oxidised metal additives will be easily reduced to metals in presence of an inflammable gas. Consumption of oxygen adsorbates on the metal, in addition to those on the metal oxide surface, by reaction with flammable gases, causes the enhanced sensitivity. In this case therefore the promoting effect arises mainly from the change in the oxidation state of the loaded material.

1.10 Metal Oxide Semiconductor Nanoparticles for Chemical Gas Sensors

Gas adsorption is mainly a surface related process. The grain size and area of active surface layers are the main parameters, controlling gas sensing effects in semiconducting gas sensors. Hence decreasing the particle size has a dramatic effect in gas sensing related topics. Due to a high specific surface area, semiconductor nanoparticles are very well suited to the fabrication of chemical gas sensors. Their surface to bulk ratio is much larger than that of coarse micro-grained materials, which yields a large interface between the oxide and the gaseous medium. Therefore, for the same chemical composition, the smaller the nanomaterials are, the more sensitive the sensor is. The interaction taking place between a gas and a solid mainly takes place on the surface and interfaces are critical for controlling the properties of the
gas sensor. In a nanocrystalline material the portion of the surface atoms is very high [174-177]. Indeed the large density of molecules which can possibly adsorb on the semiconductor nanoparticles, results into large variations of the electrical conductivity. Hence decreasing the crystallite size can dramatically improve the sensor sensitivity. The gas sensing principles are same as that of standard metal oxide sensors [178].

Crystallite size effects on sensor performance are generally explained in terms of the relative values of the characteristic dimensions of the connection between adjacent particles (the neck width) and thickness of the space charge layer. The thickness of the space charge layer is typically indicated by the Debye length, $L_D$, of the electrons in the oxide sensor. The change in conductivity of a sensing layer is often explained by ‘grain boundary models’ [179]. In this context, the term grain is used as a synonym for a single crystalline particle, regardless of whether or not the grain is agglomerated or sintered to form larger entities (polycrystalline). It has been shown, that the particle size as well as the connection of adjacent metal oxide grains, either agglomerated or sintered, affects substantially the conductivity and thus the sensitivity of a sensor. The gas response increases abruptly when the particle size $D$ becomes comparable or smaller than the depletion layer thickness $L$, which for example, is determined to be 5-15 nm for SnO$_2$ grains. Furthermore, a proportional relation between the sensitivity to $1/D$ was obtained by theoretical simulation, confirming the experimental results [164,180]. In this regard, a semi quantitative model was proposed by Xu et al. [179], which concerns the relationship between grain size $D$ and $L$ of sintered and agglomerated grains, whereas three different cases can be distinguished, illustrated in figure 1.6.
In case of large grains with a small surface-to-volume ratio, $L$ is significantly smaller than the single crystallite size ($D >> 2L$). Most of the volume of the crystallites is unaffected by the surface interactions with the gas phase. The electron conducting channels through necks are too wide to be influenced by the surface effect. Basically, the conductivity depends on the grain boundary barrier height (GB) for inter crystallite charge transport from one grain to another (see Figure 1.6, a) and is therefore independent of the grain size (grain boundary controlled). In case of higher surface-to-volume ratio, i.e. smaller grains but still larger than twice the depletion layer ($D \geq 2L$), that region extends into the grains forming constrictions, so called necks (see Figure 1.6, b). As a consequence, the conductivity is affected by the cross section area of these necks which is dependent on the ambient gas composition (neck controlled). Compared to the former case ($D >> 2L$) the...
mentioned constriction effect adds up to the effect of GB barriers resulting in an improvement of the gas sensitivity. Again, oxidizing gases increase the depletion layer thickness leading to smaller necks, whereas reducing gases cause a decrease, resulting in larger necks. When \( D < 2L \), the depletion layer extends throughout the whole grain and the crystallites are almost entirely depleted (see Figure 1.6, c). Under this situation, grains share a major part of the resistance and control the gas sensitivity. Thus the conductivity decreases steeply since the conduction channels between the grains are not present. The energy bands are nearly flat throughout the whole structure of the interconnected grains, and since there are no significant barriers for intercrystallite charge transport the conductivity is primarily controlled by the intracrystallite conductivity (grain controlled). It was found empirically as well as theoretically, that the highest gas sensitivity towards reducing gases (CO and H\(_2\)) is obtained in this case. Already very small variations in the trapped charge density lead to a significant change in the effective carrier concentration and finally in the electrical conductivity. Moreover, a proportional relation between the sensitivity to \( 1/D \) was found theoretically by Rothschild [181], approving the results previously obtained experimentally by Xu et al [179]. The considerations reveal that high surface-to-volume ratios, present in nanocrystalline metal oxides, are desired for gas sensing purposes. A more extensive discussion about the complex processes of the gas detection is given in some reviews [179, 182, 183]. Superior gas sensing properties have been reported for semiconductor metal oxide materials for sizes in 5-50 nm range [7, 8, 14, 15, 172]. Due to this enhanced sensitivity metal oxide semiconductor nanoparticles present a new trend in the area of gas sensing.

1.11 Objective of Present Study

The essentially positive outlook for the gas sensors industry stems from the undeniable fact that gas sensors are indispensable to numerous, key
An Introduction to gas sensors

industries, since they provide vital information about the gaseous composition of the ambient. Moreover, driven by the continued proliferation of more advanced electronic control systems to increase efficiencies, users of gas sensors require ongoing advances in sensor accuracy, reliability, response time, robustness, miniaturization, and/or communications capability. Such requirements drive the trends of R&D in gas sensors industry, which in turn fuels opportunities for technology advancements that can open up new applications of gas sensors. While many different approaches to gas detection are available, the R&D of solid state gas sensors has enormously advanced in recent years. Gas sensors operate on the principle of conversion of gas concentration into a measurable signal. Among the solid-state gas sensors, semiconductor metal oxide gas sensors have received the most attention as they show good potential for continuous monitoring of gases.

Gas sensors using oxide semiconductors have been subjected to extensive research and development and have now grown to be important devices for detecting the leakage of several inflammable gases and toxic gases, since the pioneering works reported in 1962 by Seiyama et al. and Taguchi [26,27]. These sensors offer a wide variety of advantages over the traditional analytical instruments which include lower cost, easier manufacturing, smaller size, short response and faster recovery. The basic part of efforts made nowadays by scientific research community in semiconductor gas sensor field is devoted both to optimize the performances of gas sensors by improving their sensitivity, selectivity and stability for the detection of single gases and the development of electronic noses for application mainly in environmental control and in food industry. In the field of this type of gas sensors, recent applied studies and products releases have shown some significant trends on nanotechnologies. Several theoretical and applied articles have shown the advantage of reducing the metal oxide grain size down to nanometer scale in
order to improve the sensing properties (mainly sensitivity and selectivity) as well as stability over time of the oxide layer. Nanocrystalline semiconducting metal oxides as gas sensors constitute a new and exciting subject of research.

The aim of present work is development of nanocrystalline oxide semiconductor gas sensors based on tungsten oxide (WO$_3$), zinc oxide (ZnO) and indium oxide (In$_2$O$_3$) for the detection of environmental polluting gas like nitrogen dioxide (NO$_2$) and hydrogen sulphide (H$_2$S). Nitrogen dioxide is produced from combustion processes, which is a typical air pollutant. It can react with water in the atmosphere to form nitrous acid and nitric acid, which are one of the factors that cause the acid rain. Hence, detection and emission control of toxic NO$_2$ gases is of great importance. H$_2$S is a colourless gas with odour of rotten eggs at very low concentrations. It occurs naturally in crude petroleum, natural gas, in volcanic gases, lake and marine sediments. It is formed also from bacterial breakdown of organic matter containing sulphur, or produced by human and animal wastes. The fabrication of gas sensor and different structural characterisation techniques adopted for the sensor are presented in the thesis. The sensor response is different at different working temperatures depending upon the oxide sensor and the analyte gases. Hence the response of the sensor at different operating temperatures is studied in this work and the sensitivity at different temperature for all the oxides for both gases is obtained. The major problem associated with metal oxide gas sensors is poor selectivity. Better selectivity to the gases studied can be obtained by suitable addition of dopants. The additives added can enhance the sensor response, decrease the optimum operating temperature for maximum sensor response, decrease the response and recovery time in addition to better selectivity. In our studies we have used dopants like copper and indium to study the effect of presence of additives in the gas sensing properties of the fabricated sensor. Thick as well
as thin film sensors of the oxides are studied for the purpose of gas sensing. The optimum operating temperature, response time, recovery time, minimum and maximum detectable limits of the fabricated sensors are also presented. A detailed discussion of the sensing mechanism associated with the test gas for each sensor is also included in the thesis.

References

Chapter 1


An Introduction to gas sensors

Chapter - 1


An Introduction to gas sensors


An Introduction to gas sensors

Chapter - 1


An Introduction to gas sensors


An Introduction to gas sensors


