Chemical and Biological Materials

Unit-Chemical Sensors

B.Tech Sem I

Syllabus Unit: Chemical Sensors

Chemical sensors:

I. Introduction

II. Types of Chemical sensors

III. Applications in environmental monitoring

IV. Air quality monitoring

V. Fire detection and prevention

VI. Gas sensors for storage

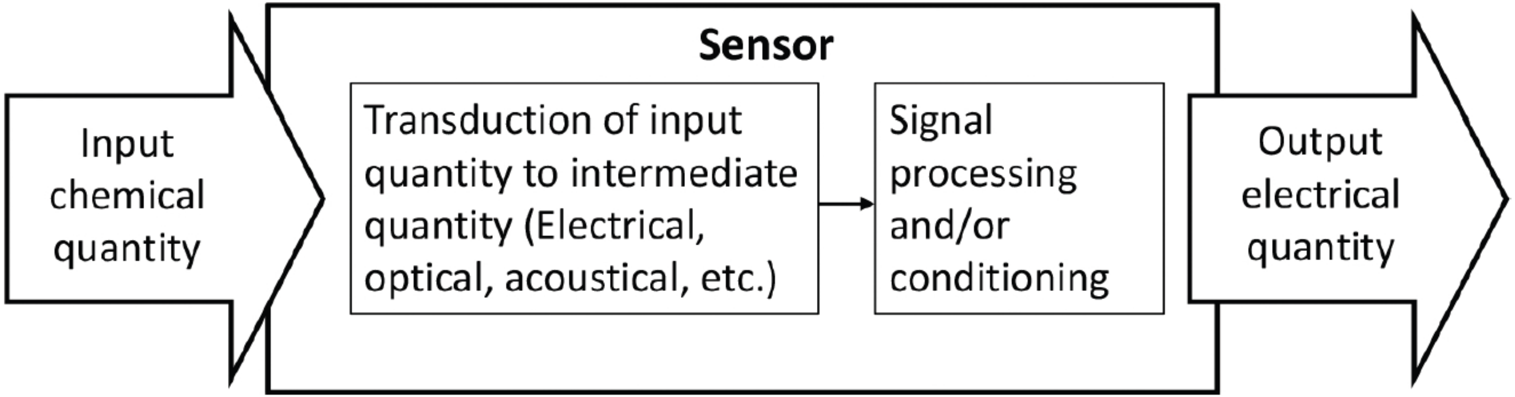
VII. Industrial emission control

VIII. Mobile devices

IX. Wearables

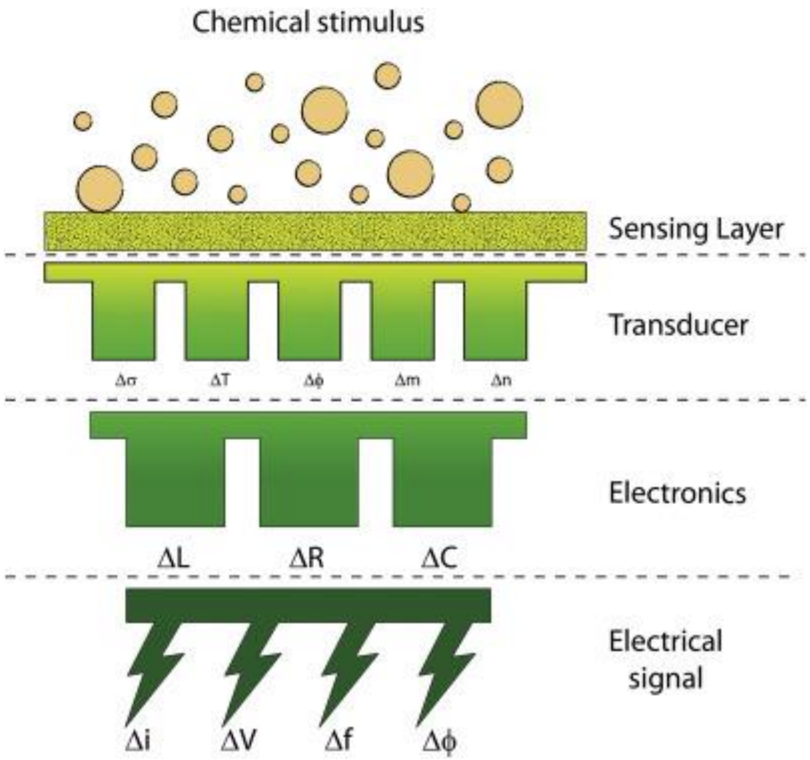
Chemical Sensors: Introduction

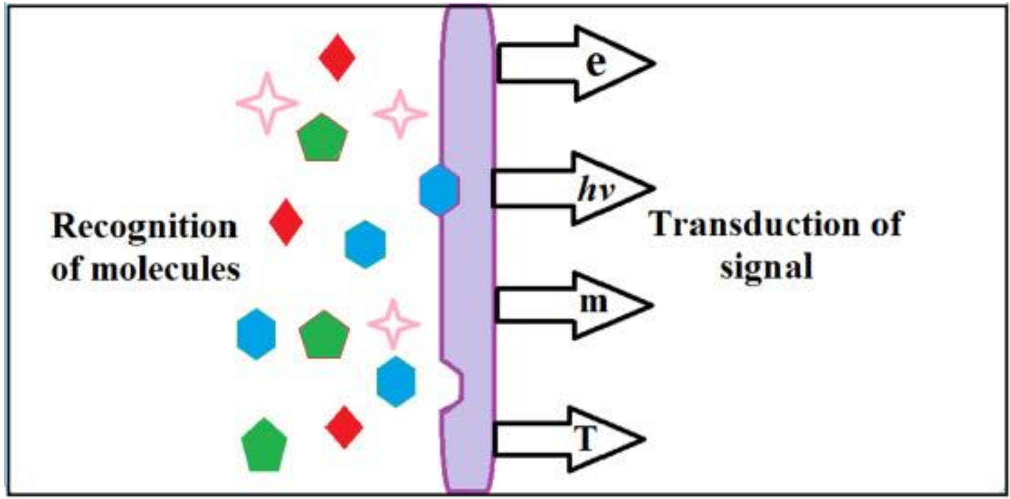
The ***chemical sensor*** is an analyzer that responds to a ***particular analyte in a selective and reversible way*** and transforms ***input chemical quantity***, ranging from the concentration of a specific sample component to a total composition analysis, into an analytically electrical signal



A chemical sensor is a device ***that measures and detects chemical qualities in an analyte*** (the scientific term for a chemical substance being observed) and ***converts the sensed chemical data*** into electronic data.

Chemical Sensors: Introduction





Chemical Sensors: working principle

Chemical sensors usually contain two basic components connected in series: ***a chemical (molecular) recognition system (receptor)*** and a ***physicochemical transducer***.

In the majority of chemical sensors, the receptor interacts with analyte molecules. As a result, its physical properties are changed in such a way that the appending transducer can gain an electrical signal.

Receptor: The function of the receptor is fulfilled in many cases by a thin layer which is able to interact with the analyte molecules, catalyze a reaction selectively, or participate in a chemical equilibrium together with the analyte. The receptor layer can respond selectively to particular substances or to a group of substances. The term molecular recognition is used to describe this behavior.

Chemical Sensors: working principle

- **Transducer:** Nowadays, signals are processed almost exclusively by means of electrical instrumentation. Accordingly, every sensor should include a transducing function, *i.e.* the actual concentration value, a non-electric quantity must be transformed into an electric quantity, voltage, current or resistance. Some of them develop their sensor function only in combination with an additional receptor layer. In other types, receptor operation is an inherent function of the transducer.

FEW EXAMPLES:

CO is a colorless and odorless compound produced by incomplete combustion. It is also known as "silent killer" because it is virtually undetectable without using detection technology.

Chemical Sensors: Examples

Blood glucose monitors measure the amount of sugar in a sample of blood using a complex chemical process. Within the test strip the blood is mixed with glucose oxidase, which reacts with the glucose in the blood sample to create gluconic acid.

Mosquitoes have a battery of sensors in their antennas and one of them is a chemical sensor. They can sense carbon dioxide and lactic acid up to 36 meters away. Mammals and birds release these gases when they breathe.

PREGNANCY TEST

the easiest and most reliable test is one that looks for the presence of the hormone known as human chorionic gonadotropin, or hcG. hcG is produced by the placenta and can be found in a woman's system as soon as implantation of a fertilized egg has occurred.

Chemical Sensors: Introduction

The chemical information may originate from a ***chemical reaction*** by a ***biomaterial, chemical compound, or a combination of both*** attached onto the ***surface of a physical transducer*** toward the analyte.

Although the history of chemical sensor dates back not long ago, it has gained increasing attraction for applications in ***environmental monitoring***, ***industrial process monitoring***, ***gas composition analysis***, ***medicine***, ***national defense*** and ***public security***, and ***on-site emergency disposal*** owing to its many excellent properties such as ***small size***, ***satisfactory sensitivity***, ***larger dynamic range***, ***low cost***, and ***easy to realize automatic measurement*** and online or in situ and continuous detection.

Chemical Sensors: Classification

Chemical sensors may be classified according to:

- The operating principle of the transducer.
- The type of substance either, chemicl,biochemical or physical(in terms of optical) it is sensing from its vicinity.

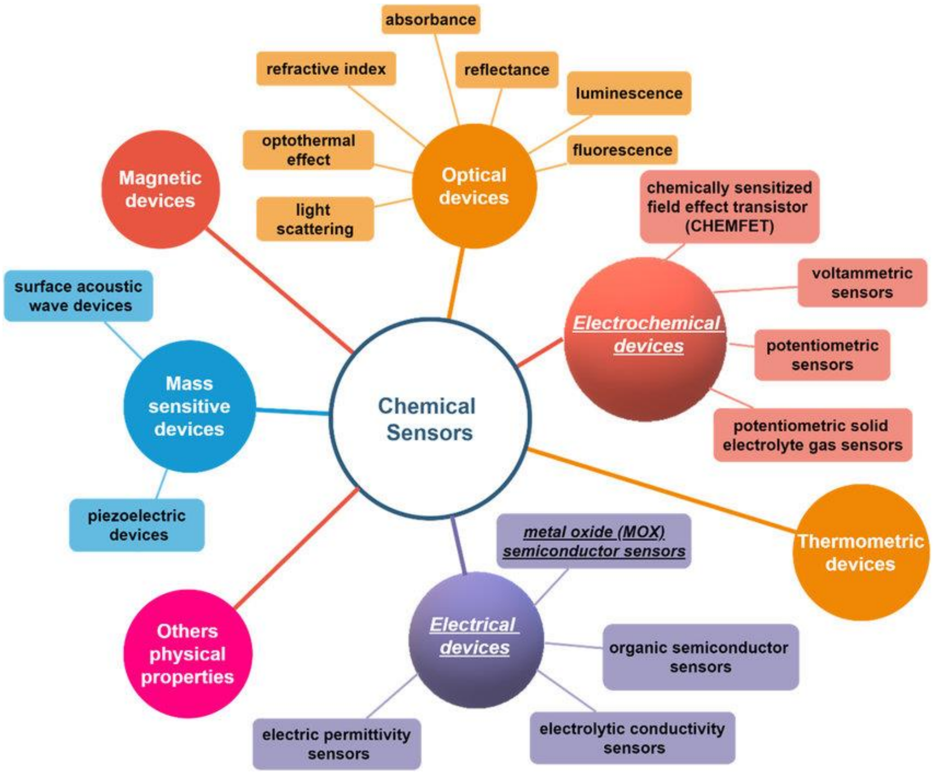
And they types include the folowing:

1. **Optical devices** transform changes of optical phenomena, which are the result of an interaction of the analyte with the receptor part.
2. **Electrochemical devices** transform the effect of the electrochemical interaction analyte - electrode into a useful signal.
3. . **Electrical devices** based on measurements, where no electrochemical processes take place, but the signal arises from the change of electrical properties caused by the interaction of the analyte.

Chemical Sensors: Classification

4. **Mass sensitive devices** transform the mass change at a specially modified surface into a change of a property of the support material.
5. **Magnetic devices** based on the change of paramagnetic properties of a gas being analysed. These are represented by certain types of oxygen monitors.
6. **Thermometric devices** based on the measurement of the heat effects of a specific chemical reaction or adsorption which involve the analyte. for example in the so called catalytic sensors the heat of a combustion reaction or an enzymatic reaction is measured by use of a thermistor.
7. Other physical properties as for example X-, p- or r- radiation may form the basis for a chemical sensor in case they are used for determination of chemical composition.

Chemical Sensors: Introduction



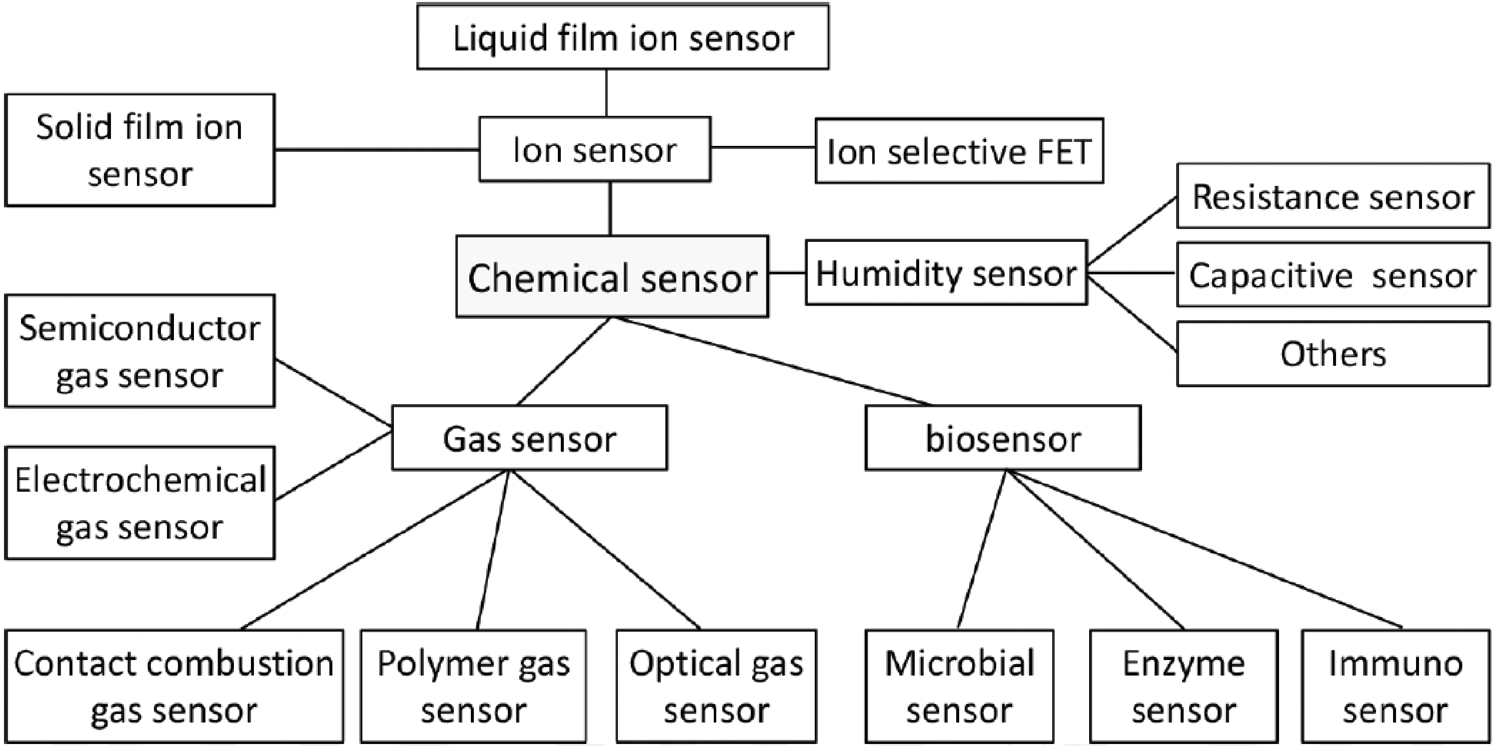
Gas sensors

Another way to categorize the ***chemical sensors*** is based on the ***object to be detected***, that is, the chemical sensors can be classified as ***gas sensors*** for trace gas analysis and monitoring, various ***ion sensors*** represented by the pH sensor, humidity sensor, and biosensors made by biological characteristics.

It is well known that the ***environment monitoring is the major application*** field of the chemical sensor, therein, the ***gas sensor plays a pivotal role***.

The ***key performance indicators*** of the gas sensor include ***sensitivity, selectivity, and stability***, which are determined mainly by the characteristics of the sensing material and mechanism.

Gas sensors



Liquid film ion sensor
Solid film ion sensor
Ion sensor
Ion selective FET
Resistance sensor
Chemical sensor
Humidity sensor
Capacitive sensor
Others
Semiconductor gas sensor
Gas sensor
biosensor
Electrochemical gas sensor
Contact combustion gas sensor
Polymer gas sensor
Optical gas sensor
Microbial sensor
Enzyme sensor
Immuno sensor

Gas sensors

Generally speaking, the ***gas sensor*** is categorized mainly by its working principle as a ***semiconductor type***, an ***electrochemical type***, a ***solid electrolyte type***, a ***contact combustion type***, a ***photochemical type***, and a ***polymer type***.

Semiconductor gas sensor

Semiconductor gas sensor is a sensitive element made by metal oxides or metal semiconductor oxide materials. As regards the electrical conductivity sensors, the resistance of their active sensing layer changes due to contact with the gas to be detected.

Since the first semiconductor metal-oxide-ceramic gas sensor was reported in 1962, the semiconductor gas sensors have become the most comprehensive and widely used gas sensors.

Gas sensors

Electrochemical gas sensor

The electrochemical gas sensor can be categorized into galvanic cell type, controlled potential electrolysis type, coulometric type, and ion-selective electrode type. The galvanic cell gas sensor evaluates the target gas composition by measuring the shift in current.

The controlled potential electrolysis gas sensor senses the target gas by measuring the electrolytic current and is different from the galvanic cell sensor, and a specific voltage should be imposed externally.

Furthermore, the oxygen in blood can also be detected in addition to CO, NO, NO_2, and SO_2.

Gas sensors

Contact combustion gas sensor

The contact combustion gas sensor includes direct contact sensor with the combustion and catalysis combustion sensor.

Its working principle is that oxidative combustion of the combustible gas occurs directly or by using catalysts in the energized state, accordingly, the burning gas sensitive material (Pt wire) is heated up, resulting in the shift in the resistance value.

By evaluating the resistance shift, the gas concentration can be extracted. Sometimes, such a sensor is called a thermal conductivity sensor, which is widely used for sensing combustible gas in petroleum chemical plant, shipyards, mine tunnels, kitchens, and bathrooms.

Gas sensors

Optical gas sensor

Optical gas sensors include infrared absorption sensors, spectrum absorptive sensors, fluorescence sensors, and fiber sensors, in which, the infrared absorption sensor is the most widely used for sensing gas by measuring and analyzing the infrared absorption peak from various gas adsorption.

Such a sensor has a lot of outstanding advantages of excellent antivibration and antipollution ability, autocorrection, and possibility of continuous and longer dynamic monitoring.

Polymer gas sensor

The polymer gas sensitive materials have grown enormously in the past several years, which plays an important role in sensing trace poisonous gas because of its easy operation, simple process, good selectivity at normal temperature, low price, and easy to combine with the micro structure or surface acoustic wave (SAW) devices.

Chemical sensors: Applications

- Environmental protection and monitoring, prevention and treatment of disease and the continuous improvement of people's quality of life are still the main application areas of the chemical sensors in the foreseeable future.
- A variety of gas sensors used widely in environmental protection and monitoring are highly valued, which are the mainstays of three mainstreams of chemical sensors.
- High sensitivity, miniaturization, integration, and low cost are still the development tendency of the gas sensors.
- The electromechanical sensor dominated by ion selective electrode (ISE) continues to trend to high sensitivity, low detection limit, fast response, and long operating life.

Chemical sensors: Applications

Application	Detected Chemicals and Gases
Automotive	O_2, H_2 , CO, NO_x , HCs,
Water treatment	pH, Cl_2, CO_2 , O_2, O_3, H_2S,
Food	Bactreria, biologicals, chemicals, fungal toxins, humidity, pH, CO_2
Agriculture	NH_3 , amines, humidity, CO_2 , pesticides, herbicides
Military	Agents, explosives, propellants
IAQ	CO, CH_4 , humidity, CO_2 , VOCs
Industrial safety	Indoor air quality, toxic gases, combustible gases, O_2
Petrochemical	HCX, and conventional pollutants
Steel	O_2, H_2 , CO, conventional pollutants
Medical	O_2 , glucose, urea, CO_2 , pH, Na_1, K_1, Ca, Cl_2, bio-molecules, H2S,Infectious disease, ketones, anesthesia gases
Environmental	SO_x , CO_2 , NO_x , HCs , NH_3 , H_2S, pH, heavy metal ions
Utilities [gas, electric]	O_2 , CO, HCs, NO_x , SO_x , CO_2

Applications: Environmental Monitoring

Air Quality Monitoring

- Chemical sensors can detect and quantify various chemical compounds and physical parameters in the environment, providing crucial data for informed decision making and regulatory action.
- Chemical sensors are extensively employed to monitor air quality in urban areas, industrial zones, and indoor environments.
- They detect pollutants such as particulate matter, nitrogen oxides (NOx), sulfur dioxide (SO2), volatile organic compounds (VOCs), and carbon dioxide (CO2).
- These sensors provide real-time data that informs air quality management and helps reduce health risks associated with poor air quality

Applications: Environmental Monitoring

Water quality assessment:

- Ensuring the safety and quality of drinking water sources is a critical environmental concern. Chemical sensors are used to detect contaminants like heavy metals, pathogens, pesticides, and industrial pollutants in water bodies. This monitoring is essential for safeguarding public health and maintaining ecosystem balance.

Soil monitoring:

- Soil quality affects agriculture, ecosystem health, and groundwater contamination. Chemical sensors can measure soil parameters such as pH, moisture content, nutrient levels, and the presence of harmful substances like heavy metals. This data aids in optimizing agricultural practices and identifying contaminated areas.

Applications: Environmental Monitoring

Industrial emissions control:

- Industries use chemical sensors to comply with emissions regulations and minimize their environmental impact. These sensors monitor emissions of pollutants like sulfur compounds, volatile organic compounds, and greenhouse gases. Timely data allows industries to adjust processes and reduce their emissions.

Hazardous waste management:

- Chemical sensors are integral in identifying and managing hazardous waste materials. They assist in the detection and quantification of toxic substances, ensuring proper disposal and minimizing environmental contamination risks.

Applications: Air Quality Monitoring

- Pollutants are emitted by human activities and natural sources. Hundreds of hazardous pollutants in our living environment have been identified.
- However, six of these pollutants are well studied and ubiquitous in our daily lives, including carbon monoxide (CO), nitrogen dioxide (NO_2), ground level ozone (O_3), sulfur dioxide (SO_2), particulate matter (PM) and lead (Pb).
- There are five types most suitable and widely used low-cost portable gas sensors, namely:
  - Electrochemical Sensors
  - Catalytic Sensors
  - Solid-state (Semiconductor) Sensors
  - Non-dispersive Infrared Radiation Absorption (NDIR)
  - Photo-ionization Detector (PID) Sensors

Applications: Air Quality Monitoring

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Applications: Air Quality Monitoring

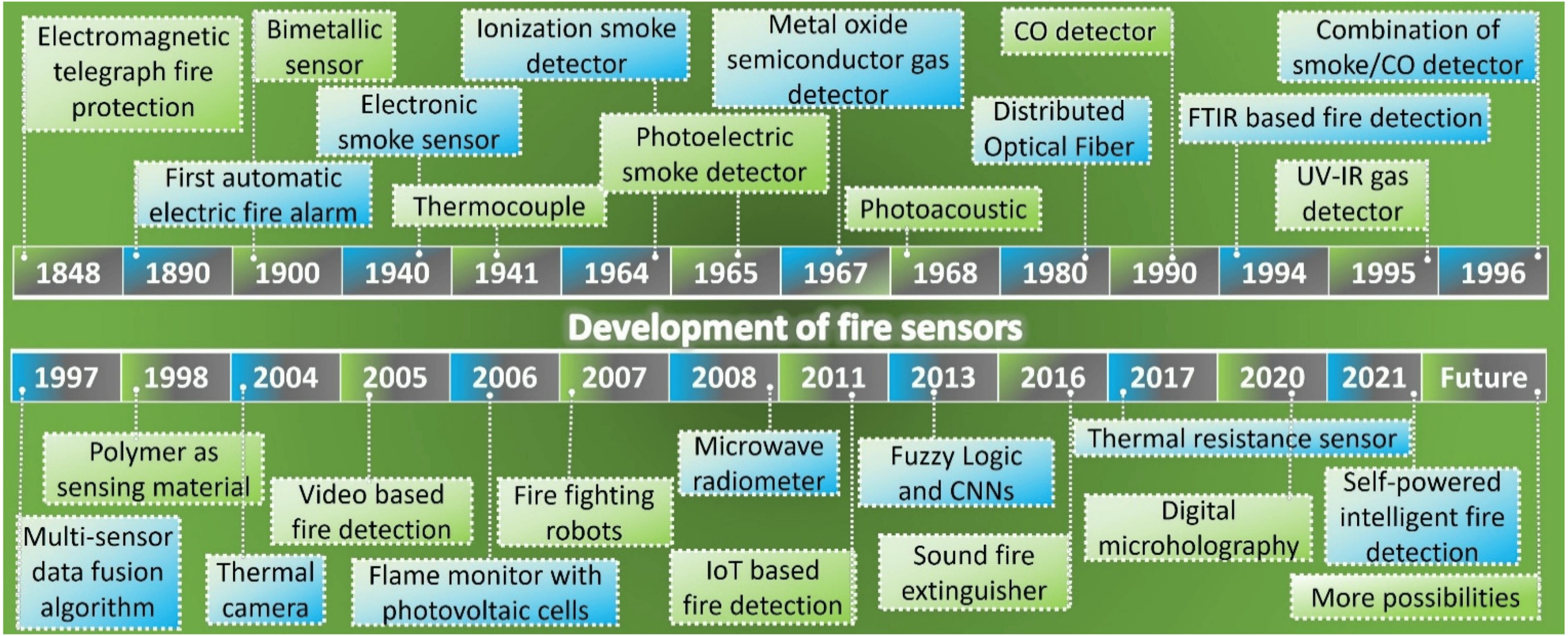
Table 7. Comparison of the five types of gas sensors.

Sensor Type	Detectable Gases	Linearity	Cross Sensitivity	Power Consumption	Maintenance	Response Time (T90)	Life Expectancy
Electro-chemical [78]	Gases which are electrochemically active, about 20 gases	Linear at room temperature	Can be eliminated by using chemical filter	Lowest, very little power consumption	Low	<50 s	1–2 years
Catalytic [79]	Combustible gases	Linear at 400 °C to 600 °C	No meaning when measuring mixed gases	Large, need to heat up to 400 °C to 600 °C	Lose sensitivity with time due to poisoning and burning out	<15 s	Up to 3 years
Solid-state [80]	About 150 different gases	Linear at operational temperature	Can be minimized by using appropriate filter	Large, need heating element to regulate temperature	Low	20 s to 90 s	10+ years
Non-dispersive Infrared [81]	Hydrocarbon gases and carbon dioxide	Nonlinear, need linearize procedure	All hydrocarbons share a similar absorption band, make them all cross sensitive	Small, mainly consume by the infrared source	The least	<20 s	3–5 years
Photo-ionization [82]	Volatile organic compounds (VOCs)	Relatively linear	Any VOCs with ionization potentials less than the ionizing potential of the lamp used will be measured	Medium, mainly consume by the ultraviolet source	The lamp requires frequent cleaning	<3 s	Depend on the Ultraviolet lamp, normally 6000 h

Applications: Air Quality Monitoring

- All of these sensors are low cost, light weight (less than one hundred grams) and with fast response time (in tenths seconds or few minutes).
- However, no single type of sensors is able to measure all the hazard gases (hundreds of hazard gases have been identified).
- **CO**: Can be well detected by solid-state and electrochemical sensors.
- **NO_2** : Can be well detected by solid-state and electrochemical sensors. Need to consider the interference gas O_3. Proper methods can be applied to reduce the interference.
- **O_3** : Can be well detected by solid-state and electrochemical sensors. Need to consider the interference gas NO_2. Proper methods can be applied to reduce the interference.
- **SO_2**: Can only be well detected by solid-state and electrochemical sensors. It poisons the catalytic sensors. The sensitivity of NDIR sensors is not high enough.

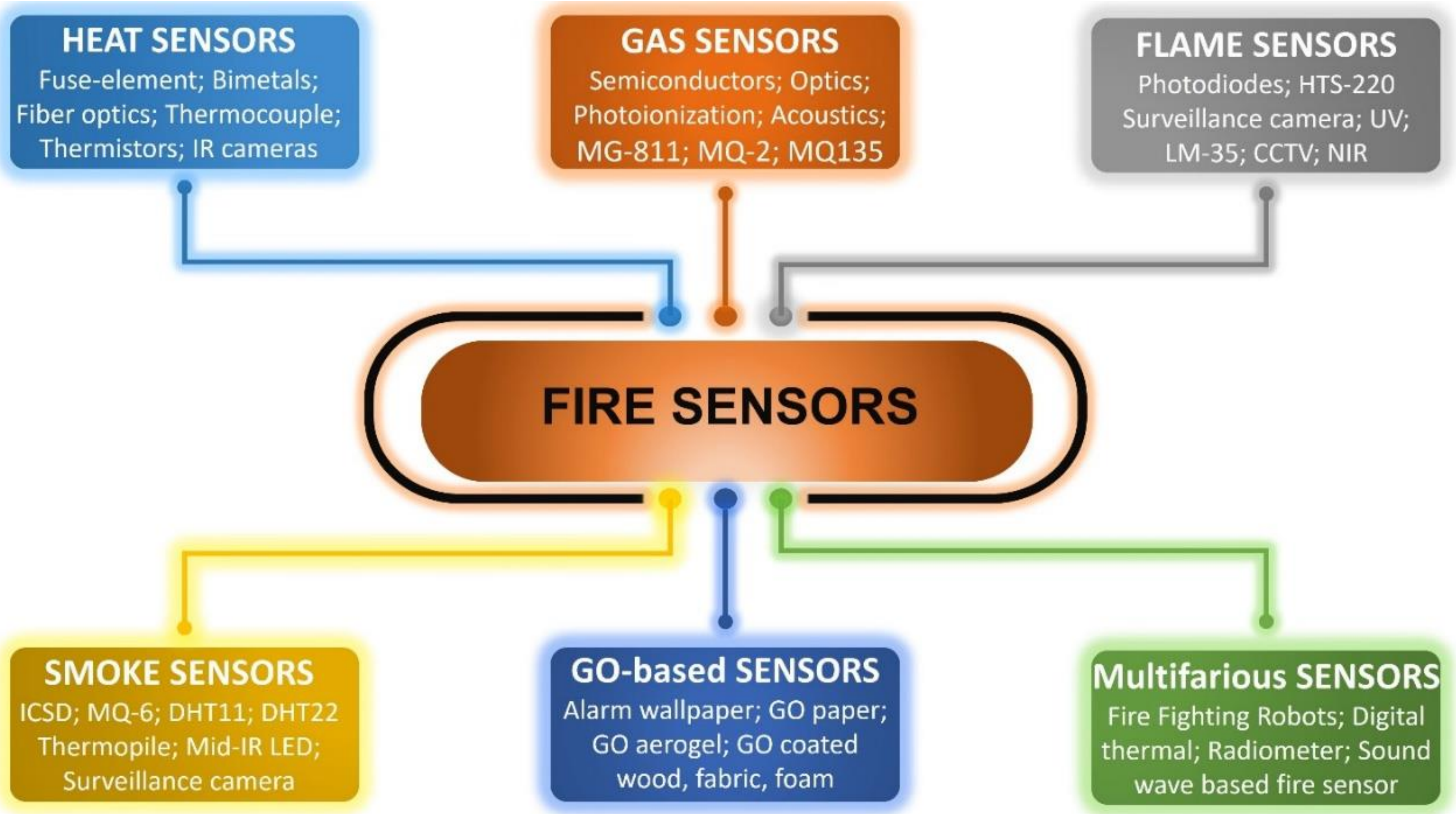
Applications: Fire detection



Applications: Fire detection

- The key five detecting methods comprise of heat, gas, flame, smoke, and graphene oxide (GO) based sensing.
- Among different gas sensing technologies, gas sensors based on semiconductor metal oxides have been useful in practice due to their great sensibility, small size and reduced cost.
- Currently, research is also underway in the field of carbon nanotube-based gas sensing for fire detection.
- Microwave radiometer-based fire sensing is one of the most important contemporary approaches due to its key benefit of fire detection across barriers such as walls.
- For fire detection, the multisensor fusion method based on wireless sensor networks (WSNs) and the Internet of Things (IoT) is suitable.
- The new emerging technique of graphene oxide (GO) based sensing has shown an outstanding short response time.

Applications: Fire detection



Applications: Fire detection

- Heat sensors are used to measure the ambient heat in a residence because of the occurrence of fires.
- Gases are emitted at every stage of combustion, and unique gas characteristics can be used to reliably detect fires.
- The density of CO, CO_2, H_2, O_2, and smoke produced by wood fire, cotton fire, plastic fire, liquid n-heptane and spirit fires has been studied and it has been noted that the chemical composition of smoke from various types of fires varies radically, according to their source.
- CO is the best of the four warning gases, appearing in all six types of fires.
- CO fire sensors that work at room temperature, require a low-power source in comparison to traditional detectors and can protect against smoldering fire, including the combustion of organic materials in which substantial amounts of carbon dioxide are emitted early in the combustion process.

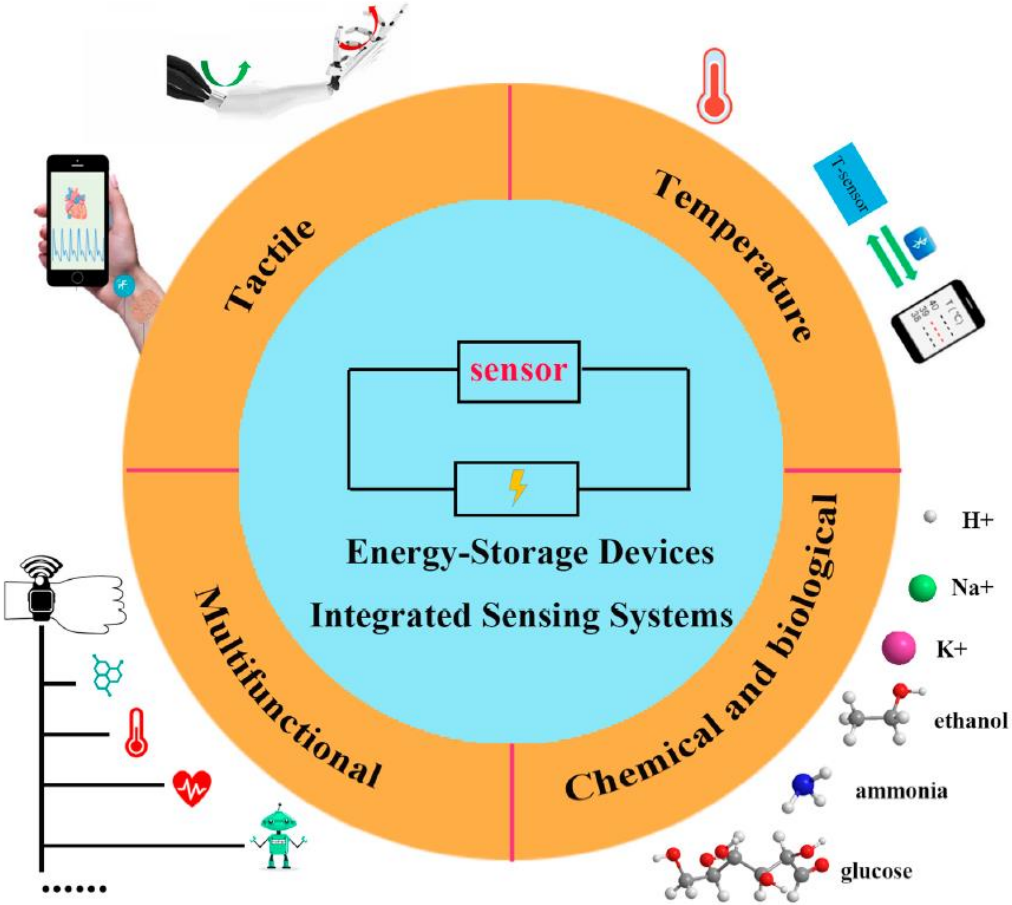
Applications: Fire detection

- Flame is the visible part of fire, which is caused by the exothermic reaction between fuel and oxidant.
- The flame temperature depends on the material being burned. It has both features of flame that are color (chromatic properties) and radiation.
- Centered on non-visual and visual techniques, there are two methods of flame detection. The non-visual technology is based on flame radiation, while the visual technology is based on the color of the flame.
- The ultraviolet, visible, and infrared sensors are available for flame sensing and categorized on the basis of their spectrum.
- In order to minimize the cost, a surveillance camera can be used instead of a dedicated fire detection camera.
- The two types of cameras utilized for flame detecting are IR and visible cameras.

Applications: Fire detection

- In the initial phases of fire, quick smoke detection will increase the likelihood of effective fire suppression, successful firefighting, escape, and survival.
- Smoke mass concentration, volume fraction, and size dissemination are known as primary smoke detection parameters.
- Smoke detectors must be able to respond to combustion and the smoke generated by flaming because there are significant differences in the structure and composition of the smoke generated by these fires.
- Fire creates smoke during combustion, which is a collection of solid particles, liquid particles, and gases in the air. It is created by material combustion and also reduces the air quality in the environment.
- Each sensor is ideal for a specific variable to be sensed, nevertheless, it is also vulnerable to a slew of other factors that can act as disturbance or noise signals.

Applications: Gas sensors for storage



Applications: Gas sensors for storage

- In past decades, numerous sensors that detect various chemical information have been widely developed including temperature sensors, humidity sensors, chemical and biological sensors.
- These well-developed sensors show the advantages of thinness, a small volume, light weight, and flexibility, and provide promising platforms for flexible and portable intelligent sensing systems.
- However, they still need an external power supply, which greatly limits their practical application.
- To solve the above problem, self-powered sensing systems without external power supplies, including energy-harvester-integrated systems and energy-storage-device-integrated systems, are regarded as effective methods.
- Sensing systems integrated with energy-storage devices can greatly avoid the requirement for an external source of energy and will work directly and effectively.

Applications: Gas sensors for storage

- In recent years, the flexible energy-storage devices that are compatible with sensor components have been developed with an increasingly mature manufacturing process, which provides more possibilities for wearable electronics in practical meaning.
- Energy-storage-device-integrated sensing systems further connected with the energy-harvesters, especially, will dominate the main trend of wearable and flexible electronics in the future.
- Wearable chemical and biological sensors for different kinds of biological and environmental indexes have been extensively applied.
- Most self-powered gas sensors currently rely on the photovoltaic effect (PV), because UV light can activate the gas sensing ability of many metal oxides, and PV gas sensors can truly achieve the goal of zero power consumption for independent devices by harnessing ambient energy.
- Storing PV energy can reduce excessive dependence on external energy sources.

Applications: Industrial emission control

- To prevent or minimize the damage caused by industrial emissions, monitoring and controlling systems are needed that can rapidly and reliably detect and quantify pollution sources within the range of the regulating standard values.
- A gas sensor that is compact, robust, with versatile applications and a low cost, can be used as an effective technology for emission control.
- There are several solid-state gas sensors currently available for gases such as O_2, H_2O, and LNG at relatively high concentrations.
- However, the range of air pollutant concentrations that can be detected only reaches as low as ppm in combustion exhaust control or indoor monitoring and ppb in atmospheric environmental monitoring.
- Therefore, the development of more sensitive and selective gas sensors than the above conventional sensors is still required.

Applications: Industrial emission control

COMPARISON BETWEEN ANALYTICAL INSTRUMENTS AND GAS SENSORS

	Analytical instruments (GC, UV)	Gas sensor
Resolution	Excellent	Comparable
Cost	Very high	Fair
Size	Bulky (Factory)	Compact
Rigidity	Fragile	Rigid (replaceable)
Process control	Difficult	Easy
Mass production	Difficult	Easy
Measurement	Instantaneous	Continuous

Applications: Industrial emission control

- Gas sensors for detecting air pollutants must be able to operate stably under deleterious conditions, including chemical and/or thermal attack.
- Therefore, solid-state gas sensors would appear to be the most appropriate in terms of their practical robustness.
- Even though there are many kinds of solid-state gas sensors; only solid electrolyte, semiconductor, and non-dispersive infrared absorption types are normally utilized.
- Semiconductor gas sensors are widely used for detecting inflammable gases and certain toxic gases in air.
- The adsorption or reaction of a gas on the surface of the semi-conducting material induces a change in the density of the conducting electrons in the polycrystalline sensor element triggering a series of reactions which eventually detects the gaseous emissions.

Applications: Industrial emission control

- The use of infrared for atmospheric environmental measuring, especially for monitoring exhaust gas, is focused on selective and reliable gas detection.
- Since a NASICON solid-electrolyte potentiometric gas sensor using alkali metal carbonate as an auxiliary phase solid electrolyte is known to be sensitive to CO_2, a lot of recent research has focused on the development of compact NASICON sensors.
- This type of solid electrolyte sensor can be used for the detection of NO_x or SO_x.
- Among the various existing NO sensors, semiconducting oxides and solid electrolytes would appear to be the best.

Applications: Mobile devices and wearables

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