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Recent Advances in Doped ZnO Thin Films for Gas Sensing Application

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Abstract
Studies on the synthesis and characterization of doped zinc oxide (ZnO) thin films for gas sensing applications have been a subject of significant research interest due to their potential in developing high-performance, cost-effective, and robust gas sensors. The primary focus of these studies is to enhance the gas sensing performance of intrinsic (ZnO) by incorporating various dopants. Doping is employed to modify the morphological, structural, and electrical properties of the (ZnO) thin films, which directly influence their sensitivity, selectivity, and response/recovery times. Common dopants investigated include metals (Al), (Cu), (Fe), (Li) and other metal oxides. A various deposition techniques are explored for preparing the thin films, including chemical vapor deposition (CVD), physical vapor deposition (PVD), sol-gel synthesis, and sputtering. Each method influences the film's crystallinity, thickness, and surface morphology .Characterization: Comprehensive analysis of the fabricated films is performed using techniques like X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS) to examine their structural, morphological, and compositional characteristics .Gas Sensing Mechanisms: The research explores the underlying sensing mechanisms, primarily relying on the principle of surface adsorption and desorption of gas molecules, which alter the electrical conductivity of the (ZnO) material .Performance Optimization: Comparative studies investigate how different dopant concentrations affect performance parameters like optimal operating temperature, response magnitude, and selectivity towards specific target gases.
Keywords
- *MOS based gas sensor*
- *Metal-Oxide Semiconductor (MOS) Nano Material*
- *Doping*
- *Zinc oxide (ZnO)*

I. Introduction

The world's energy demand is very high and continues to grow rapidly. This increase is driven by industrialization, urbanization, and the widespread use of portable electronic devices, which has necessitated the development of efficient and sustainable energy storage systems. Among various energy storage technologies, electrochemical systems such as batteries and supercapacitors have gained prominence due to their high energy efficiency[1], scalability, and environmental compatibility.

At the same time, the global need for continuous environmental monitoring, industrial safety, and air quality control has encouraged researchers to develop highly efficient and cost-effective gas sensors. Metal oxide semiconductor (MOS) technologies play a key role here, with applications ranging from microprocessors (CMOS) and displays (thin-film transistors, TFTs) to gas sensing, optoelectronics, and catalysis.

MOS materials are promising as both p-type and n-type semiconductors. Examples of p-type semiconductors include nickel oxide (NiO), cuprous oxide (Cu_2O), copper aluminium oxide ($CuAlO_2$), and tin oxide (SnO). Common n-type semiconductors include indium oxide (In_2O_3), zinc oxide (ZnO), and tin oxide (SnO_2). Among these, MOS gas sensors based on zinc oxide (ZnO) stand out for their simplicity, small size, low cost, and high sensitivity.

In recent years, research has focused on materials with dissimilar and anomalous properties, opening new avenues for innovative sensor designs. Metal oxide (MOX) gas sensors are widely studied for their affordability, ease of manufacture, and high sensitivity. However, they often face challenges such as low selectivity, high operating temperatures, and signal drift.

Broadly speaking, a sensor is a device that detects changes in physical factors such as pressure or temperature and converts them into measurable signals. Sensors are the fundamental building blocks of any control or measurement system. The term "sensor" gained prominence in the 1970s, and with the rapid growth of microelectronics, information technology became widely accessible.

As machines grow more autonomous and intelligent, there is an increasing need for artificial sense organs to assist robots in their independent functioning. Today, sensors are deeply integrated into modern life and play a crucial role in shaping the pace of technological change.

- **Properties of sensors:**

a) They have direct contact with the subject of study.
b) They transform electrical impulses from non-electric information.
c) They respond quickly.
d) It runs constantly or in periodic cycles.
e) Its small size and light

1.2 Gas Sensors

Sensors are devices that detect changes in physical factors such as pressure or temperature and convert them into measurable signals. They form the foundation of control and measurement systems, gaining prominence in the 1970s with the rise of microelectronics. Today, as machines become smarter and more autonomous, sensors act as artificial sense organs, playing a vital role in modern life and driving rapid technological change.

Among the many types of sensors, gas sensors are particularly important. These devices are designed to detect and measure the concentration of gases in the environment. They play a crucial role in monitoring air quality, ensuring industrial safety, and protecting environmental health[1]. Gas sensors can identify a wide range of gases—including toxic, combustible, and pollutant gases—making them essential for preventing hazardous situations, enhancing safety measures, and safeguarding human health[2]. Their importance lies in their ability to provide real-time data on gas concentrations, enabling timely interventions and corrective actions to minimize risks and potential damage[3].

The history of gas sensors dates back to the early 20th century. In coal mines, gas detection initially relied on canaries or chemical reactions to signal the presence of dangerous gases such as methane and carbon monoxide[5]. A major breakthrough came in the 1960s with the invention of the metal-oxide semiconductor (MOS) sensor, which offered more accurate and reliable detection compared to earlier methods.

Since then, gas sensor technology has evolved significantly. Various types have been developed, including electrochemical, infrared, and catalytic sensors. Advances in materials science, nanotechnology, and electronics have enabled the creation of sophisticated, compact, and versatile gas sensors capable of detecting multiple gases simultaneously with high sensitivity and selectivity. This continuous evolution has expanded their applications and improved performance across diverse industries [6].

1.3 Types of Gas Sensors

Gas sensors are used to detect toxic gases such as carbon monoxide (CO), hydrogen sulphide (H_2S), and chlorine (Cl_2). These sensors operate by producing a chemical reaction that generates an electrical current proportional to the gas concentration.A typical sensor consists of three main components: Electrolyte, Electrodes, Sensing layer that reacts with the target gas,

Based on their sensitivity and the materials used for gas sensing, sensors are divided into different types.

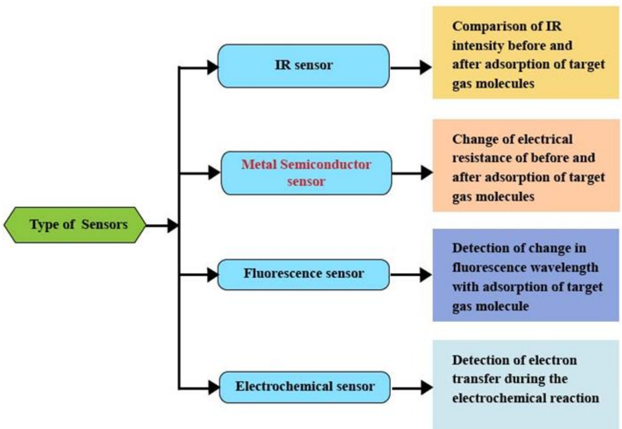

Fig.1.1 The classification of gas sensor

II. Metal-Oxide Semiconductor (MOS) Sensors

MOS sensors operate by detecting changes in the resistance of a semiconductor material when exposed to gases.[6] Metal-Oxide Semiconductor (MOS) sensors are known for their high sensitivity and relatively low cost. They are widely used for detecting a variety of gases, including carbon monoxide (CO), methane (CH_4), and hydrogen (H_2).The sensing element typically consists of metal oxides such as tin dioxide (SnO_2), which is porous to increase the surface area for gas interaction .When gases adsorb onto the metal oxide surface, the sensor's electrical conductivity changes, altering its resistance. Metal-Oxide Semiconductor (MOS) sensors are known for their high sensitivity and relatively low cost.[7]

2.1 Electrochemical Sensors

Electrochemical sensors are commonly used for detecting toxic gases such as carbon gas. Electrochemical sensors are highly selective and provide accurate measurements, making them ideal for applications requiring precise gas detection[8],[9].

2.2 Infrared Sensors Infrared (IR) sensors

Infrared (IR) sensors consist of an infrared source, a gas chamber, and a detector that measures the intensity of the transmitted or reflected infrared light. These sensors detect gases by measuring the absorption of infrared light by gas molecules. The amount of absorbed light is directly related to the gas concentration, allowing for accurate and reliable measurements. They are particularly effective for detecting gases such as carbon dioxide (CO_2), methane (CH_4), and hydrocarbons.[10]

2.3 Catalytic Bead Sensors

Catalytic bead sensors consist of a pair of platinum wire coils embedded in a bead coated with a catalyst. These sensors are used for detecting combustible gases such as methane, propane, and hydrogen. When the target gas comes into contact with the catalyst, it undergoes an exothermic reaction, generating heat. This heat changes the sensor's resistance, which is then measured and converted into a gas concentration reading.[11] Thus, catalytic bead sensors operate by oxidizing the target gas on a catalytic surface.

2.4 Photoionization Detectors (PID)

Photoionization detectors (PIDs) work by ionizing gas molecules using ultraviolet (UV) light, which produces an electrical current proportional to the gas concentration. They are used for detecting volatile organic compounds (VOCs) and other organic gases. PIDs are highly sensitive and can detect low levels of VOCs. This makes them suitable for applications such as environmental monitoring and industrial safety.[12],[13]

2.5 Other Types (e.g., Acoustic, Optical)

Other types of gas sensors include acoustic and optical sensors. Acoustic gas sensors detect gases by measuring the sound waves generated when gas molecules interact with a surface[14]. They are useful for detecting gases in low concentrations and in environments with high humidity. Optical gas sensors detect gases using light absorption or scattering. These sensors are highly selective and can detect gases such as carbon dioxide, methane, and oxygen[15].

III. Materials used in Gas Sensors

3.1 Semiconductor Materials

Semiconductor materials, such as metal-oxides, are commonly used in gas sensors because they can change their electrical properties in response to gas exposure. Metal-oxide semiconductors like tin dioxide (SnO_2), zinc oxide (ZnO), and titanium dioxide (TiO_2) are popular choices due to their effectiveness. These materials have a high surface area, which enhances their sensitivity to gases. When a target gas interacts with the semiconductor surface, it donates or accepts electrons, resulting in a change in electrical resistance. This resistance change is measured to determine the gas concentration. Semiconductor gas sensors are widely used for detecting gases such as carbon monoxide, methane, and volatile organic compounds (VOCs). They are valued for their high sensitivity, fast response times, and relatively low cost[16].

3.2 Conducting Polymers

Conducting polymers are organic materials that can conduct electricity and are used in gas sensors for their unique properties. Examples of conducting polymers include polyaniline, polypyrene, and polythiophene. These materials can undergo reversible redox reactions in the presence of gases, which alters their electrical conductivity. Conducting polymer-based gas sensors are valued for their flexibility, low power consumption, and ability to operate at room temperature[17]. They can be tailored to detect specific gases by modifying their chemical structure or incorporating selective functional groups. Such sensors are applied in areas including environmental monitoring, medical diagnostics, and wearable devices.

3.3 Nanomaterials

Nanomaterials have gained significant attention in gas sensor development due to their exceptional properties, such as high surface area, enhanced reactivity, and unique electronic characteristics[18]. Types of nanomaterials used in gas sensors include carbon nanotubes (CNTs), graphene, nanowires, and nanoparticles. Carbon nanotubes and graphene, for instance, provide high sensitivity and fast response times because of their one-dimensional and two-dimensional structures, respectively. Nanomaterials can also be functionalized with specific molecules to improve selectivity for target gases. The incorporation of nanomaterials has enabled the development of highly sensitive and miniaturized gas sensors with improved performance. These sensors are applied in diverse fields, including air quality monitoring, industrial safety, and healthcare.

3.4 Advanced Composites

Advanced composites combine different materials to leverage their individual strengths and create gas sensors with enhanced properties. These composites can consist of semiconductors, polymers, nanomaterials, and other substances. For example, a composite sensor may include a metal-oxide semiconductor matrix embedded with carbon nanotubes to improve sensitivity and selectivity. The versatility of composite materials allows customization of sensor properties to meet specific application requirements. Advanced composites can also be designed to detect multiple gases simultaneously or operate in challenging environments. Such sensors are employed in diverse fields, including industrial process control, environmental protection, and smart building systems[19].

IV. MOS based gas sensor

The variation of resistance in semiconductors due to the surrounding gaseous environment was first observed by Brattain and Bardeen in 1950. Later, Heiland studied the modification of ZnO properties under different gas pressures. Following these pioneering works, many researchers investigated metal oxide semiconductor (MOS) gas sensors using various synthesis strategies, with the primary aim of developing highly sensitive and selective MOS nanomaterials. The rapid progress in MOS gas sensor technology, driven by advanced synthesis and fabrication methods, has contributed significantly to improving healthy and secure lifestyles[20]. Among these, N-type and P-type semiconducting metal oxides are widely employed in chemoresistive gas sensors, where their electrical conductivity changes in response to analyte gases. MOS gas sensor technology has attracted considerable attention from research communities due to its many advantages: high sensitivity, strong selectivity, low cost, low power consumption, simple design, and long operational life. To further enhance sensing performance and integration into electronic circuits, various physical and chemical deposition techniques are employed to prepare MOS materials. Performance improvements are achieved through strategies such as altering morphology, controlling particle size, surface modification via heteroatom doping, fabricating composites and hybrid structures, and introducing oxygen vacancies. These approaches enable larger sensitivity and selectivity, even to trace amounts of analyte gases. Ultimately, the reaction between the target gas and the MOS surface boosts sensor performance, leading to the synthesis of materials with excellent surface properties tailored for gas detection.

4.1 Gas sensing mechanism

When a MOS-type gas sensor is exposed to an analyte gas, its resistance changes due to reactions occurring between the sensor surface and the analyte. These interactions — including adsorption of gas particles, chemical reactions, and diffusion — alter the number of charge carriers in the sensing material. The magnitude of this change depends on the concentration or extent of the analyte gas. After adsorption, the gas molecules act as either donors or acceptors, depending on the nature of the MOS material and the analyte gas[21]. In P-type semiconducting materials, holes are the majority charge carriers. Their number decreases when the material is exposed to a reducing gas, leading to an increase in resistivity. Conversely, exposure to an oxidizing gas increases the number of holes, thereby decreasing resistivity. For N-type semiconducting materials, the exact opposite mechanisms are observed[22],[23]. These reversible redox phenomena occurring at the analyte–sensor interface constitute the reception function of MOS gas sensors, as they directly modify the electrical properties of the material. Such changes in electrical conductivity or surface charge are then converted into analytically useful signals, defining the transduction function, which typically involves measuring the DC resistance of the MOS sensing surface. To explain these sensing mechanisms, several theoretical models have been proposed, among which the potential barrier model and the band bending model are considered the most suitable[24],[25].

4.2 Potential barrier model

The active layer or thin film of a MOS material is typically composed of many closely packed grains. The sensor response is explained through receptor and transducer functions, which provide insights into depletion region formation within the grains and the presence of a double Schottky barrier across grain boundaries[26]. In N-type MOS gas sensors, oxygen vacancies act as electron traps and determine the conductivity. At the initial stage of increasing temperature, adsorption of oxygen species on the surface leads to the formation of a depletion region. When the sensor is exposed to an oxidizing analyte gas, the width of the depletion region increases, thereby raising the resistivity. This increase in resistance elevates the potential required to cross the barrier. The barrier height is influenced by factors such as temperature, atmospheric oxygen pressure, and the nature of the analyte gas. At higher concentrations of oxidizing gases, the formation of byproducts restricts the availability of adsorption sites, thereby confining the sensor's response. In contrast, when exposed to a reducing analyte gas, interactions between the gas molecules and pre-adsorbed oxygen release trapped electrons. This process decreases the barrier height and consequently lowers the resistance of the sensor [27].

4.3 Band bending model

This model relies on the adsorption of oxygen and its subsequent reaction with the MOS surface. At the operating temperature of the gas sensor, oxygen is adsorbed in the form of O^- or O_2^- species, which induces band bending and leads to the formation of a depletion region. The adsorbed oxygen traps electrons, initiating further sensing mechanisms. As a result, changes in the band position alter the resistance of the sensor, and this variation in resistance is measured as the sensor output[28]. In case of N type MOS gas sensor, when exposed to oxidising gas, large extent of band bending occurs and increases the height of potential barrier and hence resistance of sensor, in accordance with the concentration of oxidizing analyte gas. A decrease in height of potential barrier and hence, the resistance of sensor, in accordance with the concentration of oxidizing analyte gas occurs when N type MOS gas sensor exposed to reducing gas. Thus, height of potential barrier with respect to concentration of analyte gas is valuable to discuss the performance of MOS gas sensor[29].Zinc oxide (ZnO) materials can be synthesized through various methods, each offering distinct advantages in controlling the material's properties for different applications. The common methods for ZnO synthesis include hydrothermal, chemical bath deposition (CBD), sol-gel, chemical vapor deposition (CVD), and spray pyrolysis .

•Synthetic Methods for ZnO Material

1)Hydrothermal

The hydrothermal method is a process that uses water as a solvent at high temperatures and pressures to synthesize ZnO nanostructures. In this technique, zinc precursors like zinc nitrate or zinc acetate are dissolved in water, and the pH is adjusted to control the reaction. The solution is then heated in a sealed container, called an autoclave, leading to the formation of ZnO crystals. This method allows for the synthesis of various ZnO morphologies, such as nanorods, nanowires, and flower-like structures, by controlling parameters like temperature, pH, and the use of capping agents[30]

2)Chemical Bath Deposition (CBD)

Chemical Bath Deposition (CBD) is a technique used to deposit thin films of ZnO on a substrate from a solution at low temperatures. The process involves immersing a substrate in a solution containing a zinc salt and a complexing agent. The deposition occurs as the chemical reaction proceeds, leading to the formation of a solid ZnO film on the substrate's surface. CBD is considered a cost-effective and straightforward method for producing ZnO thin films with controlled thickness and morphology. The properties of the films can be tuned by adjusting the bath temperature, pH, and precursor concentration [31]

3)Sol Gel Method

The sol-gel method is a versatile wet-chemical technique used to produce ZnO nanoparticles and thin films. This process involves the transformation of a solution (sol) into a gel-like solid phase. Typically, a zinc precursor, such as zinc acetate, is dissolved in a solvent, and then a catalyst is added to initiate hydrolysis and condensation reactions, forming a ZnO network. The resulting gel is then dried and heat-treated to obtain crystalline ZnO. The sol-gel method offers excellent control over the particle size, morphology, and purity of the final product [[32]].

4) Chemical Vapour Deposition (CVD)

Chemical Vapor Deposition (CVD) is a process used to grow high-quality, crystalline ZnO thin films and nanowires on a substrate. In this method, a substrate is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit. For ZnO synthesis, a zinc-containing precursor is introduced into a reaction chamber where it reacts with an oxidizing agent, such as oxygen, to form

ZnO. The growth temperature and precursor flow rates are critical parameters that influence the crystal quality and morphology of the resulting ZnO material [33].

5)Spray-pyrolysis

Spray pyrolysis is a technique used to deposit thin films of ZnO by spraying a solution onto a heated substrate. The solution, containing a zinc salt like zinc chloride or zinc acetate, is atomized into fine droplets, which are then directed towards the hot substrate. As the droplets come into contact with the substrate, the solvent evaporates, and the precursor decomposes to form a ZnO film. The properties of the film, such as its thickness, transparency, and electrical conductivity, can be controlled by adjusting the substrate temperature, spray rate, and solution concentration. This method is known for being a cost-effective way to produce large-area ZnO thin films [34].

V. Zinc oxide (ZnO) as MOS material for gas sensor

ZnO is the promising N – type metal oxide possessing unique optical and electrical properties. It is a transparent semiconducting material having direct band gap energy of value 3.3 eV and wurtzite structure. Due to its outstanding photochemical properties, high porosity and surface area, it is used in solar cells, gas sensors, photodetectors, light emitting diodes etc. Out of its various hierarchical nanostructures, nanorods or nanowires possess high surface area due to close packing and it enables rapid charge transportation.

Table No. 1 :- Literature review of ZnO based gas sensors.

Sr. No.	Method of preparation	Detected of gas	Morphology	Sensing properties	Ref.
1.	Hydrothermal	40 ppm NO_2	Mesoporous	1507 % at 150ºC	[35]
2.	Hydrothermal	100 ppm NO_2	Nanorods	113 at 200ºC	[36]
3.	Hydrothermal	100 ppm NO_2	Nanorods	67.5 at 150ºC	[37]
4.	Hydrothermal	1-50 ppm NO_2	Hierarchical Nanorods	at 200ºC	[38]
5.	Hydrothermal	250 ppm ethanol	Nanorods	6.83 at 400ºC	[39]
6.	Hydrothermal	50 ppm ethanol	Nanorods	at 320ºC	[40]
7.	Hydrothermal	15 ppm CO	Nanorods	--	[41]
8.	Hydrothermal	6 ppm CO	Nanostructure	75 % at 300ºK	[42]
9.	Hydrothermal	100 ppm of H_2	Nanosheets	115 % 300ºK	[43]
10.	Hydrothermal	200 ppm ethanol	Nanosheets	at 400ºC	[44]
11.	Hydrothermal	2000 ppm LPG	Nanorods	78 % at 350ºC	[45]
12.	Hydrothermal	0.25 ppm NO_2	Nanoplates	76 % at 200ºC	[46]
13.	Solvothermal	100 ppm acetone	Nanospheres	33 at 230ºC	[47]
14.	Solvothermal	100 ppm acetone	Nanorods	48 % at 350ºC	[48]
15.	Solvothermal	100 ppm NO_2	Nanosheets	74 % at 200ºC	[49]
16.	Solvothermal	0.25 ppm NO_2	Nanorods	at 350ºC	[50]
17.	Wet chemical	100 ppm NO_2	Nanorods	3100% at 150ºC	[51]
18.	Sol-gel	100 ppm acetone	Nanorods	30.4 at 300ºC	[52]
19.	Photolithography	100 ppm CO	Nanosheets	at 300ºC	[53]
20.	CBD	1 ppm NO_2	Nanoclusters	at 300ºK	[54]
21.	CBD	5200 ppm LPG	Nanorods	49 % at 573ºK	[55]
21.	CBD	3900 ppm LPG	Mesoporous	52 % at 573ºK	[56]
23.	CBD	3900 ppm LPG	Hexagonal nanorods	94 % at 200ºC	[57]
24.	SILAR	200 ppm NO_2	nanoparticles	910% at 150ºC	[58]
25.	SILAR	5200 ppm LPG	thin film	20 % at 673ºK	[59]
26.	RF sputtering	15 ppm H_2	thin film	at 250ºC	[60]
27.	Spin coating	100 ppm NO_2	Nanocrystalline	37 % at 200ºC	[61]

5.1 Dopped ZnO Thin Films for Gas sensor

Dopped ZnO thin films are widely studied for gas sensors because doping improves sensitivity, selectivity, and stability by tuning electrical conductivity, surface defects, and adsorption sites. Different dopants enhance detection of gases like NO_2, NH_3, ethanol, and H_2 under varying conditions ZnO thin films are highly effective for gas sensors because their intrinsic properties, surface morphology, and tenable defects via doping collectively improve sensitivity and functionality

1) Al Dopped

Al doping in ZnO thin films modifies lattice parameters, increases strain/stress, and reduces grain size, while maintaining the hexagonal wurtzite structure with strong (002) orientation — making them promising for optoelectronic and sensing applications was studied by L.H Kathwate.[62] Al-doped ZnO thin films show enhanced formaldehyde sensing at 2 at% Al, but performance declines at higher doping levels and under high humidity conditions (≥60%), highlighting the importance of optimizing both doping concentration and environmental factors was studied by K. Khojier [63] Spin-coated ZnO thin films are transparent and effective for gas sensing, while Al doping improves band gap, reduces grain size, and enhances purity, making Azano films more reliable for detecting toxic vapours. was studied by Tirtha Raj Acharya[64]. CW-CO_2 laser-induced evaporation produces highly conductive, transparent AZO films with performance comparable to sputtered films, making them a promising low-cost alternative for optoelectronic applications. was studied by X.J. Yin[65]

2) Cu Dopped

L. Chow et al. has investigated by Cu-doped ZnO rods synthesized hydrothermally demonstrate superior room-temperature hydrogen sensing performance, making them strong candidates for efficient, miniaturized gas sensors.[66] A. Mhamdi et al. has successfully synthesized Cu-doped ZnO thin films exhibit thermally activated hopping conduction and demonstrate stable, sensitive ethanol gas sensing behaviour, with 2% Cu doping being the most effective condition.[67] Ayush Singh Chauhan et al. has investigated by Spray pyrolysis is an effective method for producing high-quality ZnO thin films, with undoped films showing the strongest crystallinity, while Cu doping modifies structural, optical, and morphological features for potential device applications.[68] Om Shree Rijal et al. has successfully Mn doping introduces magnetism into ZnO and enhances its sensitivity to CO and NH_3 adsorption. Combined with accurate band gap predictions (via PBE+U), these materials show strong potential for gas sensing applications.[69]

3) Other Metal Doped

Deniz Tural et al. has successfully synthesized ALD-grown ZnO thin films are a low-cost, indium-free alternative for TTFHs, while Al-doped ZnO (AZO) films deliver record high heating performance with superior conductivity and transparency, making them highly suitable for practical applications.[70] Moez Hajji et al. has investigated by Bismuth doping significantly enhances the physical properties and application efficiency of CuO–ZnO thin films, with 8% Bi doping emerging as a promising condition for pharmaceutical applications.[71] Ayush Singh Chauhan et al. has reported by Spray pyrolysis is an effective method for preparing high-quality ZnO thin films, with undoped films showing the strongest crystallinity, while Cu doping modifies the structural, optical, and morphological features for potential device applications.[68] H. Hoopla et al. has successfully by Nitrogen doping in ZnO thin films modifies their optical properties (band gap and refractive index) while preserving the hexagonal wurtzite structure, making them promising for optoelectronic applications.[72] R.A. Mereu et al. has reported by Aqueous solution deposition yields high-quality ZnO thin films with smooth morphology and strong UV emission. Al and Ho doping effectively tunes the band gap (3.01–3.56 eV), enhancing optical properties for potential optoelectronic applications.[73] Xu Li et al. has successfully synthesized by Mn doping modifies the crystallinity of ZnO thin films, weakening orientation, while increased thickness enhances crystallization but introduces structural defects (cracks).[74] Lekoui F. et al. has reported by Annealing enhances crystallization and enlarges crystallite size in Mn-doped ZnO thin films, but Mn incorporation also introduces structural degradation, highlighting a trade-off between improved crystallinity and defect formation.[75] Baktiyar Soltabayev et al. has successfully synthesized by Indium doping (5%) in ZnO thin films prepared via SILAR improves crystallinity, morphology, and gas-sensing performance, with nanoflower structures and a tuned band gap (3.32 eV) contributing to enhanced sensitivity.[76]

VI. Fabrication Techniques

Various fabrication techniques are employed to develop gas sensors, depending on the sensor type and the materials used:

a)Thin-Film Deposition: Methods such as chemical vapor deposition (CVD), physical vapor deposition (PVD), chemical bath deposition (CBD), and sputtering are commonly applied to deposit thin films of sensing materials onto substrates. These techniques provide uniform and well-controlled layers, thereby enhancing sensor performance[77].

b)Screen Printing: In this cost-effective method, a paste containing the sensing material is printed onto a substrate and subsequently cured or sintered to achieve the desired properties. Screen printing is particularly suitable for large-scale production.

c)Electrochemical Deposition: This approach is widely used for electrochemical sensors, where sensing materials are deposited onto electrodes. It offers precise control over both the thickness and composition of the sensing layer.

d)Microfabrication: Techniques such as photolithography, etching, and micromachining are employed to construct micro-scale sensor components. These methods improve sensitivity and facilitate sensor miniaturization.

e)Nanofabrication: Advanced nanofabrication strategies enable the integration of nanomaterials into sensors, providing a high surface area and superior performance. This approach enhances both sensitivity and selectivity, making it highly effective for next-generation gas sensors.

VII. Integration with Electronics

Integrating gas sensors with electronic systems is crucial for signal processing, data acquisition, and communication. The sensor's output, whether a change in resistance, current, or voltage, must be converted into a readable and interpretable format. This involves using microcontrollers, amplifiers, analogy-to-digital converters (ADCs), and signal conditioning circuits. Wireless communication modules, such as Bluetooth, Wi-Fi, or LoRa, enable remote monitoring and data transmission. Power management is another critical aspect, ensuring the sensor operates efficiently with minimal power consumption, especially in portable and battery-powered applications. Integration with electronics also allows for features like self-calibration and diagnostic functions, enhancing sensor performance and reliability.

7.1 Miniaturization and Portability

Miniaturization and portability are key trends in gas sensor development, driven by the demand for compact, lightweight, and user-friendly devices. Advances in microfabrication and nanotechnology have enabled the production of miniaturized sensors with enhanced performance. Portable gas sensors are designed to be easy to use, with features such as small size, low weight, and battery operation. These sensors are used in applications requiring on-the-go monitoring, such as personal safety devices, handheld air quality monitors, and wearable health sensors. The challenge in miniaturization lies in maintaining sensitivity, selectivity, and reliability while reducing the sensor's size. Innovations in materials science, fabrication techniques, and electronic integration continue to push the boundaries of what is possible in portable gas sensor technology.

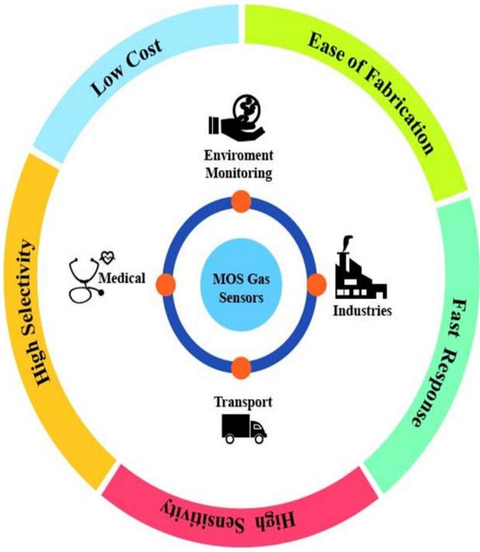

Fig1.2 The characteristics and applications of MOS gas sensors

VIII. Applications of Gas Sensors

a) Environmental monitoring –

Gas sensors play a crucial role in environmental monitoring, as they provide real-time data on the presence and concentration of atmospheric pollutants. They are capable of detecting gases such as carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NOx), and volatile organic compounds (VOCs). By monitoring air quality, these sensors help identify pollution sources and ensure compliance with environmental regulations. A study published in the Sensors journal demonstrated the effectiveness of gas sensors in detecting airborne pollutants in urban areas, enabling timely interventions to reduce pollution levels. Beyond air quality monitoring, gas sensors are also widely applied in climate research, where they are used to track greenhouse gas emissions and assess their impact on global warming.

b) Industrial safety –

In industrial environments, gas sensors are essential for worker safety and accident prevention. They are designed to detect hazardous gases, including flammable gases such as methane (CH_4) and propane (C_3H_8), as well as toxic gases like hydrogen sulphide (H_2S) and ammonia (NH_3). By providing early warnings of gas leaks or dangerous concentrations, these sensors help prevent explosions, fires, and toxic exposures. A report published in the Journal of Loss Prevention in the Process Industries emphasized the critical role of gas sensors in risk management and safety protocols across industries such as oil and gas, chemical manufacturing, and mining.

Integrated into safety systems, gas sensors can automatically trigger alarms and shutdown mechanisms, thereby mitigating potential hazards and ensuring a safer working environment.

c) Medical diagnostics –

Gas sensors have emerged as valuable tools in medical diagnostics, particularly through non-invasive breath analysis. They are capable of detecting biomarkers such as acetone, ammonia, and nitric oxide in exhaled breath, which provide critical information about various health conditions. For instance, elevated acetone levels are associated with diabetic ketoacidosis, while increased nitric oxide concentrations can serve as a marker for asthma[88]. A review published in Sensors and Actuators B: Chemical highlighted the rapid advancements in gas sensor technology for medical applications, underscoring their potential in early disease detection and continuous monitoring. These sensors offer a fast, non-invasive, and cost-effective approach to diagnosing and managing diseases, ultimately contributing to improved patient outcomes.

d) Automotive Industry –

In the automotive industry, gas sensors are essential for optimizing engine performance, reducing emissions, and ensuring passenger safety. Oxygen sensors monitor the oxygen levels in the exhaust gases, allowing the engine control unit (ECU) to adjust the air-fuel mixture for optimal combustion. This improves fuel efficiency and reduces harmful emissions. Additionally, gas sensors detect pollutants like carbon monoxide (CO) and nitrogen oxides (NOx) in the exhaust system to ensure compliance with emission standards. A study in the "Journal of Sensors" discussed the integration of gas sensors in modern vehicles, highlighting their role in enhancing vehicle performance and environmental sustainability. These sensors also contribute to cabin air quality monitoring and safety systems.

e) Smart Homes and Consumer Electronics –

Gas sensors are increasingly being integrated into smart home devices and consumer electronics to enhance safety and convenience. In smart homes, gas sensors detect hazardous gases like carbon monoxide (CO) and methane (CH_4), providing early warnings to occupants and triggering ventilation systems or alarms. They are also used in air purifiers and HVAC systems to monitor and improve indoor air quality. A study in the "IEEE Internet of Things Journal" explored the application of gas sensors in smart home environments, highlighting their role in creating safer and healthier living spaces. In consumer electronics, gas sensors are incorporated into wearable devices to track air quality and personal exposure to pollutants, offering users real-time information and alerts.

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