Metal oxide nanoparticles: Synthesis, properties, and Applications

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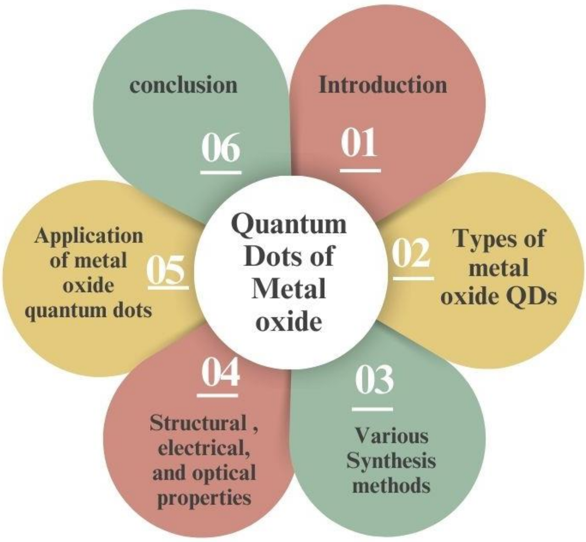
Abstract

This review paper provides an information of metal oxide QDs, focusing on their types, synthesis methods, properties, and applications. Various types of metal oxide QDs, including binary, ternary, and quaternary compositions, are discussed, highlighting their diverse chemical compositions and structural configurations. Synthesis methods for metal oxide QDs, such as hydrothermal, chemical vapor deposition (CVD), simple chemical methods, microwave-assisted synthesis, and others, are detailed, emphasizing their role in controlling the size, shape, and properties of the QDs. The optical, electrical, and structural properties of metal oxide QDs are examined in depth, elucidating their tunable bandgaps, luminescence properties, charge carrier mobility, and crystalline structures. Furthermore, the application of metal oxide QDs in various fields, including optoelectronics, photovoltaic, catalysis, energy storage, sensors, and biomedical imaging, is explored, demonstrating their versatility and potential impact. Overall, this review provides valuable insights into the synthesis, properties, and applications of metal oxide QDs, highlighting their significance in nanotechnology and materials science research.

Keywords:- Metal oxide quantum dots, Synthesis methods ,Optical properties, Electrical properties, Structural properties, Applications

Graphical abstract

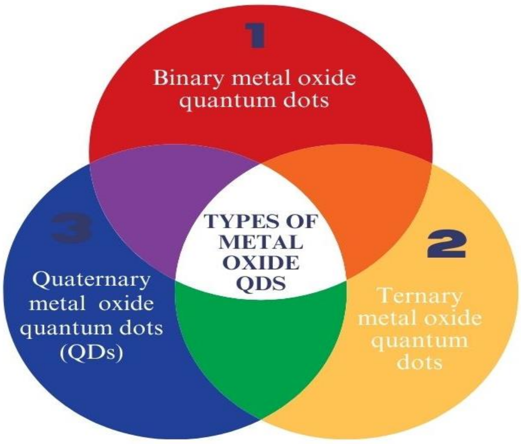


Introduction:

Metal oxide quantum dots (MOQDs) are nanoscale semiconductor particles composed of metal cations and oxygen anions. These tiny crystalline structures exhibit unique optical, electronic, and catalytic properties due to their quantum confinement effects and high surface-to-volume ratios [1]. MOQDs have garnered significant attention in various fields due to their tunable optical properties, high photo stability, and potential applications in areas such as optoelectronics, photo catalysis, sensing, and biomedical imaging. One of the primary reasons for the preference of MOQDs lies in their size-dependent properties [2]. As the size of the quantum dot decreases, the energy levels of electrons and holes become quantized, leading to the tunability of their optical and electronic properties. This allows researchers to tailor the absorption and emission wavelengths of MOQDs by simply controlling their size, composition, and surface chemistry [3]. Such tunability is highly desirable for applications like light-emitting diodes (LEDs), photo detectors, and solar cells, where precise control over the spectral properties is crucial for device performance. Moreover, MOQDs possess excellent photo stability, making them suitable for long-term applications in harsh environments [4]. Unlike traditional organic dyes or fluorescent proteins, MOQDs exhibit minimal photo bleaching and degradation under prolonged exposure to light, making them ideal candidates for imaging and sensing applications where stability is paramount. Another advantage of MOQDs is their large surface area-to-volume ratio, which enables efficient surface interactions with other molecules or substrates [5]. This property is particularly advantageous for catalytic applications, where MOQDs can act as highly active and selective catalysts for various chemical reactions, including water splitting, CO2 reduction, and pollutant degradation.Furthermore, MOQDs can be synthesized using relatively simple and scalable methods, such as sol-gel, hydrothermal, or microwave-assisted techniques, making them attractive for large-scale production [6]. Many properties are shown by metal oxide quantum dots (MOQDs) because of the size-effect, quantum-confined effect, and surface effect, which are very unique and attractive for their use in many applications [7]. For instance, quantum capacitance allows for the property with the influence of ionization potential and electron affinity and thus gives a key control of electrical behavior indispensable for enhanced device performance. The classical electrostatic models, reminiscent of the Thomson problem, show MOQD charge behavior [8]. They reveal an electron shell filling similar to the plum pudding model that helps in prediction and manipulation. In fact, from the 1980s, these MOQDs have been synthesized by scalable methods such as sol-gel and hydrothermal techniques and have been in the front line of nanotechnology and materials science, capable of offering different optical and electrical properties at the nanoscale [9]. They confine electron movement, so it results in a unique electrical and optical character that is very essential in development in most sectors. MOQDs find applications in solar energy conversion due to their tunable bandgap, increasing cell efficiency in light absorption and generation of charge carriers [10]. Added to this, their light-emission properties open many possibilities of use in the fields of entertainment, health, and security; radiation sensing and imaging are just a few. Overall, MOQDs show a very promising class of materials with an unprecedented level of versatility, which is going to trigger necessary innovation across several technological fronts [11].

In summary, the unique combination of tunable optical properties, high photostability, large surface area, and facile synthesis methods makes metal oxide quantum dots highly desirable for a wide range of applications, from next-generation electronic devices to environmental remediation and biomedical technologies [12].

2. Types of metal oxide quantum dots



2.1 Binary metal oxide quantum dots:-

Binary metal oxide quantum dots are semiconductor nanocrystals composed of two different metal cations and oxygen anions. These nanocrystals exhibit unique optical, electrical, and catalytic properties, making them highly attractive for a variety of applications [13]. For example, zinc oxide (ZnO) quantum dots consist of zinc cations (Zn2+) and oxygen anions (O2-) and have been extensively studied for their applications in optoelectronic devices such as LEDs and photodetectors due to their wide bandgap and efficient charge transport properties [14]. Another example is titanium dioxide (TiO2) quantum dots, which are composed of titanium cations (Ti4+) and oxygen anions (O2-) and are widely utilized in photocatalysis for environmental remediation and solar energy conversion due to their high surface area and efficient charge separation abilities. These binary metal oxide quantum dots offer tunable properties and versatile applications, driving research and innovation in various fields [15].

Table:-1 Table describing ten binary metal oxide quantum dots, their synthesis methods, stabilizing/capping agents, morphology, size, and applications.

Quantum Dot	**Synthesis Method**	**Stabilizing/Capping Agent**	**Morphology**	**Size**	**Applications**	**Reference**
Zinc Oxide (ZnO)	Hydrothermal	Polyvinylpyrrolidone (PVP)	Nanorods	5-20 nm	Optoelectronic devices (LEDs, photodetectors), photocatalysis, gas sensors,	[16]

					biomedical imaging.	
Titanium Dioxide (TiO2)	Sol-gel, hydrothermal	Oleic acid, oleylamine	Nanoparticles	5-20 nm	Photocatalysis, water splitting, solar cells, self-cleaning coatings.	[17]
Cadmium Oxide (CdO)	Chemical precipitation	Sodium citrate	Nanoparticles	3-10 nm	Near-infrared photodetection, sensors, photovoltaics, gas sensing.	[18]
Copper Oxide (Cu2O)	Thermal decomposition	Polyvinylpyrrolidone (PVP)	Nanocubes	5-20 nm	Photocatalysis, solar cells, gas sensors, photodetectors, biomedical applications.	[19]
Iron Oxide (Fe2O3)	Co-precipitation	Sodium citrate	Nanoparticles	5-30 nm	Magnetic nanoparticles, drug delivery, wastewater treatment, MRI contrast agents.	[20]
Aluminum Oxide (Al2O3)	Sol-gel	Oleic acid, oleylamine	Nanoparticles	5-20 nm	Catalysis, sensors, coatings, electronic devices.	[21]
Magnesium Oxide (MgO)	Sol-gel	Polyvinylpyrrolidone (PVP)	Nanocubes	5-20 nm	Insulation materials, electronic devices, catalysis, flame retardants.	[22]
Nickel Oxide (NiO)	Hydrothermal	Polyvinylpyrrolidone (PVP)	Nanoparticles	5-30 nm	Electrochromic devices, supercapacitors, gas sensors, battery electrodes.	[23]
Tin Oxide (SnO2)	Sol-gel, hydrothermal	Polyvinylpyrrolidone (PVP)	Nanowires	5-50 nm	Transparent electrodes, gas sensors, solar cells,	[24]

					electrochromic devices.	
Lead Oxide (PbO)	Hydrothermal	Oleic acid, oleylamine	Nanoparticles	5-30 nm	Photodetectors, solar cells, electrochemical sensors, catalysis.	[25]

2.2 Ternary QDs:-

Ternary quantum dots (QDs) are semiconductor nanocrystals composed of three different elements, typically two metals and one chalcogen (such as sulfur, selenium, or tellurium), forming a compound with a specific crystal structure. These QDs exhibit unique optical, electrical, and chemical properties that can be tailored by controlling the composition, size, and surface chemistry [26]. Ternary QDs offer advantages over binary QDs by providing additional degrees of freedom for tuning their properties, such as bandgap, emission wavelength, and carrier dynamics. One example of ternary QDs is copper indium sulfide (CuInS2) QDs, which have gained significant attention for applications in photovoltaics, light-emitting diodes (LEDs), and biomedical imaging due to their tunable bandgap and high photoluminescence quantum yield [27]. Another example is cadmium selenium sulfide (CdSeS) QDs, which combine the optical properties of cadmium selenide (CdSe) QDs with the chemical stability of cadmium sulfide (CdS) QDs, offering enhanced performance in solar cells and light-emitting devices. Ternary QDs represent a promising class of nanomaterials with diverse applications in optoelectronics, catalysis, sensing, and bioimaging, driving ongoing research efforts to explore their potential across various fields.

Table:2;This table provides comprehensive information about the synthesis, stabilization, morphology, size, and applications of ten ternary metal oxide quantum dots, showcasing their diverse properties and potential uses across various fields.

Quantum Dot	**Synthesis Method**	**Stabilizing/Capping Agent**	**Morphology**	**Size**	**Applications**	**reference**
LaFeO3	Sol-gel, hydrothermal	Polyvinylpyrrolidone (PVP)	Nanoparticles	5-20 nm	Catalysis, oxygen reduction reactions, photoelectrochemical cells, sensors.	[28]
CuInS2	Colloidal	Trioctylphosphine	Nanoplatelets	5-20	Photovoltaic devices,	

	synthesis	(TOP), trioctylphosphine oxide (TOPO)		nm	light-emitting diodes (LEDs), biomedical imaging.	[29]
CdZnS	Hot injection	Trioctylphosphine (TOP), trioctylphosphine oxide (TOPO)	Nanoparticles	3-10 nm	Quantum dot displays, luminescent solar concentrators, biological labeling.	[30]
CuInxGa(1-x)Se2	Spray pyrolysis, electrodeposition	Thioglycolic acid (TGA), mercaptopropionic acid (MPA)	Nanoparticles	5-20 nm	Thin-film solar cells, photodetectors, luminescent devices.	[31]
ZnxCd(1-x)S	Co-precipitation, solvothermal	1-dodecanethiol	Nanorods	5-20 nm	Light-emitting diodes (LEDs), photodetectors, biomedical imaging.	[32]
CdIn2S4	Ligand-assisted synthesis	Trioctylphosphine (TOP), trioctylphosphine oxide (TOPO)	Nanowires	5-30 nm	Photovoltaic devices, sensors, quantum dot lasers, luminescent markers.	[33]
ZnxCd(1-x)Te	Chemical vapor deposition	Tri-n-octylphosphine (TOP), trioctylphosphine oxide (TOPO)	Nanoparticles	5-20 nm	Infrared photodetectors, medical imaging, environmental sensing.	[34]
CuInxS(1-x)Te	Solvothermal	Oleic acid, oleylamine	Nanoparticles	5-30 nm	Thin-film solar cells, photodetectors, luminescent devices.	[35]
CdZnSxTe 1-x	Microwave-assisted synthesis	Trioctylphosphine (TOP), trioctylphosphine oxide (TOPO)	Nanoparticles	3-10 nm	Quantum dot lasers, luminescent solar concentrators, biological labeling.	[36]
ZnxCd(1-x)SeyS(1-y)	Colloidal synthesis	Mercaptopropionic acid (MPA)	Nanoparticles	5-20 nm	Photodetectors, light-emitting diodes (LEDs), biomedical imaging.	[37]

3.3. **Quaternary quantum dots (QDs)**

Quaternary quantum dots (QDs) are semiconductor nanocrystals composed of four different elements, offering even greater versatility in tuning their properties compared to binary or ternary QDs [38]. These QDs exhibit unique optical, electrical, and chemical characteristics that can be precisely controlled by adjusting the composition, size, and structure. Quaternary QDs are particularly attractive for applications requiring finely tuned properties, such as optoelectronic devices, biological imaging, and catalysis [39]. One example of quaternary QDs is zinc cadmium selenide sulfide (ZnCdSeS) QDs, which combine the optical properties of zinc selenide (ZnSe) and cadmium selenide (CdSe) QDs with the chemical stability of zinc sulfide (ZnS) and cadmium sulfide (CdS) QDs. These QDs offer tunable emission wavelengths across the visible spectrum, making them suitable for applications in color displays, LEDs, and biological labeling.

- Another example is lead-free quaternary QDs such as copper zinc tin sulfide (CZTS) QDs, which have garnered interest as environmentally friendly alternatives to traditional lead-based QDs. CZTS QDs exhibit excellent optical properties and are being explored for use in solar cells, photodetectors, and photocatalysis [40].

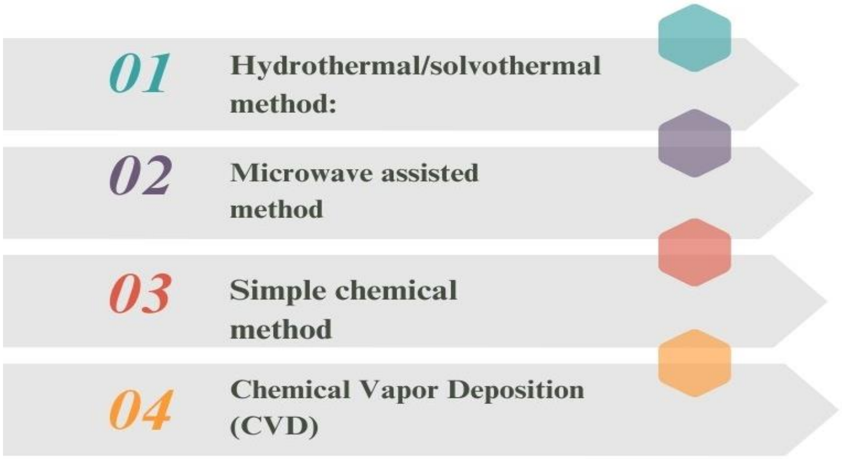
Quaternary QDs represent a cutting-edge area of research in nanomaterials science, offering unprecedented control over their properties and enabling innovative applications across various fields. Continued advancements in synthesis techniques and understanding of their fundamental properties hold promise for further expanding the capabilities and applications of quaternary quantum dots [41].

Table:3 This table provides information about the synthesis, stabilization, morphology, size, and applications of ten quaternary metal oxide quantum dots, showcasing their diverse properties and potential uses across various fields.

Quantum Dot	Synthesis Method	Stabilizing/Capping Agent	Morphology	Size	Applications	reference
Zinc Copper Tin Oxide (ZnCuSnO)	Sol-gel, hydrothermal	Oleic acid, oleylamine	Nanoparticles	5-20 nm	Thin-film transistors, transparent conductive films, photodetectors, sensors.	[42]
Iron Nickel Cobalt Oxide (FeNiCoO)	Co-precipitation	Polyvinylpyrrolidone (PVP)	Nanoparticles	5-30 nm	Lithium-ion batteries, supercapacitors, magnetic nanoparticles, catalysis.	[43]
Copper Zinc Tin Sulfide	Sputtering, solution-	Thioglycolic acid (TGA),	Nanoparticles	3-10	Thin-film solar cells,	

(CZTS)	based	mercaptopropionic acid (MPA)		nm	photodetectors, gas sensors, photocatalysis.	[44]
Nickel Manganese Cobalt Oxide (NMC)	Sol-gel, hydrothermal	Polyvinylpyrrolidone (PVP)	Nanoparticles	5-20 nm	Lithium-ion batteries, supercapacitors, electrochromic devices, catalysis.	[45]
Copper Zinc Tin Oxide Sulfide (CZTOS)	Microwave-assisted synthesis	Trioctylphosphine (TOP), trioctylphosphine oxide (TOPO)	Nanowires	5-30 nm	Photovoltaic devices, gas sensors, transparent conductive films.	[46]
Iron Cobalt Nickel Oxide (FeCoNiO)	Sol-gel, hydrothermal	Oleic acid, oleylamine	Nanoparticles	5-20 nm	Electrocatalysis, oxygen reduction reactions, sensors, magnetic nanoparticles.	[47]
Zinc Iron Cobalt Oxide (ZnFeCoO)	Co-precipitation	Polyvinylpyrrolidone (PVP)	Nanoparticles	5-30 nm	Magnetic nanoparticles, water treatment, catalysis, electromagnetic interference shielding.	[48]
Copper Nickel Manganese Oxide (CuNiMnO)	Sol-gel, hydrothermal	Oleic acid, oleylamine	Nanoparticles	5-20 nm	Gas sensors, electrochemical sensors, energy storage devices, photocatalysis.	[49]
Nickel Cobalt Iron Oxide (NiCoFeO)	Co-precipitation	Sodium citrate	Nanoparticles	5-30 nm	Magnetic nanoparticles, water treatment, catalysis, supercapacitors.	[50]
Zinc Nickel Cobalt Oxide (ZnNiCoO)	Sol-gel, hydrothermal	Polyvinylpyrrolidone (PVP)	Nanoparticles	5-20 nm	Gas sensors, transparent conductive films, supercapacitors, energy storage devices.	[51]

4. Method of synthesis for metal oxide Quantum dots:-



4.1 Hydrothermal/solvothermal method:

The hydrothermal and solvothermal methods stand out as versatile techniques for synthesizing metal oxide quantum dots (QDs), offering precise control over size, shape, and composition. In these methods, a mixture of metal salts and solvents is heated in a sealed container, typically above the boiling point of the solvent, creating high-temperature and high-pressure conditions conducive to QD formation [52]. What makes these methods particularly valuable is their ability to produce complex materials. Hydrothermal synthesis excels in generating dense, mixed-metal oxide materials, while solvothermal synthesis can yield open-framework inorganic solids like zeolites and metal-organic framework structures. This adaptability enables the one-step preparation of chemically complex materials with controlled properties [53]. Furthermore, these methods are environmentally friendly and can operate at lower temperatures compared to traditional synthesis approaches, making them attractive alternatives for QD production. With increasing evidence of rational control over product materials, hydrothermal and solvothermal methods continue to be pivotal in advancing the field of nanomaterial synthesis [54].

The chemical reaction for the synthesis of ZnO quantum dots using the hydrothermal/solvothermal method typically involves the hydrolysis and subsequent condensation of zinc precursor compounds in the presence of a base. Here's a generalized chemical equation:

ZnO Quantum Dots Synthesis Reaction:

$$\mathbf{Zn\,(CH_3COO)_2+2NaOH \rightarrow ZnO+2CH_3COONa+H_2O}$$

This equation represents the reaction between zinc acetate (Zn(CH3COO)2Zn(CH3COO)2) and sodium hydroxide (NaOHNaOH), resulting in the formation of zinc oxide (ZnOZnO), sodium acetate (CH3COONaCH3COONa), and water (H2OH2O).

In the hydrothermal/solvothermal method, this reaction takes place under elevated temperature and pressure conditions within the reaction vessel, promoting the formation of ZnO quantum dots [55]. The specifics of the reaction conditions, such as temperature, pressure, and duration, may vary depending on the desired properties of the synthesized quantum dots and the chosen experimental parameters.

4.2 Microwave assisted method:-

Microwave-assisted synthesis has emerged as a powerful and efficient technique for the fabrication of metal oxide quantum dots (QDs), offering advantages such as rapid reaction kinetics, high yields, and precise control over nanoparticle properties. In this method, metal salts or metal-containing compounds are dissolved in a suitable solvent along with stabilizing agents, such as surfactants or capping agents, to control particle size and stability [56].

- The reaction solution is then subjected to microwave irradiation in a specialized reactor. Microwave energy is rapidly absorbed by the solvent and reactants, leading to uniform and rapid heating throughout the reaction mixture. This elevated temperature promotes the nucleation and growth of metal oxide nanoparticles within a short period, typically minutes to hours, compared to conventional heating methods [57]. The controlled parameters such as microwave power, irradiation time, temperature, and precursor concentration are carefully adjusted to tailor the size, morphology, and composition of the synthesized metal oxide QDs. After irradiation, the reaction mixture is allowed to cool, and the resulting suspension contains the synthesized metal oxide QDs dispersed in the solvent 58].

$$\mathbf{Zn(CH_3COO)_2 + 2NaOH \rightarrow Zn(OH)_2 + 2CH_3COONa\ (1)}$$

$$\mathbf{Zn(OH)_2 \rightarrow ZnO + H_2O\ (2)}$$

In this reaction, zinc acetate (Zn(CH3COO)2) and sodium hydroxide (NaOH) are dissolved in a solvent such as water. Upon microwave irradiation, zinc acetate reacts with sodium hydroxide to form zinc hydroxide (Zn(OH)2) according to Equation (1). Subsequently, zinc hydroxide undergoes dehydration to form zinc oxide (ZnO) nanoparticles and water, as shown in Equation (2). The microwave irradiation accelerates the reaction kinetics, leading to the rapid formation of ZnO quantum dots with controlled size and morphology [59].

Common characterization techniques, including transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and UV-visible spectroscopy, are employed to evaluate the size, shape, crystallinity, and optical properties of the synthesized nanoparticles.

4.3 Simple chemical method :-

The aqueous-based synthesis method for producing metal oxide quantum dots (QDs) offers a straightforward and environmentally friendly approach to nanoparticle fabrication [60]. Here's an outline of the simple chemical method:

The chemical reaction involved in the synthesis of zinc oxide (ZnO) quantum dots using the simplified method described above can be termed as a precipitation reaction followed by thermal decomposition.

Precipitation Reaction:

$$Zn\,(CH_3COO)_2{\cdot}2H2O + 2NaOH \rightarrow Zn(OH)2 + 2CH3COONa$$

Thermal Decomposition:

$$Zn(OH)2 \rightarrow ZnO + H2O$$

In the first step, zinc acetate dihydrate (Zn(CH3COO)2·2H2O) reacts with sodium hydroxide (NaOH) to form zinc hydroxide (Zn(OH)2) via a precipitation reaction [61]. Subsequently, upon thermal treatment, zinc hydroxide decomposes into zinc oxide (ZnO) and water.

- **Preparation of Precursor Solutions**: Begin by preparing precursor solutions containing the necessary metal salts or metal-containing compounds. For example, in the case of Sahraei et al.'s study, precursor solutions containing silver (Ag), nickel (Ni), zinc (Zn), cadmium (Cd), and sulfur (S) sources would be prepared.
- **Addition of Base**: Introduce a base into the precursor solution to trigger the nucleation and growth of quantum dots. The base serves as a catalyst for the reaction and helps in controlling the size and morphology of the nanoparticles. In this method, the base initiates the formation of metal oxide nuclei, which subsequently grow into quantum dots [62].

- **Growth-Doping Strategy**: Implement a growth-doping strategy, as described by Sahraei et al., to synthesize water-soluble dual-doped Ag,Ni:ZnCdS/ZnS core/shell QDs. This strategy involves incorporating dopant ions (Ag, Ni) into the crystal lattice of the quantum dots during their growth process, leading to unique properties and functionalities.
- **Formation of Core/Shell Structure**: Sahraei et al.'s approach includes the formation of a core/shell structure, where the metal oxide quantum dot core (Ag,Ni:ZnCdS) is coated with a ZnS shell. This shell provides stability to the quantum dots and enhances their luminescence properties [63].

After synthesis, the quantum dots are characterized using various analytical techniques to assess their size, shape, composition, crystallinity, and optical properties. Techniques such as transmission electron microscopy (TEM), X-ray diffraction (XRD), and photoluminescence spectroscopy are commonly used for this purpose.

4.4 Chemical Vapor Deposition (CVD) :-

Chemical Vapor Deposition (CVD) is commonly used for the synthesis of thin films and coatings, it is less frequently employed for the synthesis of metal oxide quantum dots (QDs) due to challenges in controlling the size, shape, and uniformity of the nanoparticles [64]. However, some modified CVD techniques have been developed for the synthesis of metal oxide QDs.

Example: **For instance, in the synthesis of zinc oxide (ZnO) quantum dots using CVD [65][66]:**

- Precursor: Zinc acetate dihydrate (Zn(CH3COO)2·2H2O)
- Reactant Delivery: Introduce Zn(CH3COO)2 vapor along with carrier gas (e.g., nitrogen) into the CVD chamber.
- Substrate Preparation: Use a silicon substrate coated with a thin layer of gold nanoparticles as a catalyst.
- Temperature and Pressure Control: Maintain chamber temperature at 500°C and pressure at 1 atm.
- Surface Reaction and Nucleation: Decomposition of Zn(CH3COO)2 vapor on the gold nanoparticle-coated substrate, leading to the nucleation of ZnO quantum dots.

- Growth and Size Control: Control growth kinetics and conditions to achieve desired size and distribution of ZnO quantum dots.
- Characterization: Analyze the synthesized ZnO quantum dots using TEM, SEM, XRD, and UV-visible spectroscopy to determine their size, morphology, crystallinity, and optical properties.
- Optimization and Scale-up: Fine-tune synthesis parameters and scale up the process for large-scale production of ZnO quantum dots.

While CVD offers potential advantages such as precise control over deposition and scalability, its application for metal oxide quantum dot synthesis requires careful optimization and modification of the conventional CVD process to achieve the desired nanoparticle properties.

5. Properties of metal oxide quantum dots:-

5.1 Structural properties:-

Metal oxide quantum dots (QDs) are fascinating nanoscale materials with intricate structural properties that underpin their diverse applications. Their size, typically ranging from 1 to 10 nanometers, offers a unique platform for size-dependent phenomena like quantum confinement, where electrons and holes are confined within the QD's dimensions, influencing their electronic and optical properties [67]. The shape diversity of metal oxide QDs, including spherical, cubic, or rod-like morphologies, not only affects their surface area but also governs their reactivity and optical characteristics. Crystal structures, such as cubic, tetragonal, or hexagonal arrangements, determine the spatial distribution of atoms within the QDs, influencing their electronic band structure and overall stability [68]. Surface chemistry plays a crucial role, with ligands or functional groups passivating the QD surface, thereby controlling their stability, solubility, and interactions with surrounding molecules. Defects within the QD lattice or intentional doping with other elements provide additional avenues for tailoring their electronic and optical properties to suit specific applications, such as sensing or catalysis [69]. Moreover, the composition of metal oxides within QDs, whether titanium, zinc, iron, or others, dictates fundamental properties like bandgap energy, conductivity, and chemical reactivity. Finally, the interfaces formed between metal oxide QDs and other materials, such as organic polymers or inorganic matrices in composite structures, profoundly influence charge transfer processes, stability, and overall device performance in applications ranging from solar cells to light-emitting diodes [70]. Understanding and harnessing these structural properties enable precise control over the design and optimization of metal oxide quantum dots for a myriad of technological advancements.

5.2 Optical properties of metal oxide QDs:

Table 4 : The table provided optical properties of metal oxide quantum dots (QDs) along with their descriptions and advantages.

Optical Property	Description	Advantage	Reference
Quantum Confinement Effect	Metal oxide QDs exhibit quantum confinement effect due to their nanoscale dimensions, resulting in size-dependent electronic properties. As the size of the QDs decreases, the bandgap energy increases, leading to a blue-shift in the absorption and emission spectra.	• Tunability of optical properties • Potential for optoelectronic applications such as LEDs and solar cells	[71]
Size-Dependent Absorption and Emission	The absorption and emission spectra of metal oxide QDs are size-dependent. Smaller QDs absorb and emit light at shorter wavelengths (e.g., blue or ultraviolet), while larger QDs absorb and emit light at longer wavelengths (e.g., red or near-infrared).	• Spectral tunability for various applications • Potential for multi-color imaging and display technologies	[72]
Stokes Shift	Metal oxide QDs typically exhibit a Stokes shift, which is the difference between the absorption and emission maxima. The magnitude of the Stokes shift depends on the size and composition of the QDs, as well as the presence of surface defects.	• Reduction of self-absorption and reabsorption effects. • Improved color purity and spectral separation in multiplexed assays and imaging	[73]
Photoluminescence Quantum Yield (PLQY)	PLQY refers to the efficiency of light emission upon excitation of the QDs. High-quality metal oxide QDs with well-passivated surfaces and minimal defects exhibit high	• Enhanced brightness and intensity of emitted light • Improved sensitivity and signal-to-noise ratio in optical sensing and imaging applications	[74]

	PLQY values, indicating efficient light emission.		
Photostability	Photostability refers to the ability of metal oxide QDs to retain their optical properties upon prolonged exposure to light, heat, or chemical environments. Surface passivation and proper encapsulation techniques enhance the photostability of QDs.	• Long-term stability and durability of QDs in real-world applications • Reduced degradation and loss of optical performance over time	[75]
Broad Absorption Spectrum	Metal oxide QDs typically exhibit broad absorption spectra, allowing them to absorb a wide range of wavelengths. This broad absorption spectrum enables efficient light harvesting for various applications.	• Improved light absorption and energy conversion efficiency • Potential for broadband photodetection and solar energy harvesting	[76]
Narrow Emission Spectrum	Despite their broad absorption spectra, metal oxide QDs typically emit light at relatively narrow wavelengths. This narrow emission spectrum results in high color purity and excellent spectral tunability.	• High color fidelity and accuracy in display and lighting applications • Precise control over emission wavelengths for multiplexed imaging and sensing	[77]
Exciton Binding Energy	The exciton binding energy represents the energy required to create an electron-hole pair (exciton) within the QD. Metal oxide QDs with higher exciton binding energies exhibit greater stability against thermal dissociation and carrier recombination.	• Enhanced charge carrier transport and carrier lifetime in devices • Improved efficiency and performance of QD-based optoelectronic devices	[78]
Surface Plasmon Resonance	Some metal oxide QDs exhibit surface plasmon resonance (SPR) due to the collective oscillation of free electrons on their surfaces. SPR can enhance light absorption and scattering properties, leading to improved optical	• Enhanced light-matter interaction and absorption cross-section • Potential for enhanced photothermal therapy and photocatalysis applications	[79]

	performance.		
Tunable Optical Properties	Metal oxide QDs offer tunable optical properties through controlled synthesis parameters such as size, composition, and surface functionalization. This tunability enables customization of QD properties for specific applications.	• Tailored optical properties for diverse applications • Flexibility in designing QD-based devices with desired functionalities and performance	[80]

5.3 Electrical properties of metal oxide quantum dots :-

Metal oxide quantum dots (QDs) exhibit a range of electrical properties that are influenced by factors such as size, composition, crystallinity, surface defects, and doping [81]. Here are some key electrical properties observed in metal oxide QDs:

- **Tunable Bandgap:** Metal oxide QDs display a tunable band gap, which refers to the energy difference between the valence band and the conduction band. As the size of the QDs decreases, the band gap increases due to quantum confinement effects. This tunability allows for the engineering of QD band gaps matching specific electronic or optoelectronic device requirements [82].
- **Carrier Mobility:** Carrier mobility in metal oxide QDs refers to the ability of charge carriers (electrons or holes) to move through the material under the influence of an electric field. The mobility of carriers depends on factors such as crystal structure, defect density, and surface passivation. High carrier mobility is desirable for efficient charge transport in electronic and photovoltaic devices [83].
- **Charge Carrier Concentration:** Metal oxide QDs can be doped with impurities to introduce additional charge carriers into the material . Doping alters the electrical conductivity and semiconductor properties of the QDs, enabling control over their electronic behavior. For example, n-type doping introduces excess electrons, while p-type doping introduces excess holes [84].
- **Trap States**: Trap states in metal oxide QDs refer to localized energy levels within the bandgap that can capture and release charge carriers. Surface defects, impurities, and crystal imperfections create trap states, affecting the efficiency of charge transport

and recombination processes in QDs. Minimizing trap states is essential for improving device performance and stability [85].

- **Charge Transport Mechanisms:** Metal oxide QDs exhibit various charge transport mechanisms, including band-to-band tunneling, thermionic emission, and variable-range hopping. The dominant charge transport mechanism depends on factors such as QD size, temperature, and doping concentration. Understanding and optimizing charge transport mechanisms are critical for designing efficient electronic and optoelectronic devices [86].
- **Electrical Conductivity:** The electrical conductivity of metal oxide QDs can range from insulating to semiconducting or metallic, depending on their composition and doping level. Semiconducting QDs with intermediate conductivity are commonly used in electronic and photovoltaic applications, while metallic QDs may find applications in plasmonic devices [87].
- **Dielectric Properties:** Metal oxide QDs exhibit dielectric properties that influence their capacitance, permittivity, and polarization behavior in electrical circuits and devices . Dielectric properties are crucial for applications such as capacitors, insulators, and dielectric resonators [88].
- **Fermi Level Position**: The Fermi level position in metal oxide QDs determines their energy levels relative to the vacuum level and influences charge carrier injection, extraction, and transport at interfaces with other materials. Control over the Fermi level is essential for optimizing device performance in semiconductor devices [89].

These electrical properties are essential for harnessing the potential of metal oxide quantum dots in various electronic, optoelectronic, and energy-related applications . Manipulating the electrical properties of QDs through synthesis, doping, surface engineering, and device integration strategies enable the development of next-generation electronic and photonic devices with enhanced performance and functionality [90].

6. Application of metal oxide QDs:-

6.1 Optoelectronics and photovoltaic:-

Metal oxide quantum dots (QDs) find extensive application in optoelectronics and photovoltaics, where their unique optical and electronic properties contribute to the development of high-performance devices [91]. In light-emitting diodes (LEDs), metal oxide

QDs serve as phosphors to produce spectrally pure visible light with superior color rendering properties, enabling vibrant displays and energy-efficient lighting.

- Metal oxide QDs enhances the efficiency of solar cells by extending the absorption spectrum, improving charge carrier generation, and facilitating efficient charge transport. These QDs are utilized in various solar cell architectures, including quantum dot-sensitized solar cells (QDSCs) and tandem solar cells, offering tunable bandgaps, high absorption coefficients, and efficient charge separation properties [92].
- Metal oxide QDs play a crucial role in photodetectors, where they enhance sensitivity, response time, and spectral selectivity, enabling high-performance imaging, sensing, and optical communication applications. In displays and lighting systems, metal oxide QDs enable the production of vibrant colors, wide color gamuts, and energy-efficient backlighting, contributing to the advancement of display technologies such as quantum dot displays (QLEDs) and liquid crystal displays (LCDs) [93].

Overall, metal oxide QDs hold significant promise for driving innovation and efficiency in optoelectronic and photovoltaic devices, with continued research poised to further expand their applications and impact.

6.2 Catalysis:-

Metal oxide quantum dots (QDs) have emerged as promising catalysts for various chemical transformations due to their unique structural, electronic, and surface properties. These QDs exhibit catalytic activity in a wide range of reactions, including environmental remediation, energy conversion, and organic synthesis [94]. In environmental catalysis, metal oxide QDs are utilized for the degradation of organic pollutants, such as dyes, pharmaceuticals, and pesticides, through photocatalytic and electrocatalytic processes [95].

Table 5:- This table provides a concise overview of the catalytic applications of metal oxide quantum dots, highlighting their versatility and potential impact in various fields.

Catalysis Name	Application Use	Example
Photocatalysis	Environmental remediation, water purification	Degradation of organic pollutants (e.g., dyes, pharmaceuticals) using TiO2 QDs under UV or visible light irradiation

Electrocatalysis	Energy conversion, electrolysis, fuel cells	Water splitting, carbon dioxide reduction, oxygen evolution reactions using metal oxide QDs (e.g., TiO2, ZnO) as electrocatalysts in electrolyzers and fuel cells
Heterogeneous catalysis	Organic synthesis, fine chemicals production	Photochemical reactions for selective bond formation using ZnO QDs as photocatalysts in organic synthesis applications

- For example, titanium dioxide (TiO2) QDs is widely studied for their photocatalytic activity in degrading organic contaminants under UV or visible light irradiation, offering a sustainable approach for wastewater treatment and air purification. Metal oxide QDs also serve as efficient electrocatalysts for water splitting, carbon dioxide reduction, and oxygen evolution reactions in energy conversion devices such as electrolyzers and fuel cells [96].
- Additionally, metal oxide QDs exhibit catalytic activity in organic synthesis, facilitating selective bond formation and transformation reactions. For instance, zinc oxide (ZnO) QDs is employed as photocatalysts for the synthesis of fine chemicals and pharmaceuticals through photochemical reactions, enabling green and efficient synthetic routes. Overall, the catalytic application of metal oxide QDs holds great potential for addressing global challenges in environmental sustainability, renewable energy, and chemical synthesis, with ongoing research focused on optimizing their catalytic performance and exploring new applications in catalysis [97].

6.3 Energy storage device:-

Metal oxide quantum dots (QDs) hold significant promise for energy storage applications, particularly in the development of advanced electrochemical energy storage devices such as batteries, supercapacitors, and electrochemical capacitors [98]. Here's how metal oxide QDs are utilized in energy storage:

1. **Supercapacitors**: Metal oxide QDs are utilized as electrode materials in supercapacitors, also known as ultracapacitors, due to their high specific surface area,

tunable electronic properties, and rapid charge-discharge kinetics. These QDs offer advantages such as enhanced charge storage capacity, high power density, and long cycle life compared to traditional carbon-based electrodes. For example, manganese oxide (MnO2) QDs exhibit pseudocapacitive behavior, allowing for reversible redox reactions at the electrode-electrolyte interface, thus enabling high energy and power densities in supercapacitor devices [99].

2. **Lithium-ion Batteries**: Metal oxide QDs are investigated as electrode materials in lithium-ion batteries to improve their energy density, cycling stability, and rate capability. QDs such as tin dioxide (SnO2), titanium dioxide (TiO2), and iron oxide (Fe2O3) offer high lithium ion storage capacity, low volume expansion, and good structural stability during cycling. These QDs can be incorporated into the anode or cathode of lithium-ion batteries to enhance their electrochemical performance and enable the development of next-generation energy storage devices for portable electronics, electric vehicles, and grid-scale energy storage applications [100].
3. **Electrochemical Capacitors**: Metal oxide QDs are employed as active materials in electrochemical capacitors, also known as supercapacitors or double-layer capacitors, due to their high specific capacitance, rapid charge-discharge kinetics, and excellent cycling stability. QDs such as ruthenium oxide (RuO2), manganese dioxide (MnO2), and nickel oxide (NiO) offer high charge storage capacity and electrochemical stability, making them suitable for use in electrochemical capacitor devices. These QDs enable the development of high-performance energy storage systems for applications requiring rapid energy release and long cycle life, such as regenerative braking systems in vehicles and grid stabilization solutions [101].
4. **Sodium-ion Batteries**: Metal oxide QDs are investigated as electrode materials in sodium-ion batteries as an alternative to lithium-ion batteries for large-scale energy storage applications. QDs such as sodium titanium oxide (Na2Ti6O13) and sodium vanadium oxide (NaV6O15) offer advantages such as abundant raw materials, low cost, and high safety compared to lithium-based materials. These QDs exhibit high sodium ion storage capacity, good rate capability, and excellent cycling stability, making them suitable for use in sodium-ion battery devices for renewable energy storage, electric grid integration, and portable electronics [102].

Overall, metal oxide quantum dots hold great potential for advancing energy storage technologies, offering opportunities to enhance energy density, power density, cycling stability, and safety in electrochemical energy storage devices.

6.4 Sensor:-

Metal oxide quantum dots (QDs) are extensively utilized in sensor applications across diverse fields due to their unique optical, electrical, and surface properties. These QDs serve as sensitive materials in gas sensors, chemical sensors, environmental sensors, biomedical sensors, and optical sensors, enabling the detection and measurement of various analytes with high sensitivity and selectivity [103].

- In gas sensors, metal oxide QDs exhibit changes in electrical conductivity or optical properties in response to specific gas molecules, allowing for the detection of toxic gases, VOCs, and environmental pollutants. Similarly, in chemical sensors, metal oxide QDs can be functionalized with receptor molecules or surface ligands to selectively bind to target analytes, leading to changes in their optical or electrical properties for biomolecular detection and environmental monitoring [104].
- Furthermore, metal oxide QDs find application in environmental sensors for monitoring parameters such as temperature, humidity, pH, and heavy metal ions, as well as in biomedical sensors for disease detection, drug delivery, and medical imaging. Overall, the unique properties of metal oxide QDs make them versatile materials for sensor technologies, with potential applications in healthcare, environmental monitoring, safety, and security. Continued research and development efforts are focused on optimizing the performance and expanding the capabilities of metal oxide QDs for sensor applications to address emerging challenges and meet the demands of diverse sensor systems [105].

Metal oxide quantum dots offer tremendous potential for advancing sensor technologies, enabling the development of highly sensitive, selective, and miniaturized sensor devices for a wide range of applications in environmental monitoring, healthcare, safety, and security. Continued research and innovation in metal oxide QDs are expected to further enhance their performance and expand their applications in sensor technologies [106].

Conclusion:-

In conclusion, metal oxide quantum dots (QDs) have emerged as a fascinating class of nanomaterials with diverse properties and promising applications across various fields. This review has provided a comprehensive overview of the synthesis methods, structural, optical, and electrical properties, as well as the wide-ranging applications of metal oxide QDs. Moving forward, future research directions in this area could focus on several key aspects. Firstly, continued efforts to advance synthesis techniques will enable precise control over the size, shape, and composition of metal oxide QDs, leading to enhanced properties and performance in applications. Additionally, further investigation into the fundamental understanding of the optical, electrical, and structural properties of metal oxide QDs will facilitate the development of novel materials with tailored characteristics for specific applications. Moreover, exploration of innovative applications such as in quantum computing, bioimaging, and environmental sensing could unlock new opportunities for metal oxide QDs in emerging technologies. Collaborative interdisciplinary research efforts involving materials scientists, chemists, physicists, and engineers will be essential for realizing the full potential of metal oxide QDs and driving advancements in nanotechnology. Overall, with continued exploration and innovation, metal oxide QDs hold great promise for addressing current challenges and shaping the future of materials science and technology.

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