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Overview on advancements of Zinc oxide nanoparticles: Synthesis, Properties and applications

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Abstract: Zinc oxide nanoparticles have garnered significant attention due to their unique properties and diverse applications in various fields. This review article provides a comprehensive overview of recent advances in the synthesis methods, properties and applications of ZnO nanoparticles. Various synthesis techniques including sol-gel, hydrothermal and chemical vapour deposition methods are discussed, highlighting their advantages and limitations. The properties of ZnO nanoparticles such as optical, electronic, magnetic and catalytic properties are explored in detail. Furthermore the diverse applications of ZnO nanoparticles in area such as photocatalysis, sensors, biomedical and environmental remediation are extensively reviewed, showcasing their potential impact in different sectors.

Keywords: Zinc oxide nanoparticles, Synthesis methods, Properties, Applications, Sol-gel, Hydrothermal, Chemical vapor deposition

I. INTRODUCTION

Zinc oxide nanoparticles (ZnO NPs) have emerged as promising nanomaterials due to their unique physicochemical properties such as high surface area, large aspect ratio and exceptional optical and electronic properties. This review article aims to provide an up-to-date overview of the synthesis methods, properties and applications of ZnO NPs. The synthesis methods are categorized into physical, chemical and biological routes [1], [2], each offering distinct advantages in terms of control over size, shape and morphology [3], [4], [5], [6]. The properties of ZnO nanoparticles including their optical, electronic, magnetic and catalytic properties are crucial for understanding their behaviour and potential applications. Additionally, the diverse applications of ZnO nanoparticles in photocatalysis, sensors, biomedical and environmental remediation are discussed, highlighting their versatility and significance in various fields.

One common physical method for preparing zinc oxide nanoparticles is the sol-gel method. It involves the hydrolysis and condensation of zinc precursors in a solvent to form a colloidal suspension followed by controlled drying and annealing to obtain the desired nanoparticles. Another physical method for preparing zinc oxide nanoparticles is vapour phase synthesis technique. In this method, zinc vapour is generated by heating zinc metal in a controlled environment and then it reacts with oxygen to form zinc oxide nanoparticles. This process is typically occurs at high temperatures.

Structure of Zinc Oxide: Zinc oxide (ZnO) has a hexagonal wurtzite crystal structure, depicted as a lattice of zinc ions (Zn^{2+}) surrounded by oxygen ions (O^{2-}). The zinc ions are positioned in every other layer of the hexagonal lattice, forming a regular octahedron with oxygen ions at the corners. The oxygen ions create a hexagonal lattice with zinc ions occupying half of the octahedral interstitial sites. The band gap of zinc oxide is approximately 3.37 eV [7], [8] at room temperature which corresponds to the energy difference between its valence band and conduction band. This wide band gap makes ZnO a promising material for various applications including transparent conductive films, UV light emitters and sensors.

II. METHODS FOR THE PREPARATION OF NANOPARTICLES

There are various method for the synthesis of nanoparticles which are given below as-

Hydrothermal Method: The hydrothermal method for synthesizing zinc oxide nanoparticles involves the reaction of zinc salts with a hydroxide source under high temperature and high pressure conditions in an aqueous solution. Typically zinc acetate or zinc nitrate is used as the zinc precursor [9] while sodium hydroxide or ammonium hydroxide serves as the hydroxide source.

In a typical process the zinc salt is dissolved in water to form a clear solution. Then the hydroxide source is slowly added to the solution under constant stirring. The reaction mixture is transferred to a sealed reactor and heated under autogenously pressure at temperatures ranging from 80^0C to 200^0C for several hours.

During the hydrothermal process zinc hydroxide intermediates are formed which then undergo dehydration

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and further reaction conditions such as temperature, pressure and reaction time can be adjusted to control the size, morphology and crystallinity of the resulting nanoparticles [10].

After the reaction the nanoparticles are typically separated by centrifugation or filtration, washed to remove any impurities and then dried or annealed to obtain the final zinc oxide nanoparticle product [11].

Precipitation Method: The precipitation method for synthesizing zinc oxide nanoparticles involves the reaction of zinc salts with a precipitating agent in an aqueous solution. Common zinc salts used include zinc nitrate, zinc acetate or zinc chloride while various precipitating agents like sodium hydroxide or sodium carbonate can be employed. Here is a simplified outline of the process: 1-Dissolve the zinc salt in water to form a clear solution. 2-Add the precipitating agent dropwise to the solution under constant stirring. This causes the formation of zinc hydroxide precipitates. 3-The precipitates undergo further reaction and transformation to yield zinc oxide nanoparticles. 4-control parameters like temperature, pH and stirring rate influence the size and morphology of the nanoparticles. 5-After the reaction the nanoparticles are typically separated by centrifugation or filtration, washed to remove any impurities and then dried or annealed to obtain the final zinc oxide nanoparticles product. This method offers simplicity and scalability for producing zinc oxide nanoparticles with control over particle size achieved by adjusting reaction parameters [12], [13].

Chemical vapour transport method (CVT): The chemical vapour transport method for synthesizing zinc oxide nanoparticles involves the sublimation of a solid zinc oxide precursor at high temperatures in the presence of carrier gas followed by the controlled deposition of the vapour onto a substrate where the nanoparticles are formed. In this method a solid zinc oxide precursor, such as zinc oxide powder or zinc carbonate is heated in a tube furnace at temperatures typically ranging from 800^0C to 1200^0C. A carrier gas, such as argon or oxygen, is introduced into the system to facilitate the transport of the vaporized precursor.

As a precursor sublimes it forms zinc oxide vapour which is carried by the gas flow to a cooler region of the reactor or onto a substrate placed downstream. Upon cooling the vapour condenses and nucleates to form zinc oxide nanoparticles on the substrate surface [14], [15], [16].

The size , morphology and properties of the nanoparticles can be controlled by adjusting parameters such as the temperature, precursor concentration, carrier gas flow rate and deposition time. This method offers the advantage of producing high purity nanoparticles with controlled size and uniformity suitable for various applications such as thin film deposition and nanocomposite synthesis.

Arc Plasma Method: The arc plasma method for synthesizing zinc oxide nanoparticles involves the vaporization and subsequent condensation of a zinc source material into nanoparticles using an electric arc discharge.

In this method a high voltage electric arc is generated between two zinc electrodes in a controlled atmosphere (often inert gas like argon). The intense heat of arc vaporizes the zinc electrodes, creating a plasma plume containing zinc vapour and ions.

As the plasma cools, the zinc vapour condenses and nucleates to form zinc oxide nanoparticles [17]. The nanoparticles are then collected on a suitable substrate or in a collection chamber.

The size, morphology and properties of the nanoparticles can be controlled by adjusting parameters such as the arc current, electrode distance, gas atmosphere and cooling rate. This method offers the advantage of producing nanoparticles with high impurity and crystallinity suitable for various applications such as catalysis, sensors and optoelectronics.

Physical Vapour Deposition Method: In the physical vapour deposition method for the synthesis of zinc oxide nanoparticles, a solid zinc oxide target is bombarded with energetic particles, typically ions or electrons, in a vacuum chamber. This bombardment causes atoms from the target to be ejected into the vapour phase, where they then condense onto a substrate to form nanoparticles. During the process, the zinc oxide target is heated to a high temperature to increase its vapour pressure [18], [19]. A controlled atmosphere, usually a high vacuum, is maintained in the chamber to prevent contamination and to allow for precise control over the deposition process.

The energetic particles used for bombardment can be ions in techniques such as ion sputtering or electron beams in methods like electron beam evaporation. These particles transfer energy to the target material, dislodging atoms and allowing them to escape into the vapour phase.

As the vaporized zinc oxide atoms travel towards the substrate they undergo nucleation and growth to form nanoparticles. The properties of the nanoparticles, such as size, morphology and crystallinity can be controlled by adjusting parameters such as deposition rate, substrate temperature and pressure.

Physical vapour deposition methods offer the advantage of producing high purity nanoparticles with excellent control over their size and uniformity making them suitable for various applications such as thin film coatings, electronics and photovoltaics.

Ultrasonic irradiation: Ultrasonic irradiation is a technique used to synthesize zinc oxide nanoparticles by applying high frequency sound waves to a reaction mixture [20]. These waves cause cavitation where bubbles form and collapse rapidly generating localised heating and pressure changes. This promotes chemical reaction leading to the formation of nanoparticles. It is efficient, fast and can produce nanoparticles with controlled size and morphology.

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Laser ablation method: This technique is used to synthesize zinc oxide nanoparticles where a high power laser beam is focussed onto a target material submerged in liquid. The intense energy from the laser vaporizes the target, creating plasma plume containing atoms and ions which then condense into nanoparticles in the surrounding liquid. It is versatile method capable of producing nanoparticles from a wide range of materials with precise control over size, shape and composition. It is relatively simple and fast process making it attractive for industrial scale production of nanoparticles for various applications including drug delivery, sensors and coatings. The size of synthesized nanoparticles can be changed with the help of different parameters [21], [22]

III. CONCLUSION

In conclusion, the introduction has laid out a comprehensive framework for understanding the significance of zinc oxide nanoparticles in various fields. These nanoparticles exhibit unique physicochemical properties, such as high surface area, large aspect ratio, and exceptional optical and electronic properties, which render them promising nanomaterials for a wide range of applications. The overview provided encompasses synthesis methods categorized into physical, chemical, and biological routes, each offering distinct advantages in controlling the size, shape, and morphology of ZnO nanoparticles. Furthermore, the discussion delves into the crucial properties of these nanoparticles, including their optical, electronic, magnetic, and catalytic properties, which are pivotal for elucidating their behavior and exploring their potential applications.

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