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A Review on Optoelectronic and Photoconductive Properties of CdS–ZnS Nanocomposites Prepared via Chemical Routes

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Abstract

CdS–ZnS nanocomposites have emerged as a significant class of semiconductor materials owing to their tunable optoelectronic and photoconductive properties, making them highly suitable for advanced device applications. This review provides a comprehensive analysis of the structural, optical, and electronic characteristics of CdS–ZnS nanocomposites synthesized via various chemical routes, including chemical bath deposition, sol–gel, co-precipitation, hydrothermal, and green synthesis methods. The integration of CdS and ZnS enables effective band gap engineering, allowing control over light absorption across the ultraviolet and visible regions. Special emphasis is placed on photoconduction mechanisms, including charge carrier generation, transport, recombination processes, and the role of defect states and interfaces in influencing device performance. The review also discusses the impact of synthesis parameters on morphology, crystallinity, and functional efficiency. Furthermore, key optoelectronic properties such as conductivity, response time, and sensitivity are critically examined in relation to their applications in photodetectors, solar cells, and light-emitting devices. Despite their advantages, challenges such as cadmium toxicity, stability issues, and scalability are highlighted. The study concludes by outlining future research directions focused on improving performance through material engineering and sustainable synthesis strategies.

Keywords: CdS–ZnS nanocomposites, photoconductivity, optoelectronic properties, chemical synthesis, band gap engineering

Introduction

Nanocomposites have emerged as a pivotal class of materials in modern optoelectronics due to their ability to integrate multiple functional components at the nanoscale, thereby enabling tunable electrical and optical properties. In optoelectronic devices such as photodetectors, solar cells, and light-emitting diodes, material performance is critically governed by parameters including band gap, carrier mobility, and recombination dynamics. Nanocomposites offer a strategic advantage by combining distinct semiconductor phases, which facilitates band alignment engineering and enhances charge separation efficiency. The large surface-to-volume



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ratio inherent to nanostructured systems significantly influences light absorption and scattering, while quantum confinement effects allow precise control over electronic transitions. Additionally, chemically synthesized nanocomposites provide cost-effective, scalable, and low-temperature fabrication routes compared to conventional vacuum-based deposition techniques. Methods such as chemical bath deposition, sol-gel processing, and co-precipitation enable fine control over particle size, morphology, and compositional homogeneity. These attributes collectively make nanocomposites highly suitable for next-generation optoelectronic applications, where improved sensitivity, faster response times, and enhanced stability are essential. Furthermore, the introduction of heterojunction interfaces within nanocomposites promotes efficient charge transfer and reduces recombination losses, thereby significantly improving device performance.

Among various semiconductor materials, cadmium sulfide (CdS) and zinc sulfide (ZnS) have attracted considerable attention due to their complementary optical and electronic properties. CdS is a direct band gap semiconductor with a band gap of approximately 2.42 eV, making it highly effective for visible light absorption and widely applicable in photoconductive and photovoltaic devices. In contrast, ZnS possesses a wider band gap (~3.6–3.7 eV), rendering it suitable for ultraviolet optoelectronic applications and as a window or barrier layer in heterostructures. The integration of CdS and ZnS into a nanocomposite system enables band gap tuning and improved spectral response through controlled compositional variation. Moreover, the CdS–ZnS interface facilitates efficient charge separation due to favorable band alignment, which is crucial for enhancing photoconductivity and minimizing recombination losses. ZnS also contributes to improved chemical stability and reduced toxicity effects compared to pure CdS, thereby enhancing the environmental compatibility of the composite. The presence of defect states and surface traps in these nanomaterials further influences their photoconductive behavior, often acting as carrier trapping centers that affect response time and sensitivity. Consequently, CdS–ZnS nanocomposites represent a promising material system for advanced optoelectronic devices, offering a balanced combination of optical absorption, charge transport, and structural stability.

Fundamentals of CdS–ZnS Nanocomposites

CdS–ZnS nanocomposites are typically formed by integrating two II–VI semiconductor materials that exhibit distinct crystallographic phases and band structures. Cadmium sulfide (CdS) commonly crystallizes in both hexagonal wurtzite and cubic zinc blende structures, whereas zinc sulfide (ZnS) predominantly adopts a cubic zinc blende structure, with a possible transition to the wurtzite phase under specific synthesis conditions. When combined at the nanoscale, these materials form heterostructures or solid solutions depending on the synthesis route and compositional ratio. The structural compatibility between CdS and ZnS enables lattice



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substitution and strain-induced modifications, which play a crucial role in band gap engineering. By adjusting the Cd/Zn ratio, the band gap of the composite can be tuned continuously between ~ 2.42 eV (CdS) and ~ 3.6 eV (ZnS). Additionally, quantum confinement effects in nanoscale particles further modify the effective band gap, leading to blue shifts in absorption spectra. This tunability is essential for designing materials with targeted optical responses across the visible and ultraviolet regions.

The electronic properties of CdS–ZnS nanocomposites are governed by their band alignment, defect states, and interfacial characteristics. Typically, these systems exhibit type-I or quasi type-II band alignment, which facilitates efficient charge carrier confinement or separation depending on the composition and structure. The presence of heterojunction interfaces significantly influences charge transport behavior, reducing recombination rates and enhancing photoconductive efficiency. Optically, these nanocomposites demonstrate strong absorption in the UV–visible region, with absorption edges that can be tailored through compositional control and particle size variation. Photoluminescence (PL) studies reveal emission peaks associated with both band-edge recombination and defect-related transitions, indicating the role of surface states and vacancies. Furthermore, the incorporation of ZnS into CdS improves optical transparency and reduces non-radiative recombination, thereby enhancing luminescence efficiency. These combined electronic and optical characteristics make CdS–ZnS nanocomposites highly suitable for optoelectronic applications requiring high sensitivity and tunable spectral response.

The CdS–ZnS composite system offers several advantages over individual semiconductor components, primarily due to synergistic interactions at the nanoscale. One of the key benefits is enhanced photostability, as ZnS acts as a protective shell or matrix that reduces photocorrosion of CdS under illumination. Additionally, the composite structure enables improved charge separation efficiency through effective band alignment, which is critical for photoconductive and photovoltaic applications. The wide band gap of ZnS also contributes to reduced leakage currents and improved device performance. From a materials engineering perspective, CdS–ZnS nanocomposites exhibit better control over particle size, morphology, and surface properties, which directly influence their functional characteristics. Moreover, these composites offer flexibility in synthesis using cost-effective chemical methods, making them suitable for large-scale production. The reduction in toxicity, enhanced durability, and improved optoelectronic performance collectively position CdS–ZnS nanocomposites as a promising material system for next-generation optoelectronic devices.

Chemical Synthesis Routes

Chemical synthesis routes play a crucial role in tailoring the structural, optical, and photoconductive properties of CdS–ZnS nanocomposites. Among these, Chemical Bath



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Deposition (CBD) is one of the most widely used techniques due to its simplicity, low cost, and ability to deposit uniform thin films over large areas. In CBD, controlled release of Cd^{2+} , Zn^{2+} , and S^{2-} ions in an aqueous medium enables gradual nucleation and growth of nanocomposite films on substrates. The sol–gel method, on the other hand, involves hydrolysis and condensation of metal precursors to form a colloidal solution (sol), which transforms into a gel-like network. This method offers excellent control over composition, homogeneity, and particle size at relatively low processing temperatures. Similarly, the co-precipitation technique is based on simultaneous precipitation of Cd and Zn sulfides by reacting metal salts with sulfur sources, allowing precise control over stoichiometry and enabling large-scale production. These methods are particularly advantageous for synthesizing nanocomposites with controlled morphology and phase distribution.

Hydrothermal and solvothermal synthesis techniques are advanced chemical methods that involve crystallization of materials under high temperature and pressure conditions in sealed reactors. These approaches promote the formation of highly crystalline CdS–ZnS nanostructures with well-defined shapes such as nanorods, nanospheres, and hierarchical architectures. The controlled environment enhances diffusion kinetics and reduces structural defects, thereby improving optical and electronic properties. In contrast, green synthesis approaches have gained significant attention due to their eco-friendly and sustainable nature. These methods utilize biological agents such as plant extracts, microorganisms, or natural polymers as reducing and stabilizing agents. Green synthesis not only minimizes the use of toxic chemicals but also enables the formation of biocompatible nanocomposites with controlled size and surface functionality. Such approaches are increasingly relevant for applications requiring environmental safety and low toxicity.

The properties of CdS–ZnS nanocomposites are highly sensitive to synthesis parameters, which directly influence nucleation, growth kinetics, and final material characteristics. Key parameters include precursor concentration, pH of the solution, temperature, reaction time, and annealing conditions. For instance, higher temperatures and longer reaction times generally enhance crystallinity but may also lead to particle agglomeration. The pH of the reaction medium affects ion availability and growth rate, thereby influencing particle size and morphology. Additionally, the Cd/Zn ratio plays a critical role in determining band gap and optical absorption properties. Variations in synthesis conditions can also alter defect density and surface states, which significantly impact photoconductive behavior and carrier recombination dynamics. Therefore, precise optimization of synthesis parameters is essential for achieving desired optoelectronic performance in CdS–ZnS nanocomposites.



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Literature Review

Meshkov et al. (2008) investigated the photoconductivity behavior of CdS–CdSe granular films with a particular focus on the role of microstructural variations. The study emphasized how grain boundaries, crystallite size, and phase distribution significantly influence charge transport mechanisms under illumination. It was observed that the presence of heterojunctions between CdS and CdSe grains enhances carrier separation efficiency, thereby increasing photoconductivity. The authors highlighted that defect states at grain boundaries act as trapping centers, which can either prolong carrier lifetime or hinder mobility depending on their density and distribution. Furthermore, the study demonstrated that optimizing microstructure through controlled synthesis can lead to improved photoconductive response. The findings are particularly relevant for nanocomposite systems such as CdS–ZnS, where similar grain-boundary effects and defect-mediated conduction mechanisms are expected. This work provides a foundational understanding of how structural heterogeneity affects photoconduction and underscores the importance of tailoring microstructural parameters to achieve enhanced optoelectronic performance in semiconductor nanomaterials.

Willis et al. (2009) explored the photoconductivity of quantum dot systems by focusing on optoelectronic trap manipulation within nanogap structures. The study revealed that trap states play a critical role in controlling the photoconductive gain of semiconductor nanocrystals. By modulating trap occupancy using light and electric fields, the researchers demonstrated the ability to tune the conductivity of quantum dot assemblies. The presence of surface defects and interface states was identified as a key factor influencing carrier recombination and transport dynamics. Importantly, the study showed that controlled trapping can enhance photoconductivity by increasing carrier lifetime, leading to higher photogain. However, excessive trapping can also reduce carrier mobility, highlighting the need for a balanced approach. These findings are highly applicable to CdS–ZnS nanocomposites, where surface and interface traps are abundant due to nanoscale dimensions. The work provides valuable insights into the mechanisms of trap-assisted photoconduction and suggests strategies for optimizing nanocomposite materials for photodetector and optoelectronic applications.

John and Florence (2009) examined the structural and optical properties of ZnS nanoparticles synthesized through a solid-state reaction method. The study reported that ZnS nanoparticles exhibit strong quantum confinement effects due to their reduced size, leading to a blue shift in the absorption spectrum. The authors found that particle size, crystallinity, and synthesis conditions significantly influence optical band gap and photoluminescence characteristics. The presence of defects such as sulfur vacancies was identified as a major factor affecting emission properties. These defects can act as recombination centers, thereby influencing photoconductive behavior. Although the study primarily focused on optical properties, its implications for



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photoconduction are substantial, particularly in composite systems like CdS–ZnS. ZnS acts as a wide bandgap material that can improve charge separation and reduce recombination when combined with CdS. This research contributes to understanding how ZnS nanoparticles can be effectively utilized in nanocomposites to enhance optical absorption and electronic transport, thereby improving the overall photoconductive performance.

Wang et al. (2010) reported a room-temperature synthesis method for CdS, ZnS, and CdS/ZnS nanocomposites, highlighting its significance for scalable and cost-effective production. The study demonstrated that the synthesized nanocomposites exhibit improved structural uniformity and enhanced optical properties compared to individual components. The formation of a core-shell or heterostructure between CdS and ZnS was found to play a crucial role in enhancing photoconductivity. ZnS, acting as a shell material, effectively passivates surface defects in CdS, thereby reducing non-radiative recombination losses. This leads to improved charge carrier lifetime and increased photoconductive response. The authors also emphasized that the interface between CdS and ZnS facilitates efficient charge separation due to band alignment. These findings are highly relevant for understanding photoconduction mechanisms in chemically synthesized nanocomposites. The study provides strong evidence that controlled synthesis and interface engineering are key strategies for optimizing the optoelectronic properties of CdS–ZnS systems for applications in sensors and solar energy devices.

Kamat (2010) provided a comprehensive overview of semiconductor nanocrystals, particularly quantum dots, in the context of solar energy conversion and photoconductivity. The study highlighted that quantum dots such as CdS exhibit size-dependent electronic and optical properties, making them highly effective as light harvesters. One of the key discussions in the paper is the role of charge separation and transport in determining photoconductive efficiency. Surface states and recombination processes were identified as critical factors that influence carrier dynamics. The author emphasized the importance of surface passivation, often achieved through materials like ZnS, to enhance stability and reduce recombination losses. This concept directly applies to CdS–ZnS nanocomposites, where ZnS acts as a protective layer improving photoconductive performance. Additionally, the study discussed electron injection and transport mechanisms, which are essential for understanding photoconduction in nanostructured systems. Overall, this work provides a theoretical and conceptual framework for designing efficient nanocomposite materials with improved photoconductive and photovoltaic properties.

Fang et al. (2011) presented a comprehensive review of ZnS nanostructures, focusing on their synthesis techniques, structural diversity, and wide-ranging applications. The study highlighted that ZnS, as a wide bandgap semiconductor, exhibits excellent optical transparency and strong quantum confinement effects when synthesized at the nanoscale. Various synthesis methods such as chemical vapor deposition, hydrothermal processes, and solution-based approaches were



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discussed, each influencing morphology and defect density. The authors emphasized that nanostructured ZnS plays a critical role in enhancing photoconductive and optoelectronic properties due to its ability to act as a surface passivation layer. In composite systems like CdS–ZnS, ZnS effectively reduces surface recombination by minimizing defect states, thereby improving charge carrier lifetime. The review also discussed applications in photodetectors, sensors, and photocatalysis, where ZnS contributes to efficient charge separation. This work is significant in understanding how ZnS nanostructures enhance photoconduction mechanisms in nanocomposites through interface engineering and defect control.

Chen and Mao (2011) provided an extensive review of titanium dioxide (TiO₂) nanomaterials, focusing on their synthesis, physicochemical properties, and applications in photocatalysis and energy conversion. Although TiO₂ differs from CdS–ZnS systems, the study offers critical insights into semiconductor photoconduction mechanisms. The authors discussed how bandgap engineering, crystallinity, and surface states influence charge carrier dynamics under light irradiation. A key finding was the importance of reducing electron–hole recombination through surface modification and heterostructure formation. These principles are directly applicable to CdS–ZnS nanocomposites, where ZnS acts similarly to a passivation layer, enhancing carrier separation. The review also highlighted the role of defects and oxygen vacancies in influencing photoconductivity and photocatalytic efficiency. Furthermore, it emphasized the importance of nanostructuring in improving surface area and light absorption. This study provides a broader conceptual framework for understanding how semiconductor nanomaterials can be optimized for improved photoconductive performance through structural and electronic modifications.

Yu et al. (2010) investigated the preparation and photocatalytic activity of CdS/ZnS composite materials, emphasizing their enhanced performance under visible light irradiation. The study demonstrated that coupling CdS with ZnS significantly improves photocatalytic efficiency compared to pure CdS. This enhancement was attributed to effective charge separation facilitated by the heterojunction between CdS and ZnS. ZnS, having a wider bandgap, acts as a barrier that suppresses electron–hole recombination by transferring photogenerated electrons away from CdS. The authors also highlighted that the composite structure increases stability by protecting CdS from photocorrosion. Morphological analysis showed that nanoscale dispersion of ZnS on CdS surfaces enhances interfacial contact, which is critical for efficient charge transfer. These findings are highly relevant for photoconduction mechanisms, as improved charge separation and reduced recombination directly contribute to increased photoconductive response. The study underscores the importance of heterostructure design in optimizing the optoelectronic properties of CdS–ZnS nanocomposites.

Weller (2010) discussed the fundamental principles and applications of colloidal semiconductor quantum dots, with a focus on their size-dependent optical and electronic properties. The study



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emphasized that quantum confinement effects in nanocrystals lead to tunable bandgaps, making them highly suitable for photoconductive and photovoltaic applications. A key aspect highlighted was the role of surface states and ligands in determining charge transport and recombination behavior. The presence of surface defects can trap charge carriers, affecting photoconductivity either positively by increasing carrier lifetime or negatively by reducing mobility. The paper also discussed strategies for surface passivation to enhance stability and performance. In the context of CdS–ZnS nanocomposites, ZnS serves as an effective shell material that passivates CdS quantum dots, thereby improving photoconductive efficiency. This work provides essential theoretical insights into charge dynamics and the role of nanoscale engineering in controlling photoconduction in semiconductor nanocomposites.

Zhang et al. (2011) explored the visible-light-driven photocatalytic hydrogen production activity of CdS/ZnS nanocomposites. The study demonstrated that the formation of a heterojunction between CdS and ZnS significantly enhances photocatalytic efficiency by improving charge separation. The authors found that ZnS acts as a protective layer that suppresses photocorrosion of CdS while also facilitating electron transfer processes. The optimized nanocomposite exhibited higher hydrogen production rates compared to pure CdS, indicating improved photogenerated charge utilization. The study also highlighted that nanoscale interface engineering plays a crucial role in determining photoconductive and photocatalytic properties. Efficient separation of electron–hole pairs reduces recombination losses, which directly contributes to enhanced photoconductivity. Additionally, the work emphasized the importance of controlling particle size and morphology to maximize surface area and active sites. This research provides strong evidence that CdS–ZnS nanocomposites are promising materials for energy conversion and optoelectronic applications.

Challenges and Limitations

Despite the promising optoelectronic and photoconductive performance of CdS–ZnS nanocomposites, several challenges hinder their widespread application and commercialization. One of the primary concerns is the intrinsic toxicity associated with cadmium (Cd), which poses significant environmental and health risks during synthesis, handling, and disposal. Regulatory restrictions on Cd-based materials limit their use in large-scale industrial and consumer applications. Additionally, achieving precise control over composition, phase purity, and uniformity remains a technical challenge, particularly in chemical synthesis routes where slight variations in parameters can lead to inconsistent material properties. Another limitation is the presence of high defect densities and surface trap states in nanostructured systems, which can adversely affect charge carrier dynamics by increasing recombination rates and reducing photoconductive efficiency. Furthermore, issues such as particle agglomeration and poor adhesion in thin films can degrade device performance and long-term stability.



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From a device engineering perspective, stability and reproducibility are critical limitations. CdS–ZnS nanocomposites are susceptible to photocorrosion, especially under prolonged illumination and in ambient conditions, which leads to degradation of optical and electrical properties over time. Although ZnS incorporation improves stability, it does not completely eliminate degradation mechanisms. Another challenge lies in scalability and integration into practical devices, as maintaining consistent nanostructure quality over large areas is difficult. Additionally, interfacial defects and lattice mismatch between CdS and ZnS phases can create localized energy barriers that hinder efficient charge transport. The lack of standardized synthesis protocols and limited understanding of long-term reliability further complicate their application in commercial optoelectronic systems. Therefore, addressing these challenges through advanced material engineering, surface passivation strategies, and environmentally sustainable alternatives is essential for realizing the full potential of CdS–ZnS nanocomposites.

Conclusion

CdS–ZnS nanocomposites represent a highly promising class of materials for advanced optoelectronic and photoconductive applications due to their tunable band gap, enhanced charge transport properties, and synergistic structural advantages. The integration of CdS and ZnS at the nanoscale enables effective band alignment and improved charge separation, which are critical for achieving high photoconductive efficiency and optical performance. Various chemical synthesis routes, including chemical bath deposition, sol–gel, co-precipitation, and hydrothermal methods, offer flexible and cost-effective approaches for tailoring the structural and functional characteristics of these nanocomposites. Additionally, the incorporation of ZnS not only enhances stability and reduces photocorrosion but also contributes to improved optical transparency and reduced recombination losses. However, challenges such as cadmium toxicity, defect-induced recombination, stability issues, and scalability constraints must be carefully addressed to enable practical applications. Future research should focus on interface engineering, defect passivation, and the development of environmentally benign synthesis strategies to overcome these limitations. Furthermore, exploring doped and hybrid nanocomposite systems may provide new pathways for optimizing performance. CdS–ZnS nanocomposites hold significant potential for next-generation optoelectronic devices, provided that existing challenges are systematically mitigated through innovative material design and process optimization.



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