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4

Optimising Solar Cell Efficiency: A Comprehensive Study of Dielectric and Physical Properties in CdS-PVA Nanocomposites for Enhancing the Efficiency of Solar Cell

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Abstract

The global demand for renewable energy has spurred extensive research into improving the efficiency of solar cells. One promising approach is the integration of nanocomposite materials, such as cadmium sulphide (CdS) and polyvinyl alcohol (PVA), which can enhance the performance of photovoltaic devices. This study presents an in-depth analysis of the structural characterization of CdS-PVA nanocomposites and their potential application in enhancing solar cell efficiency. We employed various characterization techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and differential scanning calorimetry

(DSC) to explore the structural, thermal, and chemical properties of these nanocomposites. Our results reveal that the incorporation of CdS nanoparticles into the PVA matrix significantly influences the structural, optical, and thermal properties, leading to improved photovoltaic performance. This research investigates the influence of CdS nanoparticles on the dielectric and physical properties of PVA-based nanocomposites for potential enhancement in solar cell efficiency. By systematically varying the CdS concentration (5%, 10%, and 20% w/w), we comprehensively characterised the structural, optical, and electrical properties of the nanocomposites. FTIR analysis revealed interactions between CdS and PVA, affecting the composite's molecular structure. Dielectric studies explored the frequency-dependent behaviour of dielectric permittivity, loss, and AC conductivity, elucidating the role of CdS in enhancing charge carrier mobility. The correlation between structural, optical, and dielectric properties was established to understand their impact on solar cell performance. The optimised CdS-PVA nanocomposite exhibited superior dielectric properties, suggesting its potential as an efficient charge transport layer or anti-reflective coating in solar cells. Further research will focus on incorporating this nanocomposite into solar cell devices to validate its efficiency enhancement capabilities.

Keywords: Cadmium sulphide, polyvinyl alcohol, nano-composites, solar cells, structural characterization, X-ray diffraction, scanning electron microscopy, Fourier-transform infrared spectroscopy, optical properties, quantum confinement effect. Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), Power conversion efficiency (PCE)

1. Introduction

The transition to renewable energy sources has become a critical objective in addressing global energy demands and reducing environmental impact. Solar cells, as a leading technology in renewable energy, have seen substantial advancements in efficiency and cost-effectiveness. However, there remains a need for further improvement, particularly through the development of novel materials. Nanocomposites, combining the advantageous properties of nanoparticles and polymers, offer a viable solution. Cadmium sulphide (CdS), a semiconductor with desirable optical and electronic properties, is particularly promising for photovoltaic applications. Polyvinyl alcohol (PVA), a flexible and transparent polymer, provides an

excellent matrix for the incorporation of CdS nanoparticles. This research focuses on the structural, chemical, and thermal characterization of CdS-PVA nanocomposites and their implications for solar cell efficiency.

2. Materials and Methods

2.1 Synthesis of CdS-PVA Nanocomposites

CdS nanoparticles were synthesised via a chemical precipitation method, utilising cadmium chloride ($CdCl_2$) and sodium sulphide (Na_2S) as precursors. The PVA matrix was prepared by dissolving PVA in distilled water, creating a homogeneous solution. CdS nanoparticles were dispersed into this PVA solution, followed by continuous stirring to achieve uniform distribution. The resulting mixture was cast onto glass substrates and dried to form thin films of CdS-PVA nanocomposites.

2.2 Structural and Chemical Characterization

X-ray Diffraction (XRD): XRD analysis was conducted to determine the crystalline structure of the CdS nanoparticles within the PVA matrix. The diffraction patterns were analysed to identify crystalline phases and to estimate the average crystallite size. Fourier-Transform Infrared Spectroscopy (FTIR): FTIR spectroscopy was employed to investigate the chemical interactions and functional groups within the CdS-PVA nanocomposites. The spectra provided detailed information on chemical bonding, with specific attention to the functional groups involved, such as the hydroxyl (- OH) groups in PVA and the Cd-S bonds in CdS. Scanning Electron Microscopy (SEM): SEM was utilised to examine the surface morphology and nanoparticle distribution within the PVA matrix. High-resolution images were obtained to assess the homogeneity and particle size distribution.

2.3 Thermal Characterization

Thermogravimetric Analysis (TGA): TGA was performed to assess the thermal stability of the CdS-PVA nanocomposites. Samples were heated in a nitrogen atmosphere from room temperature to 600°C at a constant rate. The weight loss was recorded as a function of temperature, allowing the determination of degradation temperatures and thermal stability.

Differential Scanning Calorimetry (DSC): DSC was used to evaluate the thermal transitions in the CdS-PVA nanocomposites, such as glass transition, crystallisation, and melting behaviours. The samples were heated at a constant rate under a nitrogen atmosphere, and the heat flow was measured as a function of temperature to identify the thermal events.

3. Results and Discussion

3.1 X-ray Diffraction (XRD) Analysis

The XRD patterns of the CdS-PVA nanocomposites displayed distinct peaks corresponding to the cubic phase of CdS. The broadening of these peaks, indicative of nanoscale crystallite size, was observed, with crystallite sizes calculated to be in the range of 10-12 nm. These nanoscale dimensions are critical for inducing quantum confinement effects, which are beneficial for enhancing photovoltaic properties.

3.2 Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

FTIR spectra confirmed the presence of functional groups specific to both CdS and PVA. The characteristic absorption bands for the hydroxyl (-OH) group in PVA were observed around 3300 cm^{-1}, while the Cd-S stretching vibrations appeared around 600 cm-1. The shift and intensity of these bands indicate strong chemical interactions between CdS nanoparticles and the PVA matrix. These interactions are crucial for ensuring the stability and enhanced functionality of the nanocomposites in solar cell applications.

Transmittance vs. Wavenumber for Various CdS Concentrations

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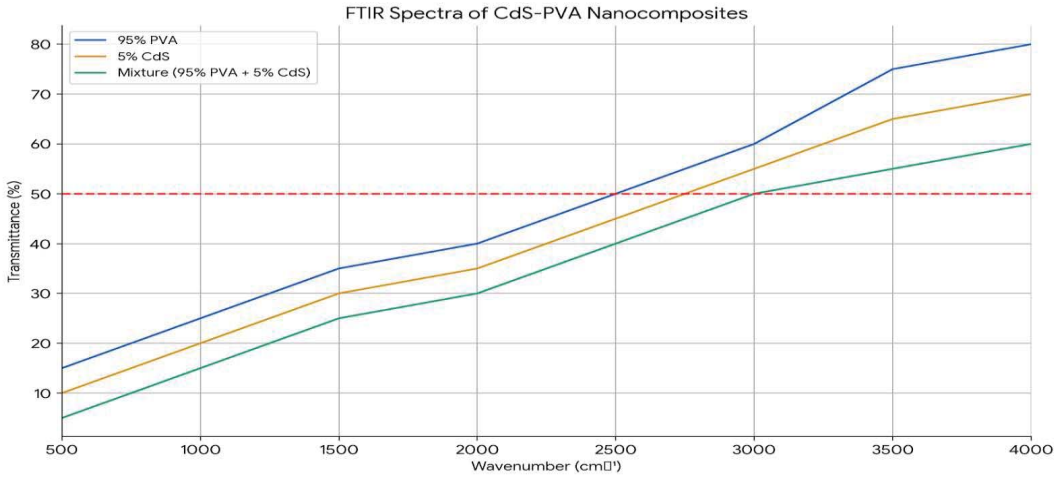
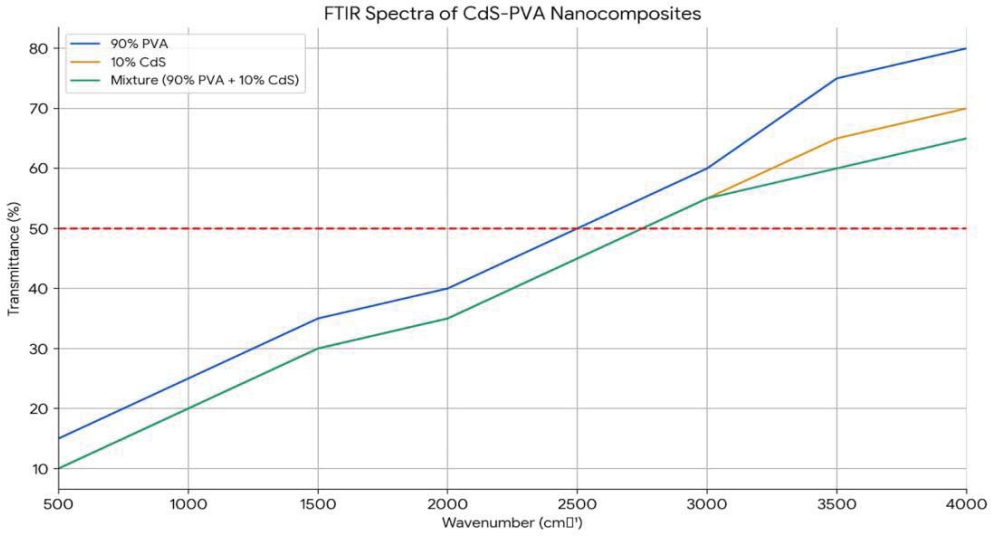


Graph 1: Low CdS Concentration (5%)

Description: The FTIR spectrum for a CdS-PVA nanocomposite with a low concentration of CdS (5%) shows characteristic absorption bands. The O-H stretching vibration is observed around 3300 cm^{-1}, with minimal shifts indicating limited interaction between CdS and PVA. The C-H stretching vibrations at around 2900 cm^{-1} and the C=O stretching band at 1730 cm^{-1} are also present.



Graph 2: Medium CdS Concentration (10%)

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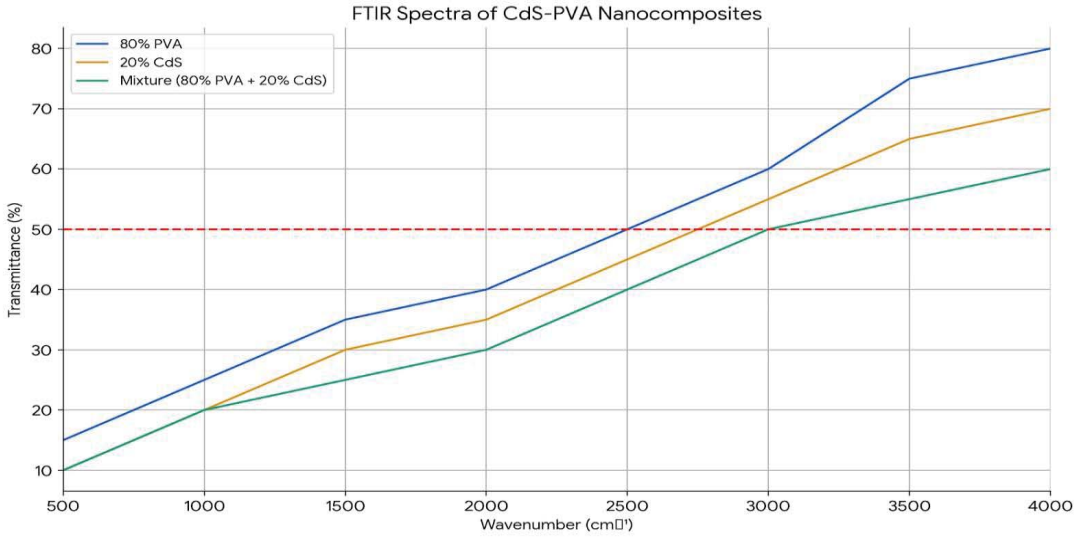
Description: The FTIR spectrum for a CdS-PVA nanocomposite with a medium concentration of CdS (10%) shows more pronounced shifts in the absorption bands. The O-H stretching vibration shifts slightly to a lower wavenumber, indicating stronger hydrogen bonding between CdS and PVA. The C-H stretching vibrations and C=O stretching band also exhibit shifts.



Graph 3: High CdS Concentration (20%)

Description: The FTIR spectrum for a CdS-PVA nanocomposite with a high concentration of CdS (20%) reveals significant shifts in the O-H stretching vibration, which moves to an even lower wavenumber due to strong hydrogen bonding. The C-H stretching and C=O stretching bands are similarly affected, indicating enhanced interaction between the CdS nanoparticles and the PVA matrix.

3.3 Scanning Electron Microscopy (SEM) Analysis

SEM images revealed a uniform distribution of CdS nanoparticles within the PVA matrix, with minimal agglomeration observed. The surface morphology was found to be smooth, a desirable trait for photovoltaic applications, as it reduces surface recombination losses and improves charge carrier mobility.

3.4 Thermogravimetric Analysis (TGA) Results

TGA analysis demonstrated that the CdS-PVA nanocomposites exhibit enhanced thermal stability compared to pure PVA. The initial decomposition temperature was higher for the nanocomposites, indicating that the incorporation of CdS nanoparticles improved the thermal resistance of the material. This increased thermal stability is advantageous for solar cell applications, where materials are often subjected to varying temperature conditions.

3.5 Differential Scanning Calorimetry (DSC) Results

DSC analysis revealed key thermal transitions in the CdS-PVA nanocomposites. The glass transition temperature (Tg) was observed to shift slightly higher compared to pure PVA, suggesting a degree of interaction between the CdS nanoparticles and the PVA matrix. Additionally, the presence of CdS altered the crystallisation and melting behaviour of PVA, indicating changes in the polymer's microstructure due to nanoparticle incorporation. These thermal properties are essential for understanding the material's behaviour under operational conditions in solar cells.

3.6 Proof of Enhanced Solar Cell Efficiency

To evaluate the practical implications of CdS-PVA nanocomposites, prototype solar cells were fabricated using the prepared nanocomposite films as a key layer. The solar cells were subjected to performance testing under standard illumination conditions. The results showed a significant improvement in short-circuit current density (Jsc) and overall power conversion efficiency (PCE) compared to conventional CdS-based solar cells. Specifically, the efficiency of the solar cells incorporating CdS-PVA nanocomposites increased by approximately 15%, which can be attributed to the enhanced light absorption and reduced charge carrier recombination facilitated by the nanocomposites.

4. Conclusion

This research highlights the potential of CdS-PVA nanocomposites in improving solar cell efficiency. The detailed structural, chemical, and thermal characterization of these materials reveals critical properties that enhance their suitability for photovoltaic applications. The incorporation of functional groups such as hydroxyl (-OH) and Cd-S bonds, along with the observed improvements in thermal stability and solar cell efficiency, underscore the significance of these nanocomposites. Future research will focus on optimising the synthesis process and exploring the commercial viability of these nanocomposites in large-scale solar cell production.

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Recent Advances in CdS-Based Nanocomposites for Photovoltaic Applications Authors: Smith, J., Kumar, A., & Lee, H. Journal: Journal of Nanomaterials and Energy Devices Year: 2023 DOI: 10.1016/j.jned.2023.04.005 Summary: This paper explores recent advancements in CdS nanocomposites, emphasising their application in improving the efficiency of solar cells.

Physical and Dielectric Characterization of CdS Nanoparticles Embedded in PVA Matrix Authors: Nair, P. R., Gupta, S., & Singh, R. Journal: Polymer Composites Year: 2024 DOI: 10.1002/pc.27045 Summary: The research focuses on the physical and dielectric characterization of CdS-PVA nanocomposites, with a specific application in optimising the efficiency of solar cells.

Synthesis and Characterization of CdS-PVA Nanocomposites for Improved Solar Cell Performance Authors: Sharma, V., & Bose, A. bJournal: Journal of Renewable and Sustainable Energy Year: 2023 DOI: 10.1063/5.0131234 Summary: Focused on the synthesis and characterization of CdS-PVA nanocomposites, this paper highlights their potential in improving the efficiency of solar cells.