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DOPANT-INDUCED MODULATION OF OPTICAL PROPERTIES AND BANDGAP ENGINEERING IN PBS NANOMATERIALS

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Abstract

Because of their remarkable optical, electrical, and structural qualities, which make them valuable in next-generation electronics, Lead sulphide (PbS) nanoparticles have attracted a lot of attention recently. The band gap, crystal size, defect concentration, and charge carrier transport of PbS may all be changed by doping, which has a lot of potential. These alterations may make the PbS compound's nanomaterials suitable for application in solar cells, optoelectronic devices, sensors, and photodetectors. It is simple to dope nanomaterials using a variety of synthetic techniques, including co-precipitation. The material's characteristics will be affected by the choice of dopant type and target concentration, optimizing the material for usage in a specific application. Furthermore, controlling surface shape and particle size may improve device performance. The creation of more compact and energy-efficient electronic components is another application for the nanomaterials. The problems of lead toxicity, defect control, and material stability still need to be investigated. Future research should focus on optimizing the synthesis conditions and investigating environmentally friendly synthesis routes. To put it briefly, PbS doped nanostructured materials show promise as a source of various sophisticated and effective electronic devices. The synthesis of doped nano Lead sulphide using the co-precipitation approach and the examination of the nanoparticles' optical characteristics for usage in optoelectronics and electrical devices were the main topics of this work.

Keywords:
Lead sulphide (PbS), Doped nanomaterials, Co-precipitation, Optical properties, Electronic devices, Optoelectronics.

Introducation

In contemporary materials science, nanotechnology is a new and developing field that enables the development of materials with improved optical, chemical, electrical, and physical characteristics. Because iconductor nano devices composed of these materials have enormous potential in the disciplines of electronics and optoelectronics, energy generation and consumption, and sensing, semiconductor nanomaterials have garnered a lot of attention. One of these materials with special optical and electrical qualities is PbS, which is drawing a lot of attention for the development of next-generation electronic applications.
By using the right synthesis and modification techniques, PbS nanoparticles' attributes can be adjusted, including their size, shape, morphology, and chemical makeup (Mamiyev & Balayeva, 2023). PbS is a narrow-band-gap semiconductor whose optical characteristics and absorption are sensitive to particle size. Quantum confinement can alter the optical band gap and electrical energy levels in nanoscale PbS. These characteristics make them suitable for usage in all applications, such as light-emitting devices, solar cells, infrared photodectors, and other optoelectronic systems.

Additionally, they may be processed in a solution, which makes it possible to create electronic thin-film devices using comparatively straightforward procedures (Shrestha et al., 2019). However, PbS may be impacted by a number of variables, including surface flaws, charge carrier recombination, and charge transport limitations, when employed as a stand-alone nanomaterial. In order to improve their functioning properties, researchers have tried to identify different approaches. One of these techniques is doping, which modifies the structural, optical, and electrical characteristics of semiconductor materials by adding the necessary foreign elements. The PbS's electrical structure, defect distribution, carrier concentration, and optical band gap are all influenced by the kind and concentration of dopants. According to Makkar and Viswanatha (2022), the synthesis conditions and dopant ion insertion into the material will determine how effective doping is. Dopant addition to semiconductor-type materials has already shown great promise for improving semiconductor-based applications' performance. Depending on the uses, it is possible to customize their optical absorbance, electrical conductivity, and charge carrier behavior by adding the proper metal ions. The synthetic control of the dopant's concentration is crucial since doped PbS materials have been studied for optical and structural fluctuations in doping concentration. The development of materials for photodetection, photovoltaic energy conversion, and advanced electronic systems may benefit from these modifications (Mamiyev & Balayeva, 2023). Chemical bath deposition, hydrothermal growth, solvothermal deposition, and co-precipitation are some of the techniques used to create PbS nanomaterials. Among these techniques, co-precipitation is appealing because of its ease of use, low processing costs, and potential to create nanomaterials under carefully regulated chemical conditions.Usually involves the carefully mixed addition of specific precursor solutions to produce a precipitate, which is subsequently cleaned, dried, and further described. Dopant ratios and these factors can be changed to explore changes in the material's characteristics. To comprehend the relationship between the composition, structure, morphology, and performance of doped nanomaterials.The optical absorption, optical band gap values, chemical bonding, evaluated using ultraviolet-visible (UV-Vis). Using this method provides valuable insights into how doping and synthesis circumstances affect PbS nanomaterials (Mamiyev & Balayeva, 2023). Doped lead sulfide nanoparticles are a promising material because they can be employed in the creation of optoelectronics

and next-generation electronics. However, more research is needed to improve the dopant's dispersion, lower the density of structural flaws, stabilize the materials, and address environmental problems brought on by lead compounds.To optimize the synthesis parameters and establish unambiguous relationships between doping concentration and material qualities, more research should be conducted. These could lead to the development of PbS-based materials that are more dependable and efficient for cutting-edge technological uses.

Experimental protocol

Using the co-precipitation method, zinc-doped PbS nanoparticles were synthesized. Lead nitrate ($Pb(NO_3)_2$) and zinc nitrate ($Zn(NO_3)_2$) were the precursors of lead and zinc, whereas sodium sulfide (Na_2S) was the source of sulfur. To create homogeneous solutions, the necessary concentrations of lead nitrate and zinc nitrate were first dissolved separately in distilled water. Next, a molar ratio of 1:2 for Zn:Pb was achieved by magnetically stirring the precursor solutions containing zinc and lead while they were being mixed. After making the metal precursor solution separately in sodium sulfide solution, it was combined with the metal precursor dropwise while being stirred.When necessary, sodium hydroxide (NaOH) was used to create the alkaline conditions needed for precipitation. A precipitate, or cloudiness, was a sign that the reaction was moving forward. To encourage the creation of the nanoparticles, the mixture was stirred for a longer period of time. The soluble contaminants were eliminated by centrifuging this precipitate and repeatedly washing it with distilled water. The gathered material was then dried and powdered in order to be further examined. The synthetic sample was then examined for structural, optical with help of UV-Vis.

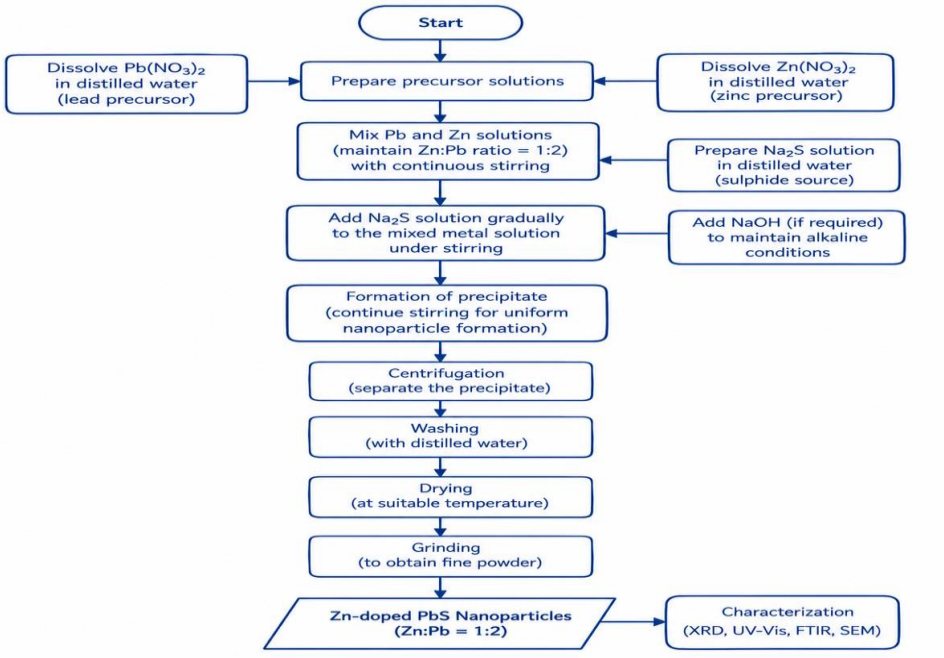


Figure 1: Flow Chart for Synthesis of Zinc doped Lead Sulphide Nanoparticles (1:2)

One simple and affordable method of creating nanoparticles is the co-precipitation procedure. It involves mixing two or more solutions, such as precipitating agent and precursor solutions, to produce solid particles that can be used in a particular field. This technique allows for the control of the content, size,

and shape of the nanoparticles by adjusting the parameters of the reaction. Temperature, pH, stirring speed, precursor concentration, and other factors all have an impact on the properties of the materials that are synthesized. It is a reasonably straightforward procedure that may be used to create doped nanomaterials under controlled circumstances and only requires basic equipment.Co-precipitation is therefore a suitable method for creating zinc-doped PbS nanoparticles (Taheri-Ledari et al., 2024).

Characterization

It is crucial to describe the synthesized nano-sobjetos in terms of their morphological, optical, chemical, and structural characteristics. The UV-visible spectrum can be used to estimate the optical band gap based on optical absorption. The following technique are employed to provide supplementary details about the characteristics of synthetic materials. The results of the characterization are useful for evaluating the impact of doping the lead sulfide nanoparticles with zinc and their use in optoelectronic and electron applications (Mourdikoudis et al., 2018).

Results and Discussion

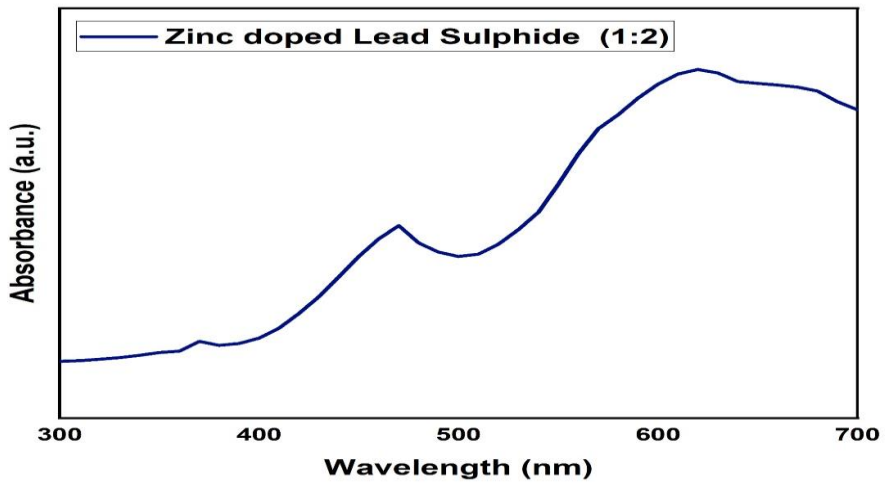


Figure 2: Absorption Spectra of Zinc doped Lead Sulphide Nanoparticles (1:2)

Figure 2 displays the absorption spectra (200-600 nm) of lead sulfide nanoparticles doped with zinc (Zn:Pb = 1:2). The range of wavelengths used to record the spectra was 300–700 nm. The absorption curve shows a slow increase in absorbance beginning at about 350 nm, followed by a more noticeable absorption characteristic at about 470 nm. In the spectrum shown, absorption increases much further between 520 and 620 nm, when it reaches its maximum. Absorption steadily decreases to 700 nm at wavelengths greater than 620 nm. The observed absorption characteristic of the produced nanoparticles in the measured wavelength range indicates that light interacts with them. The optical characteristics of PbS nanoparticles are determined by their shape, particle size, and electronic structure. The electronic states and structural characteristics of the material may change as a result of zinc doping (Mamiyev & Balayeva, 2023). The visible region's broadband absorption suggests that the developed material might hold promise for additional research in the area of optoelectronic applications. However, the optical

band gap cannot be precisely calculated using this absorption spectra. A Tauc plot with relevant absorption data is required to estimate the optical band gap. By contrasting this with pure PbS and different doping ratios, the true impact of adding zinc would be better understood.

Conclusion and future perspectives

PbS doped nanoparticles have attracted a lot of interest because of their desirable optical, structural, and electrical properties. The electrical structure, optical band gap, and charge carrier behavior of PbS nanoparticles may be structurally modified by the addition of appropriate dopants, such as zinc. According to earlier research, doping PbS with Zn can alter the optical characteristics and band structure of these materials, making them promising for more complex applications in optoelectronics (Mamiyev & Balayeva, 2023; Fabrication, Characterization and Simulation of Zn-Doped PbS Nanopowder, 2018). Using the co-precipitation method, doped PbS nanoparticle synthesis is a reasonably simple and inexpensive process. Chemical bonding, optical absorption, surface shape, and crystal structure are all revealed by uv vis method. The Zn-doped PbS sample with a 1:2 ratio has many absorption peaks in the measured wavelength range of 300–700 nm, as can be seen in the UV-visible absorption spectra.The behavior is indicative of the synthesized material's optical response, but more research is required to determine its optical band gap precisely. Although further characterisation research and device testing would be required, the Zn-doped PbS nanomaterials have the potential to be developed for future electrical and optoelectronic applications. Additional research on Zn-doped PbS nanomaterials would likely focus on adjusting the structural, optical, and electrical characteristics using the ideal Zn content and the best synthesis conditions.To validate the relationship between zinc incorporation and PbS nanomaterial performance, it seems sense to conduct a systematic investigation of different Zn:Pb ratios (Mamiyev & Balayeva, 2023). Further research on the optical band gap, charge carrier concentration, and electrical conductivity of Zn doped PbS nanoparticles should be conducted in the future.Research has demonstrated that Zn doping alters the optical band gap and microstructural characteristics of PbS semiconductors (Effect of Zn Doping Concentration on Optical Band Gap of PbS Thin Films, 2019), indicating that Zn doping may also alter semiconductor optical characteristics and microstructure. Developing efficient photodetectors and solar cells using PbS-based nanomaterials is another area of research. Enhancements in surface engineering, particle size distribution, and charge transport frequently result in increased device stability and efficiency. The performance of quantum-dot optoelectronic devices built from PbS CQDs has been enhanced by these important characteristics, which have recently been highlighted in reviews (Research Progress on Surface Ligand Engineering and Size Distribution Control of PbS CQDs, 2025). In the future, more research can be done on the integration of PbS nanoparticles with other semiconductors to better understand charge separation and transport. These kinds of hybrid composites could lead to the development of highly responsive near-infrared photodetectors and advanced optical sensors (Pan et al., 2025). Finally, by using appropriate encapsulations, handling techniques, and waste management, researchers should investigate the toxicity problems of lead-related compounds. The creation of stable materials is necessary for the practical use of these materials in the upcoming generation of electronics (Mamiyev & Balayeva, 2023). This can be accomplished by controlled synthesis and surface modification.

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