**Dependence of structural and optical properties of the Ternary Semiconductors on preparation techniques**

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**Abstract**

Ternary compounds find extensive application in the production of solar cells. This review focuses on the optical characteristics of semiconductor compounds such as pure and doped ZnS, CdZnS, and PbZnS, examining their synthesis mechanisms and the effects of different dopants. The nature of dopants, the incurred structural modifications and change in energy bandgap are reasoned. The effect of synthesis mechanism and annealing temperature on grain size, that further controls the optical properties, are explained. Although co-precipitation method is predominantly used by most of the researchers because of its energy efficiency, simple and quick preparation method, ease of handling particle size, other important synthesis mechanisms like co-precipitation method, solid-state reaction method and solvothermal methods are also discussed elaborately. Various collected nanoparticles data reveals that the bandgap varies from 2eV to 4.5eV and higher bandgap materials are preferred for window materials in solar cell applications.

**Key words:** Solar cell; Ternary Semiconductor; Energy gap; Electro-negativity.

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**1. Introduction**

According to the second law of thermodynamics, the available energy of the universe decreases continuously, so it is essential to focus on non-conventional energy sources. The best alternative for normal energy is solar energy, because of its abundant availability throughout the globe. The main challenge is how to convert this solar energy into useful energy. For this purpose, researchers put their focus on the materials, which effectively change solar energy into conventional energy. A solar cell is a device designed to convert solar energy into electrical energy. Operating on the principle of the photoelectric effect, solar cells, also known as photovoltaic (PV) cells, function by absorbing photons that impact the surface of a target material. During this process, the energy from the incident photons is completely transferred to electrons within the material's valence band. This energy is adequate to elevate the electrons to the conduction band, resulting in the release of free electrons. These liberated electrons are responsible for generating electric current within the circuit. The material targeted by photons can be either a semiconductor or a conductor. Notably, in insulators, the energy band gap separating the valence band and the conduction band is typically quite large, often exceeding 6 electron volts (eV).Generally, the photons from the sunlight do not possess this amount of energy to stimulate the electrons from the valence to conduction band for such insulators. Whereas, in conductors, these bands almost overlap with each other and hence a greater number of free electrons can be made available using solar energy photons. These free electrons alone cannot establish current unless they are forced to move in one direction in the circuit, which thus requires an external electric field. However, in case of semiconductors, the gap between the valance band and conduction band is less than those of insulators which photons of UV/visible spectrum can do the task of exciting the electrons. Further, due to the presence of a pn-junction, there is a small electric field present within the semiconductors due to the partial recombination of electrons and holes, which acts as a driving force for the free electrons, that is the reason why semiconductors are used in PV cells.

An ideal solar cell has a band gap value of 1.4 eV to absorb the maximum number of photons from the solar radiation [1]. The energy of photons in the solar spectrum ranges from 3.54 eV to 1.45 eV. So, while designing the solar cell, two factors are crucially considered: the absorption of as many photons as from the incident radiation and the minimization of material cost. Binary semiconductors are economically cheaper, but the main limitation of such materials is its discrete energy gap. Whereas, ternary compounds, which are though relatively costlier, tailoring of band gap energy is possible with [2-5]. For this reason, ternary compounds are widely used in the making of solar cells and photovoltaic devices. The widely used ternary semiconductor materials are Cadmium Zinc Sulfide (CdZnS) and Lead Zinc Sulfide (PbZnS) [6-16]. ZnS shows enormous optical transparency in the whole spectral range from UV to IR [17]. It is an environment-friendly, low priced, thermally and synthetically stable material [18], but the major limitation is its poor electrical conductivity. For this purpose ZnS is mixed with either CdS or PbS to enhance its electrical conductivity. Improvement in electrical and optical properties can also be obtained by doping CdZnS and PbZnS with Sm, Na, Cu, Mg metal ions [19-24]. Doping with different ionic radii metal ions results in structural modification which is responsible for the observed changes in the optical and other transport properties. In addition to doping, synthesis mechanism and annealing temperature also play significant roles in the modification of optical and other properties. Moreover, annealing temperature also affects the grain size, which leads to notable change in band. Considering all these above facts, the objective of this paper is to review the optical properties in connection with structural modifications of pure and doped CdZnS and PbZnS ternary semiconductor compounds, synthesized using different synthesis mechanisms and various dopants.

 **2. Synthesis Methods**

Ternary semiconductor compounds can be synthesized using various techniques, including the Co-precipitation method, solid-state reaction method, and solvothermal method, among others. Each method presents its unique set of advantages and drawbacks. Furthermore, the choice of preparation method influences the structural and morphological characteristics of the compounds, thereby altering their optical properties. In the following sections, we outline some of these synthesis methods along with their significant features, advantages, and limitations.

**2.1 Co-precipitation method:**

In this method, the starting materials are usually nitrates/acetates/sulfides/oxides of the elements, which dissolve easily in water and get mixed well, producing a homogeneousness solution. The Co-precipitation (CP) method is simple, takes less time and easy in terms of controlling the particle size and compositions. It has several ways to adjust the surface and homogeneous state of the solution and does not need any carbon-based solvents. The only drawback of this method is the management of its toxic unused liquid waste during the synthesis process.

For the synthesis of ZnS and Pb-doped ZnS compounds using the CP method [25-26], the procedure involves several steps. Initially, lead acetate, Zinc acetate, iron, Thiourea sodium sulfide, and citric acid are combined in stoichiometric proportions and dissolved in deionized water to create 1M solutions. This solution mixture is then subjected to continuous stirring. Triethanolamine (TEA), acting as a complexing mediator, is introduced into the solution mixture. Following this, Ammonium hydroxide is added gradually while maintaining constant stirring to adjust the pH value to 10. The solution is then heated to 70 ºC with constant stirring until the color of the solution changes, indicating the formation of grey precipitates. The resulting precipitate is further heated for 3 hours. Subsequently, the dried precipitate is subjected to calcination for 2 hours at 300 °C in a nitrogen atmosphere within a furnace. To achieve uniform particle size, the dried precipitate is thoroughly ground into a fine powder.

**2.2 Solid-State Reaction method:**

The solid-state reaction method is predominantly utilized for synthesizing both single crystalline and polycrystalline compounds. It is a low-cost method; easy process and it is an appropriate method for the large-scale production in industries. This method requires high temperature as compared to other chemical methods which is the limitation of this method [27]. For the synthesis of ZnS and Ni (0.5–2.0 at. %) doped solution mixtures by solid state reaction method, the starting materials used are, Zn(CH3COO)2.2H2O, NiCl2 and thiourea, which are taken in a mortar and are ground thoroughly, along with acetone mixing for every 30 minutes to get a homogeneous mixture. After which, the compounds are calcined for 4 hours at 400 °C in nitrogen atmosphere in a furnace. Following calcination, the powder is subjected to multiple washes with de-ionized water to eliminate impurities thoroughly. Subsequently, it is dried in a hot air oven at 100 ºC until completely dry.

**2.3 Solvothermal method:**

The solvothermal method is a versatile approach employed in the synthesis of various materials, including conductors, semiconductors, ceramics, and polymers. This process entails the utilization of a solvent under moderate to high pressure (typically ranging between 1 atm and 10,000 atm) and temperature (typically falling between 100 °C and 1000 °C), facilitating precursor interactions during synthesis [28].In the case of ZnS preparation, precursors such as zinc chloride, ethylene glycol, and thiourea are dissolved in distilled water under continuous stirring. After a brief period, polyvinylpyrrolidone (PVP) is introduced into the solution while stirring persistently. The resulting mixture is then transferred to an autoclave and calcined at 200°C for 5 hours within a furnace. Following centrifugation of the precipitate at a high speed of 12,000 rpm, it undergoes washing with de-ionized water and ethanol. Subsequently, the precipitate is dried in a hot air oven at 100 ºC and ground into a fine powder.

Co-precipitation (CP), solid state and solvothermal are some of the methods used for ZnS and CdS nanoparticles, out of which CP method is predominantly used by most of the researchers, because of its energy efficiency, several possibilities to change the particle surface and overall homogeneity. In addition to these, its simple and quick preparation technique and ease of control of particle size, are some major factors which favour the use of co-precipitation method over other methods.

 **3. Structural characterization:**

Significant research efforts have been directed towards exploring various synthesis techniques, temperature treatments, and doping methods aimed at mitigating secondary phases and enhancing structural transformations in ternary semiconducting compounds. The findings of several studies in this area are reviewed in the following paragraphs.

 The pure ZnS compound, prepared by CP method [26], has shown a hexagonal structure with lattice constants, 3.86A$°$ and 6.24A$°$. The Pb-doped ZnS with the compositional formula Zn1-xPbxS (x= 0 to 0.4), synthesized by CP method [26] and sintered at 800˚C for 2 hours rapidly have also retained hexagonal structure. XRD pattern confirms the formation of the single-phase structure, no secondary peaks are seen as observed from figure-1 which confirms Pb2+ ionsare well substituted in the ZnS lattice. With the increase in the concentration of Pb in ZnS, lattice parameters has increased due to the ionic radius inequality between Pb2+(1.19A$°$)and Zn2+ (0.72A$°$). Similar ******compounds prepared through solid state method have also produced similar results.

 ***Fig. 1. XRD patterns of Pb-ZnS samples(taken from Ref.26)***

Samples of Pb1-xZnxS (where x=0, 0.1, 0.2, 0.3, 0.4), synthesized via the CP method, exhibit cubic symmetry in their crystal structure. An increase in lattice parameters is observed with higher Zn concentration, likely attributable to the incorporation of Zn ions into interstitial positions within the lattice. The lattice constants show a consistent increase from 5.92 Å to 5.95 Å as the dopant concentration increases from x=0.1 to 0.5. Additionally, according to Vasudeva Reddy et al. [15], the crystallite size decreases with increasing Zn concentration.In the case of Cd0.8Zn0.2S semiconductor compounds doped with Sm3+ (at concentrations of 0.01, 0.02, 0.03, 0.04, and 0.05), prepared via the CP method, a polycrystalline hexagonal phase is observed. No diffraction peaks in the XRD pattern correspond to any impurity phase [22]. Furthermore, nanoparticles of Al-doped ZnS (Zn1-xAlxS) with varying Al concentrations (x=0.00, 0.02, 0.04, 0.06, 0.08, and 0.10), synthesized using the CP method, exhibit a cubic structure without secondary peaks. The decrease in lattice parameters with doping is attributed to the larger ionic radius of Zn2+ (0.74 Å) compared to Al3+ (0.51 Å). The lattice parameter (a) of x=0.00, 0.02, 0.04, 0.06, 0.08 and 0.10 are found to be 6.109, 6.098, 6.092, 6.069, 6.062 and 6.054 Å respectively [29]. In Fe2+, Co2+, Ni2+doped ZnS compounds [30], synthesized by solvothermal method with low dopant concentrations (1%), employing polyvinyl pyrrolidone (PVP) as a capping agent, the structure is found to be of cubic symmetry at room temperature. With doping the structure of nanoparticles remains to be cubic but the size of nanoparticle is reduced.

In Ni-doped ZnS samples, the lattice parameters decrease with an increase in Ni concentration due to the smaller ionic radius of Ni (0.69 Å) compared to Zn (0.74 Å) [31]. Co-doping of Li3+ and Nd3+ on the structure of L-arginine-passivated ZnS nanoparticles, synthesized via the chemical CP method, reveals a hexagonal structure in the XRD results, with nanoparticle sizes ranging from 4.6 to 1.8 nm and an average size of 3 nm, as confirmed by HR-TEM. As the co-dopant concentration increases, the size of the ZnS nanoparticles decreases. No diffraction peaks corresponding to the co-dopant Nd3+ are observed, resulting in broadened peak widths due to the loss of long-range order relative to the bulk. The broadening of peaks is also attributed to lattice strain [32]. For the co-doped ZnS compound Zn1-xCoxS (where x=0, 0.1, 0.2, 0.3), synthesized by the CP method, the XRD pattern reveals a single-phase cubic structure with complete solubility of Co in ZnS. The ionic radii of Co2+ and Zn2+ are 0.72 Å and 0.74 Å, respectively [33]. Similarly, cobalt (0, 1, 5, and 10%)-doped ZnS nanoparticles, prepared through the solvothermal method, also exhibit a cubic phase. While undoped ZnS has a lattice constant of 5.38 Å, co-doped ZnS with 1%, 5%, and 10% cobalt doping show lattice constants of 5.36 Å, 5.34 Å, and 5.31 Å, respectively. The decrease in lattice parameters may be attributed to the strain induced in the ZnS lattice with the insertion of Co ions [28].

Similarly, nanoparticles of Cr-doped ZnS compound Zn1-xCrxS (where x=0.00, 0.01, 0.03, 0.05, 0.07) are synthesized using the CP method with thioglycerol employed as the capping agent. The XRD analysis confirms the presence of a Zinc blende structure without any secondary phase, indicating the substitution of Zn by Cr ions within the ZnS lattice. The reduction in lattice parameter is attributed to the smaller ionic radius of Cr (0.63 Å) compared to that of Zn (0.74 Å) [34].In another investigation, Cr-doped Zn1-xCrxS nanoparticles with varying concentrations of x=0.00, 0.005, 0.01, 0.02, and 0.03 are synthesized through the CP method, revealing a cubic structure. With increasing Cr concentration, the average crystallite size decreases, ranging between 6 and 10 nm. The lattice parameters of Zn1-xCrxS nano powders, derived from XRD data, exhibit a narrow decrease from 5.4 to 5.2 Å with rising Cr content [35].Furthermore, pure CdS nanoparticles synthesized via the CP method exhibit a single-phase hexagonal structure according to XRD analysis. The lattice parameters are determined as a= 4.143 Å and c= 6.719 Å [36].

L S Devi et al. investigated Mn-doped CdS (with X=0, 0.02, 0.04, 0.06, 0.08, 0.1) compound synthesized via the CP method, revealing a cubic structure. The lattice parameters were determined as 5.729 Å, 5.723 Å, 5.717 Å, 5.721 Å, 5.693 Å, and 5.726 Å for the samples doped with 0%, 2%, 4%, 6%, 8%, and 10% Mn, respectively. The evaluated crystallite size of CdS nanoparticles doped with varying concentrations of Mn2+ ranged from 3.3 to 2.3 nm [37]. Thambidurai et al. observed Cr-doped CdS nanoparticles synthesized through the CP method, with X-ray diffraction analysis revealing a hexagonal structure. The average particle size of the nanoparticles fell within the range of 2.2 to 3.8 nm. Although doping Cr into CdS did not induce any structural phase transformation, the lattice constant values exhibited a decrease due to the smaller ionic radii of Cr (0.63 Å) compared to Cd²+ (0.96 Å) [38].

In the investigation of the Cd0.8-XPbxZn0.2S semiconductor compound synthesized via the CP method, X-ray diffraction (XRD) results unveiled the presence of both cubic and hexagonal phases within the compound. Specifically, hexagonal peaks were exclusively observed in the Cd0.8-XPbxZn0.2S compound with x=0, while mixed crystals with x=(0.1-0.6) exhibited both hexagonal and cubic phases. Samples with x=0.7 and 0.8 displayed only peaks corresponding to cubic phases. Overall, the Cd0.8-XPbxZn0.2S compounds undergo a crystalline transition from hexagonal to cubic, indicating a structural change from lower symmetry to higher symmetry. The hexagonal structure of the Cd0.8-XPbxZn0.2S compound is attributed to major peaks arising from reflections of (100), (002), and (101), while the face-cantered cubic structure of PbS is assigned to major peaks from planes (111) and (200). Additionally, the average crystalline size in Cd0.8-XPbxZn0.2S compounds decreases with an increase in Pb content [39].

G. Yellaiah et al. observed Sm-doped Cd0.8Zn0.2S compound with varying amounts of samarium (0.01, 0.02, 0.03, 0.04, and 0.05 M), synthesized using the CP method, where the XRD pattern exhibited a single phase with a hexagonal structure. The average crystallite size of the compound was found to range between 40 and 90 nm [20]. Similarly, G. Yellaiah et al. investigated Na-doped Cd0.8Zn0.2S compound with different concentrations of samarium (0.00, 0.03, 0.1, 0.2, and 0.3), synthesized via the CP method, revealing a single-phase hexagonal structure. The average crystallite size of the compound ranged from 29 to 55 nm [19].

The discussed structural results in correspondence to the synthesis methods, are tabulated in table 1.

**Table 1: Different synthesizing methods used to prepare various compounds and their structures**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S. No** | **Compound** | **Synthesis method** | **Heating conditions** | **structure** |
| 1 | Zn1-XPbXS [26] | Co-precipitation method | Subjected to a 2-hour calcination process at 300°C / sintered at 800°C for 2 hours. | Hexagonal |
| 2 | Zn1-XCrXS [35] | Co-precipitation method |  In oven for 50 ˚C for 4 h  | Cubic |
| 3 | Al doped ZnS [29] | Co-precipitation method | Kept in an oven at 60°C for a duration of 6 hours. | Cubic |
| 4 | (Fe, Ni, Co) doped ZnS [30] |  Solvothermal method | Heated in furnace at 200 ˚C for 5 h | Cubic |
| 5 | Mn doped CdS [37] | Co-precipitation method | Dried at 60 ˚C for 24 h | Cubic |
| 6 | Cr doped ZnS [34] | Co-precipitation method | Dried at 60 ˚C for overnight | Cubic |
| 7 | Li, Nd doped ZnS [32] | Co-precipitation method |  Dried at 40°C for a duration of 16 hours. | Hexagonal  |
| 8 | Cr doped CdS [38] | Co-precipitationmethod  | Dried at 100 ˚C for 4 h | Hexagonal |
| 9 | Pb1-xZnxS [15] | Co-precipitation method  | Calcined sm0˚C for 2h /sintered at 800˚C for 2 h | Cubic |
| 10 | Sm doped Cd0.8Zn0.2S [22] | Co-precipitation method | Calcined 300 ˚C for 2h /sintered at 800 ˚C for 2 h | Hexagonal  |
| 11 | Ni doped ZnS [27] | solid state method | Calcined at 400 °C for 4 h | Cubic |
| 12 | Co doped ZnS [33] | Solvothermal | Heated 180◦C for 10 hours | Cubic |
| 13 | CdS [36] | Co-precipitation method | Heated at 300 °C for 2h | Hexagonal |
| 14 | Smdoped Cd0·8Zn0·2S [20] | Co-precipitation method | Calcined 300 ˚C for 2h /sintered at 800 ˚C for 2 h | Hexagonal |
| 15 | Na doped Cd0·8Zn0·2S [19] | Co-precipitation method |  Calcined 300 ˚C for 2h /sintered at 800 ˚C for 2 h | Hexagonal |
| 16 | Co doped ZnS (28) | Co-precipitation method | Calcined 300 ˚C for 2h in vacuum |  Cubic |

**4. Optical Properties:**

 The band gap of pure ZnS compound, synthesized through the CP method and investigated by Vasudeva Reddy et al [26], is measured at 3.6 eV. Upon introduction of Pb doping, the energy gap shifts from 3.6 eV to 2.9 eV. As the concentration of Pb increases, the energy gap decreases progressively. This phenomenon can be attributed to the comparatively weaker binding force of Pb in comparison to Zn. Thus, less energy is required to disrupt the bond in Pb-doped ZnS compounds.

 T. Shekharam et al. investigated the optical characteristics of Cd0.8−xPbxZn0.2S compounds (with x values ranging from 0 to 0.8) synthesized via the CP method. The optical absorption spectra of these compounds were observed within the wavelength range of 496–508 nm. The corresponding energy gap values ranged from 2.55 to 4.43 eV. Notably, as the concentration of Pb increases, there is an observed increment in the band gap values [39].In a separate study, D. Amaranatha Reddy et al. [40] examined Zn1−xCrxS compounds with various Cr concentrations (x=0.00, 0.005, 0.01, 0.02, and 0.03), revealing band gap values ranging from 3.81 eV to 4.03 eV. These values escalate with increasing Cr concentration. Both pure and Cr-doped ZnS nanoparticles exhibit widened band gaps compared to bulk ZnS (3.6 eV). Additionally, the particle size decreases in Cr-doped ZnS, and the absorption peak shifts towards lower wavelengths, indicating the formation of new energy levels within the ZnS band structure due to Cr doping.Furthermore, Namrata Dixit et al. explored the optical properties of Ni+2-doped ZnS compounds synthesized via the CP method. It was observed that as the Ni doping concentration increases, the band gap values decrease from 4.43 eV (for pure ZnS) to 4.29 eV (for Ni-doped ZnS). The synthesized nanoparticles exhibit widened band gaps compared to bulk ZnS (3.68 eV). The absorption spectrum of Ni2+-doped samples is observed between 285 and 290 nm, whereas undoped ZnS exhibits absorption at 280 nm. Additionally, the intensity of absorption decreases with increasing dopant concentration [41].

 Various ZnS-based compounds, including ZnS, Zn0.97Mn0.03S, Zn0.97Cr0.03S, and Zn0.94Mn0.03Cr0.03S nanoparticles, were investigated by D. Amaranatha Reddy et al. These compounds were synthesized via the CP method. An optical absorption edge around 326 nm was observed for ZnS nanoparticles, representing a notable blue shift compared to the bulk material (338 nm). This shift was believed to result from the quantum size effect as the nanoparticle size approached the atomic scale. The absorption maxima for samples doped with Mn, Cr, and co-doped with Mn and Cr were detected at 313 nm, 308 nm, and 303 nm, respectively. The corresponding band gap value was found to be 3.81 eV. The energy gap values corresponding to these maxima were measured as 3.97 eV, 4.03 eV, and 4.09 eV, respectively [42]. In another study by D. Amaranatha Reddy et al. [29], the energy bandgap of Al-ZnS compounds synthesized via the CP method was examined. The observed bandgap values of the nanoparticles ranged from 3.73 eV to 4.01 eV, slightly higher than that of bulk ZnS (3.7 eV). Studies using Diffuse Reflectance Spectroscopy (DRS) revealed that the bandgap increased with increasing Al concentration. The observed blue shift was attributed to quantum confinement effects due to the nanoparticles' size (3-5 nm), which decreased with the increase in Al content. This phenomenon demonstrated a size-dependent blue shift in the DRS edge.

 The transition metal (Fe2+, Co2+, Ni2+) – ZnS compounds were synthesized using the solvothermal method. The optical properties of these materials were investigated by Z. Dehghani et al [30]. The energy bandgap values ranged from 3.92 to 3.49 eV. UV-Visible spectroscopy demonstrated a shift in the absorption edge towards lower wavelengths with the doping of Fe, Ni, and Co. Similarly, Devadoss et al. examined the optical properties of Cu-doped Cd0.9Zn0.1S compounds synthesized by a certain method. The position of the absorption edge of Cu-doped Cd0.9Zn0.1S shifted towards the lower wavelength side (a blue shift) as the doping of Cu increased from 0% to 2%. This observed absorption shift towards the lower side indicated the proper substitution of Cu2+ ions into the Cd2+ ions, confirming the quantum confinement effect [43]. Furthermore, R. Sanjeev Kumar et al. investigated the optical absorption spectra of undoped and Ni-doped ZnS. The absorption edge was observed around 320–340 nm, indicating a blue shift compared to that of bulk ZnS (345 nm), attributed to quantum size confinement. The measured bandgap was 3.82 eV for undoped ZnS, 3.70 eV for 3.3% Ni-doped ZnS, and 3.67 eV for 5.36% Ni-doped ZnS. It was observed that the band gap decreased with increasing Ni concentration. Additionally, the photoluminescence spectra showed a decrease in the intensity of photoluminescence emission with an increase in Ni concentration.

 G. Yellaiah et al. conducted a study on Sm-doped Cd0·8Zn0·2S nanocrystals synthesized through the CP method, analyzing their optical properties. The bandgap values exhibited a decrease from 3.18 to 2.52 eV with increasing Sm concentration. In a separate investigation, G. Yellaiah et al. explored the optical characteristics of Na-doped Cd0·8Zn0·2S nanocrystals, prepared via the CP method. The energy bandgap of undoped Cd0·8Zn0·2S was 2.58 eV, while Na doping increased it from 2.58 to 3.18 eV with rising dopant (Na) concentration.V. Laxminarasimha Rao et al. analyzed the optical absorption of Cu-doped ZnS, synthesized using the CP method, observing bandgap values ranging between 3.92 and 3.51 eV. They attributed the decrease in bandgap to its effect on atomic distance and grain size. Additionally, V. Laxminarasimha Rao et al. investigated the optical properties of Co-doped ZnS (x=0, 0.02, 0.04, 0.06, 0.08, 0.1) compounds, prepared through the CP method. They observed a monotonic decrease in bandgap values, from 3.91 to 3.62 eV, with increasing cobalt concentration. This reduction was associated with changes in band strength between ZnS and CoS, as well as alterations in atomic distances and grain size. Notably, for low concentrations of cobalt, the optical bandgap of the material shifted from 3.91 to 3.62 eV. Additionally, Sambasivam et al. reported on Co-doped ZnS compound Zn1-xCoxS (X=0, 0.1, 0.2, 0.3), synthesized through the CP method. They found energy bandgap values ranging from 3.78 to 3.93 eV, indicating an increase in bandgap with an increase in cobalt concentration. Some such studies on the optical properties are presented in table 2.

**Table 2: Compounds with the Energy gaps suitable for window materials in solar applications**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **S. No** | **Name of the Compound** | **Eg****(eV)** | **Reference** |  | **S. No** | **Name of the Compound** | **Eg****(eV)** | **Reference** |
| 1 | ZnS | 3.6 | [26] | 7 | ZnS | 3.78 | [33] |
| Zn0.9Pb0.1S | 3.5 | Zn1-xCoxS (x=0.1) | 3.81 |
| Zn0.8Pb0.2S | 3.3 | Zn1-xCoxS (x=0.2) | 3.85 |
| Zn0.7Pb0.3S | 3.0 | Zn1-xCoxS (x=0.3) | 3.93 |
| Zn0.6Pb0.4S | 2.9 | 8 | ZnS |  3.92 | [44] |
| 2 | Bulk ZnS | 3.68 | [41] | Cu0.02Zn0.98S | 3.88 |
| ZnS NP undoped | 4.43 | Cu0.04Zn0.96S | 3.85 |
| Ni(1.2%) - ZnS | 4.35 | Cu0.06Zn0.94S | 3.76 |
| Ni(2.5%) - ZnS | 4.34 | Cu0.08Zn0.92S | 3.67 |
| Ni (5.0%) - ZnS | 4.28 | Cu0.1Zn0.9S | 3.51 |
| 3 | ZnS | 3.92  | [30] | 9 | ZnS |  3.92 | [45] |
| Fe - ZnS | 3.8  | Co0.04Zn0.96S | 3.76 |
| Ni - ZnS | 3.64  | Co0.06Zn0.94S | 3.69 |
| C0 - ZnS | 3.49  | Co0.08Zn0.92S | 3.67 |
| 4 | Cd0.8 Zn0.2S | 2.55 | [46] | Co0.10Zn0.9S | 3.62 |
| Cd0.7Pb0.1 Zn0.2S | 3.16 | 10 | Cd0.8Zn0.2S | 2.58 | [19] |
| Cd0.4Pb0.4 Zn0.2S | 3.48 | Cd0.8Zn0.2S: Na0.03 | 2.80 |
| Cd0.2Pb0.6 Zn0.2S | 4.37 | Cd0.8Zn0.2S: Na0.1  | 2.70 |
| Cd0.1Pb0.7 Zn0.2S | 4.40 | Cd0.8Zn0.2S: Na0.2 | 2.83 |
| Pb0.8 Zn0.2S | 4.43 | Cd0.8Zn0.2S: Na0.3 | 3.18 |
| 5 |  Cd0.9Zn0.1S (Cu=0) | 3.79 | [43] | 11 | Cd0.8Zn0.2S  | 2.52 | [20] |
| Cd0.9Zn0.1S(Cu=2%) | 4.01 | Cd0.8Zn0.2S: Sm0.01 | 3.18 |
| Cd0.9Zn0.1S(Cu=4%) | 3.96 | Cd0.8Zn0.2S: Sm0.02 | 3.08 |
| Cd0.9Zn0.1S(Cu=6%) | 3.69 | Cd0.8Zn0.2S: Sm0.03 | 3.01 |
| 6 | ZnS | 3.82 | [31] |
| 3.30% Ni -ZnS | 3.70 | Cd0.8Zn0.2S: Sm0.04 | 2.87 |
| 5.36% Ni – ZnS | 3.67 | Cd0.8Zn0.2S: Sm0.05 | 2.82 |

**Conclusion:**

The bandgap values strongly depend upon the crystal structure of the material. Consequently, it depends on the synthesis conditions and the synthesis process. From the above analysis, it is found that energy bandgap of ternary semiconductor compounds varie from 0.6eV to 3.6eV, based on doping and the host material.Bandgap of 1.6eV is optimally desired for solar cell applications to have maximum efficiency. Thus, by virtue of larger band gap, the present reviewed ternary materials come under a very much suitable category for window materials in solar applications. Hence, these materials prove suitable for use in manufacturing electroluminescent devices and solid-state solar window layers.

Increasing bandgap lowers the conductivity of the semiconductor. So, these materials are not suitable for wide bandgap applications directly. Rare earth elements favour the electrical conductivity of the semiconductor compound so that study of rare earth dopants may be taken as future work on these ternary compounds.

**Conflicts-of-interest statement**:

 The authors declare no conflicts of interest. All co-authors have reviewed and approved the manuscript's contents, and there are no financial interests to disclose. We confirm that the submission represents original work and is not currently under review by any other publication.

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