Synthesis, Applications and Future perspectives of CdTe and CdS thin films: A Review

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Abstract:
Thin films refer to layers of material with a thickness ranging from a few nanometers to several micrometers. These films are used in a variety of scientific, technological, and industrial applications due to their unique properties. Thin films are fundamental to a wide array of technologies, and ongoing research continues to expand their applications and enhance their properties for future innovations. CdTe (Cadmium Telluride) and CdS (Cadmium Sulfide) thin films are a type of semiconductor material that is commonly used in various applications such as solar cells, photovoltaic cells, photodetectors, optical sensors, gas sensors, and electronic and optoelectronic devices. Due to the unique properties of CdTe and CdS thin films, researchers are now focusing their work on the synthesis and applications of CdTe and CdS thin films. CdTe is a compound semiconductor composed of cadmium and tellurium elements. While CdS is another compound semiconductor composed of cadmium and sulfur. This review paper encompasses a detailed study of CdTe and CdS thin films. It also provides brief information on pure and doped CdTe and CdS thin film fabrication, synthesis approaches and applications.

Keywords: Thin films, Cadmium Telluride, Cadmium Sulfide, photovoltaic cells, semiconductors.

1. Introduction:

Thin films play a significant role in the 21st century in advancing renewable energy sources, particularly in the field of solar energy. Thin film technologies offer unique advantages in terms of cost, flexibility, and scalability [1]. Thin film technologies often have a lower environmental impact compared to traditional solar cell manufacturing processes, particularly as they require fewer raw materials and energy during production. Researchers are exploring advanced materials and concepts, such as perovskite thin film solar cells, which have shown great promise in terms of efficiency and cost-effectiveness [1, 2]. The impact of technology on human beings and renewable energy sources is multifaceted, influencing various aspects of our lives, environment, and energy systems. Ongoing research and development in renewable energy technologies contributes to the discovery of new and more efficient ways to generate clean power [4]. Despite progress, challenges like energy storage limitations, intermittency issues, and the environmental impact of manufacturing renewable technologies need continuous attention. With the advancement of technology, there might eventually be an energy catastrophe on the planet. Resolving the global energy crisis requires the use of copious renewable energy sources, one of which is solar energy. Solar radiation is converted to electrical energy by solar cells. Recent studies have concentrated on utilising Cadmium Telluride (CdTe) and Cadmium Sulphide (CdS) heterojunction techniques to increase the efficiency of photovoltaic as well as solar cells. CdTe and CdS are both II-VI compound semiconductors with a direct band gap [5, 6]. At room temperature, the band gap of CdTe and CdS is approximately 2.42 electron volts and 1.72 electron volts, respectively. The band gap energy can be tuned by controlling the deposition conditions, making them suitable for different applications [6, 7]. CdTe and CdS exhibit good optical properties, with a wide range of transparency in the visible spectrum. CdS is commonly used as a buffer layer in thin-film solar cells [8]. CdTe has a high absorption coefficient for sunlight, allowing for the efficient conversion of photons into electrical energy. CdS thin films are used in the construction of photodetectors due to their sensitivity to light. CdS is incorporated into thin-film transistor structures for electronic devices. CdS thin films are doped with other elements to modify their electrical and optical properties. Continuous research is being conducted to improve the efficiency and stability of CdS thin films in various applications, especially in the field of solar energy [9, 10].

2. Literature review:

The highly efficient solar cell was designed from the start using CdS as the n-type partner in the junction creation process with the p-type CdTe absorber. A significant portion of the early research on solar cells focused on the development of the layers and the junction, but it quickly became apparent that the methods for depositing the absorber and creating the junction were not crucial. The CdTe/CdS layer stacks as-deposited required post-deposition treatment. Subsequently, the scientists directed their attention towards the remaining layers. Firstly, they enhanced the front-contact, considering transparency and chemical stability. Cadmium stannate (CTO), an extremely transparent and highly conductive substance, took the place of indium tin oxide (ITO), aluminum doped zinc oxide (ZAO), and fluorine doped tin oxide (FTO). Numerous fabrication facilities established in the 2000s attest to the fact that CdTe technology has reached a level of stability suitable for commercial development; at present, CdTe production capacity accounts for over seven percent of solar energy production worldwide. In this section various types of synthesis and fabrication methods of thin films of CdS and CdTe are explain according to previous work done be many researchers.

A green synthesis method for synthesized CdS quantum dots with a particle size of 2-4 nm was described by Shivaji et al. Tea leaf extract was used as a toxic-free particle-stabilizing agent. In order to produce CdS QDs biologically, an extract was mixed with a specific quantity of $CdSO_4$ and left in the dark for three days. Next, Na_2S was added, and the mixture was left for a further four days. After centrifuging and lyophilizing the bright yellow solution, more characterization investigations might be conducted. Finally, a well-diffusion experiment was used to demonstrate their antibacterial activity, and A549 cancer cells were used to illustrate the lethal effect of CdS quantum dots [11].

Sahay, P.P., et al [12] prepared CdS thin films by thermal evaporation technique at room temperature. The films were prepared on glass substrates. The vacuum of about 2×10^{-5} torr was used during preparation of thin films. Author reported that, the films were found to exhibit high transmittance (~ 60 - 93 %), low absorbance and low reflectance in the visible/near infrared region from ~ 500 nm to 1100 nm. The optical band gap energy was found to be in the range 2.28 – 2.53 eV. Author also studied the comparatively study of as deposited and annealed films at 300°C for 4 hours and reported that the annealing the films shows the decrease in the optical transmittance and optical band gap. Due to annealing the crystallinity of the films improves, resulting in decrease in the optical transmittance.

CdS thin films were produced onto glass substrates using the vacuum evaporation process by Senthil, K., et al. [13]. According to the author, prepared films primarily exhibit a hexagonal phase with small crystallites. RBS analysis reveals that the films have good stoichiometry. For the annealed films, a decrease in the band gap is seen. The rise in grain size is responsible for the reduction in band gap.

M.A. Mahdi et al. [14] Chemical bath deposition has been used to produce CdS thin films on glass substrates. A source of Cd^{+2} was cadmium acetate. Three sequences of deposition, a 100 nm CdS thin film is produced. The precise technique of chemical bath deposition, which is employed in this work, can be used to create stiochiometric CdS thin films. The thin films' structural analysis reveals that they have a single phase of hexagonal wurtzite as-deposited. While the hexagonal structure is more stable than the cubic structure in solar cells and other optoelectronic devices, other reported works that used the CBD approach to make CdS films obtained cubic structure or mixed phases, cubic and hexagonal. The thin films can be used as a window layer in solar cells because of their excellent transparency in the visible portion of the electromagnetic spectrum.

Ashour and colleagues et al. [15] thin films of cadmium sulfide (CdS) have been created using the chemical spray-pyrolysis method. The substrates were cleaned glass. The substrate temperature was adjusted between 200 and 400 °C, and it appears that this is one of the key factors influencing the semiconductor's physical characteristics. According to the authors, single-phase hexagonal CdS was present in the XRD patterns. It was noticed that the resistivity of the as-deposited films varied according to the substrate temperature, falling between 10^3 and 10^5 \Omega. Cm. Optical absorption experiments yielded direct band gap values between 2.39 and 2.42 eV.

CdTe thin films were created by Gordillo, G., et al. [16] by a novel process based on the close-spaced sublimation method. It was possible to construct an evaporation system based on the CSS approach. The ideal circumstances have been described, and the impact of various deposition factors has been examined. The findings of the authors indicate that the substrate and evaporation temperatures, as well as the pressure of the vapour formed by the separated species from the CdTe source in the reaction chamber, have a major impact on the electrical resistivity of the CdTe films. Tiny amounts of oxygen added to the reaction chamber can significantly lower the CdTe films' resistivity.

Thermally evaporated CdTe thin film electrical structure, structural characteristics, and optical properties were investigated by Lalitha, S., et al. [17]. The process of thermal evaporation was used to create thin films of CdTe on glass substrates. It is discovered through X-ray diffractogram analysis that the CdTe films are found to be polycrystalline nature.

Salaoru, I., et al. [18] studied heterojunctions were obtained by successive thermal evaporation under vacuum onto unheated SnO_2 coated glass substrates of CdS and CdTe films, respectively. The refractive, transmittance, extinction, and absorption coefficients were measured. The morphological and structural studies of the above mentioned heterojunction component films, in comparison with those of CdS and CdTe films, deposited separately, onto glass substrates, were carried out using transmission electron microscopy, X-ray diffraction and atomic force microscopy techniques.

3. Synthesis methods for CdTe and CdS nanoparticles

There are several ways to synthesis of CdTe and CdS nanoparticles, and each has benefits and drawbacks of its own. The required qualities of the nanoparticles and their particular use will determine which synthesis process is used. Finding new methods for the synthesis of CdTe and CdS nanoparticles as well as nanocomposites is the best way to control and modify the size and shape of the nanomaterials [20, 21]. These are fundamental challenges in material science because the size and shape of nanomaterials could reveal new and unknown characteristics. High-quality nanoparticles with the right sizes, shapes, and other structural features can be produced by adjusting the parameters involved in different synthesis techniques as well as the thermodynamics and kinetics conditions during synthesis [21, 22]. Fig. 1 shows that the summary of the various methods used for CdTe and CdS nanoparticles synthesis.

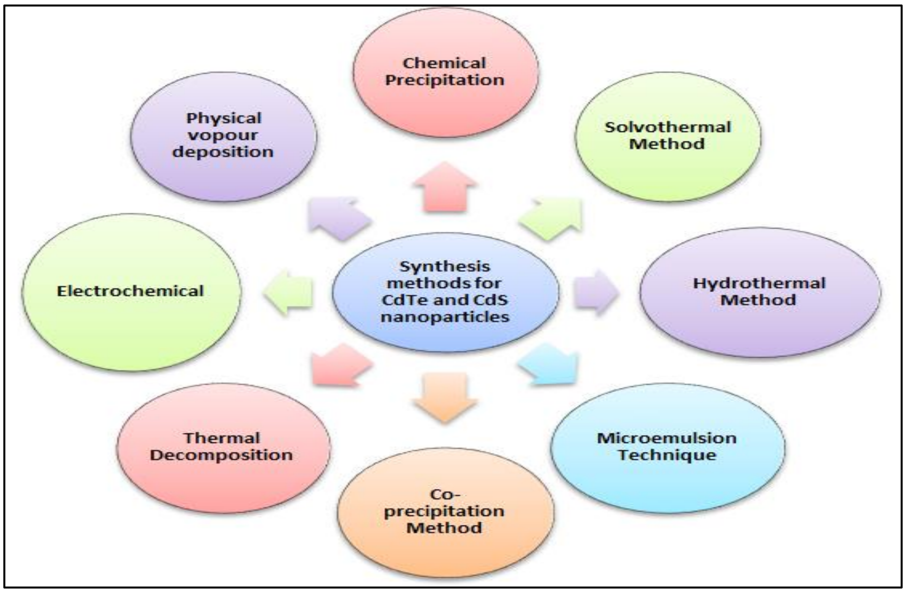

Figure 1: Synthesis methods used for CdTe and CdS nanoparticles

2. 1 Chemical Precipitation:

CdTe and CdS nanoparticles can be synthesized by chemical precipitation methods. In this method, cadmium ions are reacted with telluride or sulfide ions in a suitable solvent, leading to the formation of nanoparticles. The reaction conditions, such as temperature and pH, play a crucial role in controlling the size and morphology of the nanoparticles.

2. 2. Solvothermal Method:

Solvothermal synthesis involves the reaction of precursors in a high-temperature solvent under autogenous pressure. This method allows for the controlled growth of nanoparticles with well-defined shapes and sizes. The choice of solvent and reaction conditions influences the properties of the resulting nanoparticles. One of the best methods for synthesizing CdS NPs is the solvothermal technique. In this process, precursors react in a closed system with a solvent present at a temperature higher than the solvent's boiling point. The size and form of the result can be controlled by adjusting the processing parameters of the reaction system, which include the types of reactants and solvents, temperature, and time.

2. 3. Hydrothermal Method:

Similar to the solvothermal method, the hydrothermal method involves the reaction of precursors in water at elevated temperatures and pressures. This method is advantageous for producing highly crystalline nanoparticles with controlled sizes and shapes. The reaction time, temperature, and precursor concentrations can be tuned to achieve desired properties.

2. 4. Microemulsion Technique:

Micro-emulsion is an effective technique that produces a range of monodispersion NPs with different sizes and shapes. In essence, it is a thermodynamically stable, isotropic system comprising two immiscible liquids stabilised by a surfactant. Micro-emulsions are ideal for producing NPs because the surfactant-stabilized droplet phase can be viewed as a "nanoreactor" for synthesis. Surface tension causes all nanoreactors to be spherical, and they all equilibrate to the same size over time. Microemulsion involves the use of surfactants to form small droplets of water in an oil phase. CdTe or CdS precursors are introduced into these droplets, leading to nanoparticle formation. This method allows for good control over particle size and shape. Additionally, it provides a stable environment for the reaction.

2. 5. Co-precipitation Method:

In this method, both cadmium and tellurium or sulfur precursors are added simultaneously to a solution, leading to the co-precipitation of CdTe or CdS nanoparticles. The reaction conditions, including temperature, pH, and precursor concentrations, are critical in controlling the nanoparticle properties.

2. 6. Thermal Decomposition:

CdTe and CdS nanoparticles can be synthesized through the thermal decomposition of organometallic precursors. Cadmium and tellurium or sulfur-containing compounds are heated to high temperatures, resulting in the formation of nanoparticles. This method is often used in the presence of stabilizing agents to control the size and prevent aggregation.

2. 7. Electrochemical Synthesis:

Electrochemical methods involve the electrodeposition of CdTe or CdS nanoparticles onto a conductive substrate. By controlling the electrodeposition parameters, such as potential and deposition time, it is possible to tailor the properties of the resulting nanoparticles.

2. 8. Physical vapour deposition

The Physical Vapor Deposition (PVD) techniques can also be employed for the synthesis of nanoparticles, particularly by utilizing methods such as evaporation or sputtering. The main idea is to generate a vapor phase of the material and then allow it to condense into nanoparticles.

2.9 Green synthesis

Green synthesis methods for the production of nanoparticles involve utilizing environmentally friendly and sustainable approaches, often employing natural resources or benign materials. These methods aim to replace traditional chemical synthesis routes that may involve toxic chemicals or harsh conditions. Green synthesis refers to environmentally friendly methods of producing various materials, chemicals, or compounds. This method is typically used for benign solvents, renewable resources, or safer reaction conditions, minimizing the generation of hazardous waste and reducing environmental impact.

4. Preparation techniques of CdTe and CdS thin films

The preparation techniques for CdTe and CdS thin films involve various methods [18-24]. Few methods are illustrated in Table 1.

Table 1: Summary of preparation techniques of CdTe and CdS thin films

Sr. No.	Method	Procedure	Advantages
1	Chemical Bath Deposition	Substrates are immersed in a chemical bath containing precursors for the thin films.	Simple and cost-effective. Suitable for large-area depositions.
2	Physical Vapor Deposition	Selected NPs evaporated using resistive heating, and the vapor condenses on the substrate.	Good control over film thickness. High purity of deposited films.
3	Selenium Backfilling	CdTe thin films are initially deposited with a deficiency of tellurium.	Improves the stoichiometry of CdTe thin films.

			Enhances the efficiency of thin-film solar cells.
4	Electrochemical Deposition	Electrolyte solutions containing cadmium and tellurium or sulfur ions are used. A voltage is applied to the substrate, leading to the electrochemical reduction of ions and the deposition of CdTe or CdS thin films.	Good control over film properties. Suitable for complex substrate geometries.
5	Spin Coating	A solution containing cadmium and tellurium or sulfur precursors is dispensed onto a rotating substrate. Centrifugal force spreads the solution, forming a uniform thin film.	Simple and widely used for laboratory-scale depositions. Suitable for small-area depositions.
6	Chemical Vapor Deposition	Gaseous precursors containing cadmium and tellurium or sulfur are introduced into a reaction chamber. A chemical reaction at the substrate surface leads to the deposition of thin films.	High control over film properties. Suitable for large-scale production.
7	Close-Spaced Sublimation	Cadmium and tellurium or sulfur sources are placed close to the substrate. Heat is applied, causing the sublimation of materials, and the vapor deposits onto the substrate.	Suitable for large-area depositions. Allows for control over the stoichiometry of the films.

5. Applications of CdTe and CdS thin films

CdTe and CdS thin films used in many applications for various technological fields due to their unique semiconductor properties [25-29]. Few notable applications of CdTe and CdS thin films are display in Fig. 2.

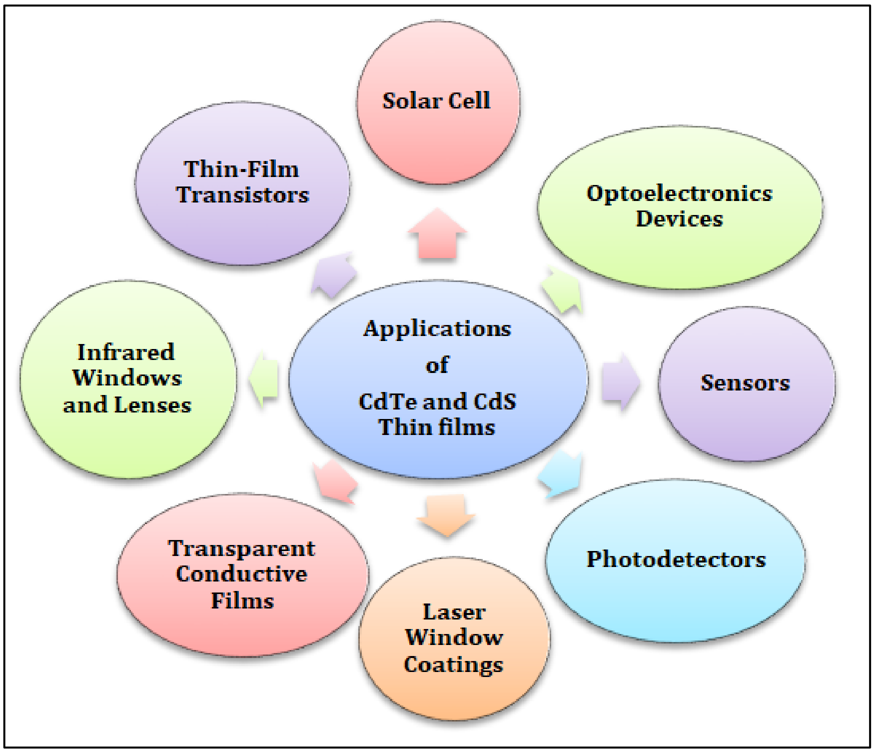

Figure 2: Applications of CdTe and CdS nanoparticles

5.1 Applications of CdTe Thin Films:

i. **Photovoltaics/Solar Cells:** CdTe thin films are widely used in the production of thin-film solar cells. CdTe solar cells are known for their high absorption coefficient, making them efficient in converting sunlight into electricity. They are used in both small-scale applications (e.g., portable solar chargers) and large-scale photovoltaic power plants.

ii. **X-ray and Gamma-ray Detectors:** CdTe is employed in the construction of X-ray and gamma-ray detectors due to its high atomic number and good stopping power for high-energy photons. These detectors are used in medical imaging, security screening, and industrial applications.

iii. **Infrared Windows and Lenses:** CdTe thin films are used in infrared optics for applications such as windows and lenses. The material's transparency in the infrared region makes it suitable for these purposes.

iv. **Thin-Film Transistors (TFTs):** CdTe thin films can be used in thin-film transistor technology. TFTs are essential components in electronic devices like flat-panel displays, sensors, and integrated circuits.

5.2 Applications of CdS Thin Films:

i. **Photovoltaics/Solar Cells:** CdS thin films are often used as a buffer layer in thin-film solar cells, improving the efficiency of the devices. They contribute to the overall performance and stability of solar cell structures.

ii. **Optoelectronic Devices:** CdS thin films are employed in optoelectronic devices such as light-emitting diodes (LEDs) and lasers. The material's semiconductor properties make it suitable for converting electrical energy into light.

iii. **Photodetectors:** CdS is used in the construction of photodetectors, devices that detect and convert light signals into electrical signals. This is valuable in applications like optical communication systems and imaging devices.

iv. **Sensors:** CdS thin films are utilized in various sensor applications, including gas sensors and photoconductors. The sensitivity of CdS to changes in light or certain gases makes it suitable for detecting environmental changes.

v. **Laser Window Coatings:** CdS thin films are used as coatings for laser windows. These coatings help control the transmission and reflection of laser beams, improving the efficiency and performance of lasers in various applications.

vi. **Transparent Conductive Films:** CdS thin films are employed as transparent conductive films in devices such as touch screens, solar cells, and flat-panel displays. They offer a combination of transparency and conductivity.

6. Future perspectives of CdTe and CdS thin films

The future perspectives of CdTe and CdS thin films involve ongoing research and development efforts aimed at improving their performance, expanding their applications, and addressing environmental concerns associated with the use of cadmium. Ongoing research focuses on enhancing the efficiency of CdTe-based thin-film solar cells [29, 30]. Innovations in material engineering, device architectures, and manufacturing processes aim to make CdTe solar cells even more competitive with other solar technologies. Tandem solar cells, which combine multiple materials with complementary absorption characteristics, are being explored to achieve higher efficiencies. Combining CdTe with other materials in tandem structures could offer improved performance in capturing a broader range of the solar spectrum. CdTe and CdS thin films may find new applications in building-integrated photovoltaics (BIPV), where solar cells are integrated into architectural elements like windows, facades, and roofing materials. Such integration can contribute to the widespread adoption of solar energy in urban environments. CdTe and CdS thin films may be explored for use in energy storage applications, such as supercapacitors and batteries. Research is ongoing to understand and optimize the electrochemical properties of these materials for efficient energy storage.

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