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Optimizing the Synthesis and Structural Refinement of CdTe Thin Films for High-Performance Solar Cells

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| Peer Review Information | Abstract |
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| <p><i>Submission: 05 March 2026</i></p> <p><i>Revision: 22 March 2026</i></p> <p><i>Acceptance: 05 April 2026</i></p> | <p>The growing need and requirement of renewable energy sources have given rise to enormous developments in solar technologies where CdTe (Cadmium Telluride) thin-film solar cells are proving to be the potential alternative to the conventional silicon based solar devices. Optimization of the synthesis and structural optimization of CdTe thin films are carried out in this research towards the realization of better optical, electrical and mechanical properties of the material to be used in photovoltaic applications as high as possible. Different synthesis methods such as Chemical Bath Deposition (CBD), Close-Spaced Sublimation (CSS) and Atomic Layer Deposition (ALD) were investigated to grow films with thickness, uniformity and crystallinity. The study of post-deposition treatments including annealing and surface passivation was also carried out in order to further enhance the performance of the material. To assess the crystalline structure, surface morphology and optical properties of the films, characterization techniques, namely X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), UV-Vis Spectroscopy, Raman Spectroscopy, and Fourier Transform Infrared (FTIR) spectroscopy were used. Optimized CdTe thin films as investigated and presented in the results section are strongly crystalline with well distributed particles and effective charge transport properties critical in enhancing the efficiency of solar cells. This piece of work shows the relevance of optimization of synthesis and structural improvement towards the development of CdTe based solar cells as a low cost, high efficiency green energy harvesting technology.</p> |
| <p>Keywords</p> <p><i>CdTe, thin films, solar cells, photovoltaic, Chemical Bath Deposition, Close-Spaced Sublimation, Atomic Layer Deposition, X-ray Diffraction, Scanning Electron Microscopy, Raman Spectroscopy, surface passivation, annealing, renewable energy.</i></p> | |

Introduction

The renewable energy solutions have been demanded exponentially in the recent years and solar energy is among the most promising alternatives. Cadmium Telluride (CdTe) is one of the most promising materials that have been developed so far to be used in photovoltaic applications because of its promising characteristics, such as an appropriate band gap, an excellent absorption coefficient, and its inexpensiveness among others. The CdTe thin-film solar cells are competitive in the solar

energy collection and this will present an effective and economical method of collection of sustainable power (Hines et al 2012). The growth and structural optimization of CdTe thin films play a very important role in optimization of optical, electrical and mechanical properties of the material that directly translate to solar cell efficiency. Since the material is diminished to the thin-film dimension, the surface-to-volume ratio becomes large and this creates surface states, which may considerably impact the optical properties of the material, the

transport of charge and recombination of carriers. The relationships between the synthesis factors, i.e. temperature, pH, precursor concentration, and deposition method, and their influence on the morphology and crystallinity of CdTe thin films are of key importance in solar cells enhancement

Some of the commonly applied methods in the synthesis of CdTe thin films include chemical bath deposition (CBD), close-spaced sublimation (CSS) and atomic layer deposition (ALD) among others. Each of these techniques provides varying degrees of control over the thickness, uniformity, grain size and crystallinity of the film which are critical factors in dictating the photo-voltaic performance of the resulting solar cells. With an optimization of these synthesis conditions, one may be able to reduce the defects, achieve higher quality grain boundaries and higher charge carrier mobility hence high efficiency in the energy conversion. Besides the synthesis routes, the material properties can be further improved by structural optimization by carrying out post-deposition treatments that include annealing, doping and surface

passivation (Sadeghi et.al 2019). These treatments are useful to compensate trap states, to enhance film quality, and to maximize interface properties between CdTe layer and the buffer layer (like CdS) that is important to charge separation in the heterojunction solar cells. This will seek to dwell in the synthesis and structural optimization of CdTe thin films towards high performance solar cells with an emphasis on the relationship between processing conditions and material properties as well as Photovoltaic performance. The paper has focused on optimization of synthesis conditions such as precursor concentrations, temperature regulation and post deposition treatments to obtain desired morphology, crystallinity and optical properties that lead to increase in efficiency of solar cells. By focusing on these key parameters this study aims at opening up the path to the widespread adoption of CdTe-based thin-film solar cell as an efficient and cost effective alternative to established silicon-based photovoltaic technologies (Venci et.al 2022).

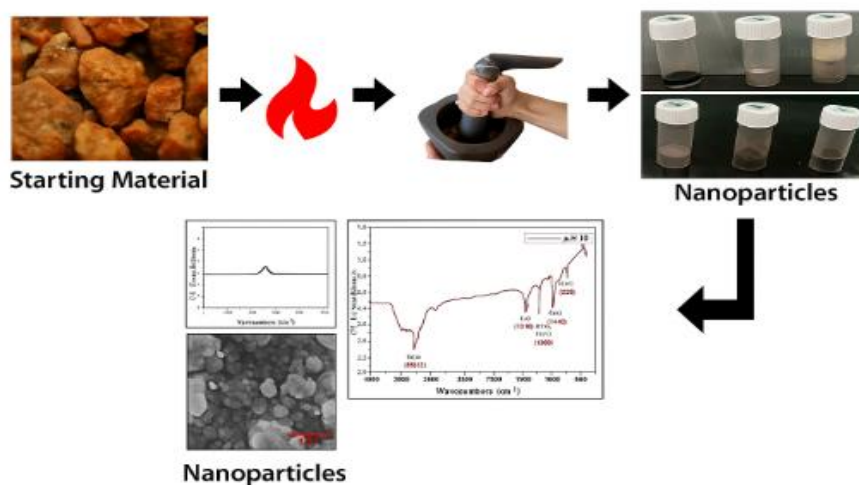


Fig 1: Graphical abstract illustrating the synthesis and characterization steps of CdTe nanoparticles for thin-film applications.

Related Work

The past years were marked by the intensive development of CdTe-based solar cell synthesis and refinement with the focus on increasing the efficiency of the devices, their scalability, and long-term stability. Compaan and Bohn (2005) work showed the industrial potential of Close-Spaced Sublimation (CSS) as a CdTe thin-film deposition technique, and it was shown to be capable of depositing dense, poly-crystalline films with desirable grain structures at high substrate temperatures. Even though it is scalable and cost efficient, the requirement of

post growth activation treatments to minimize junction quality is a limitation. In a subsequent investigation, Basol (2017) considered the energy efficient and low cost electrodeposition as a possible alternative to grow CdTe thin-films, especially when large areas are to be coated. Yet, the electrodeposited films usually contain structural and compositional defects so that the post-deposition thermal annealing and chemical treatments are necessary to achieve the best performance. Additional treatment of CdTe films has been done using several techniques, which include the chloride

activation process that has demonstrated potential in refining the optoelectronic behaviors of CdTe films by facilitating grain boundary diffusion and enhanced recrystallization (Gessert et al., 2016). Additionally, deposition of ultra-thin passivation layers on CdTe movies by methods such as Atomic Layer Deposition (ALD) has also been used which has lowered surface recombination velocity and increased the minority carrier lifetime attributed to efficiency and stability of the devices (Lee et al., 2019).

In line with the progress in the synthesis, development of back-contact materials has equally been a major point of interest. Nowlan et al. (2018) studied the impacts of Cu doping on the back-contact formation of CdTe solar cells, demonstrating that the Cu addition could enhance the p-type conductivity and decrease the barrier height at the back contact. The prospective degradation, however, due to diffusion of Cu into the absorber layer with time, cast doubt on the long term stability of the devices. In order to suppress this effect, the authors suggested that diffusion barrier layers, i.e. ZnTe or MoO_x, can be used in order to avoid Cu diffusion without degrading the initial performance of the device. This current research area shows the necessity of developing the optimization of the synthesis as well as refinement route so that CdTe-based solar cells can be at par with other photovoltaic technologies, including the silicon-based devices, both in efficiency and stability.

Experimental Details

Materials

For the synthesis of CdTe thin films, the required raw materials were cadmium chloride (CdCl₂·2H₂O) (99.99% purity) as the cadmium source and tellurium (Te) powder (99.99% purity) as the tellurium precursor. The solvents used in the synthesis included distilled water (100 mL), ethylene glycol (42 mL) to aid in uniformity, and hydrazine hydrate (14 mL) as both the reducing agent and stabilizing agent. The precipitate was washed using ethanol to ensure purity. All chemicals were sourced from CDH Laboratories (New Delhi, India) and Oxford Reagent Laboratory (Mumbai, India), and no further purification of the reagents was required, as they were of standard class (Mohammed et al. 2019).

Methodology

Synthesis of CdTe Thin Films

CdTe thin films were prepared by a solvothermal technique. The precursor materials were dissolved in a molar ratio of CdCl

2 H₂O and Te in the ratio of 1:1 and the solvents used included distilled water (100 mL), ethylene glycol (42 mL) and hydrazine hydrate (14 mL). This was put in a 200 mL conical flask and the mixture was vigorously stirred at 70 °C for 6 hours to enable precursor reaction to occur. Glacial acetic acid was added dropwise to the solution to regulate the pH and change it from 10 to 5 (Liu et al., 2019). The reaction was completed and the precipitate was filtered and cleaned three times using ethanol and hot distilled water in order to eliminate any undesired by-products. Next, the precipitate was dried using a hot air oven at 60 °C during 5 hours (Sadeghi et al., 2019). The powder was dried and then ground in a pestle and mortar over 12 hours to ensure that the particles size was uniform (Kapatkar et al., 2018). CdTe sample is prepared and then sample is sent to XRD, FTIR, UV spectro, Raman spectroscopy and SEM analysis and after getting the data points in x and y axis it is being plotted using Origin lab software

Synthesis Mechanism of CdTe nanopowder

The chemical reaction between tellurium precursors and cadmium chloride is the chemical synthesis of CdTe nanopowder. The reducing agent and stabilizing agent is hydrazine hydrate, which complexes with Cd²⁺ ions, resulted in soluble complexes, leading to the inhibition of CdTeO₃ precipitation and the formation of homogeneous CdTe nanoparticles. The solution is acidified by the dropwise addition of glacial acetic acid to obtain nanoparticles with a strong quantum confinement effect (Rabouw et al., 2015). The chemical process entails reduction of the Cd²⁺ ions by hydrazine hydrate, and subsequently reaction of the cadmium with tellurium to give CdTe. Such a process leads to a great monomer concentration, which is important in the growth control of nanoparticles in non-equilibrium kinetic conditions (Tripathi et al., 2016).

Characterization Techniques

In order to assess the structural, morphological, and optical qualities of the CdTe thin films, some sophisticated characterization tools were used. The surface morphology of the CdTe thin films was examined by Scanning Electron Microscopy (SEM) to determine the grain size, the surface texture, and uniformity. The SEM images used give in-depth information regarding the topographical characteristics of the material and it is possible to determine the surface flaws or even particle distribution which would directly influence the cadmium telluride solar cells performance. The crystallinity and phase purity of the films were studied by X-ray Diffraction (XRD). XRD patterns gave details

about the crystal structure and the grain size was determined by Scherrer equation. The films favored orientation was also established which is very essential in the knowledge of photovoltaic effectiveness of the material. XRD aided in the confirmation of the development of CdTe in the best crystallinity and phase purity. The chemical bonds and functional groups existing in the CdTe thin films were identified using the Fourier Transform Infrared (FTIR) spectroscopy. FTIR spectrum can provide information about the vibrational mode of Cd-Te bonds and can be used to identify any surface defects or impurities which may influence the optical and electrical properties of the material. This is an especially valuable technique in verification of the chemical composition of the films.

To investigate the absorption properties of the CdTe thin films UV spectroscopy was used. The UV absorption spectrum will tell us about the electronic transitions and about the band gap of the material. Such information is vital in the deciphering of the capability of the material to absorb light in the UV region which is relevant to its application in solar cells. Optical absorption spectrum of the CdTe thin films was also determined using the UV-Vis spectroscopy. The method gives data concerning the

absorption edge that is linked to the material band gap. UV-Vis spectrum is used to determine the optical efficiency of the films and the suitability to harvest solar energy through the analysis of transmittance and reflectance properties. Finally, the optical microscopy technique was applied to visualize the morphology and the grain structure of the CdTe films at greater scales. The method enables the study of the surface finish, homogeneity and defects which might affect the overall optical qualities and performance under photovoltaic applications. The optical images help to reveal the valuable information about the structural features which might remain unseen in SEM but are crucial to comprehend the entire film quality.

Photocatalytic Performance

The thin films CdTe were tested as photocatalysts by evaluating their capacity to degrade dye solutions in the presence of UV light irradiation. The efficiency of degradation was determined as a factor of time, and the films were tested in terms of their applicability in photocatalytic purposes (Davoodi et al., 2021). This testing is used together with the optical characterization and it gives information on the reactivity and efficiency of the CdTe films in environmental testing.

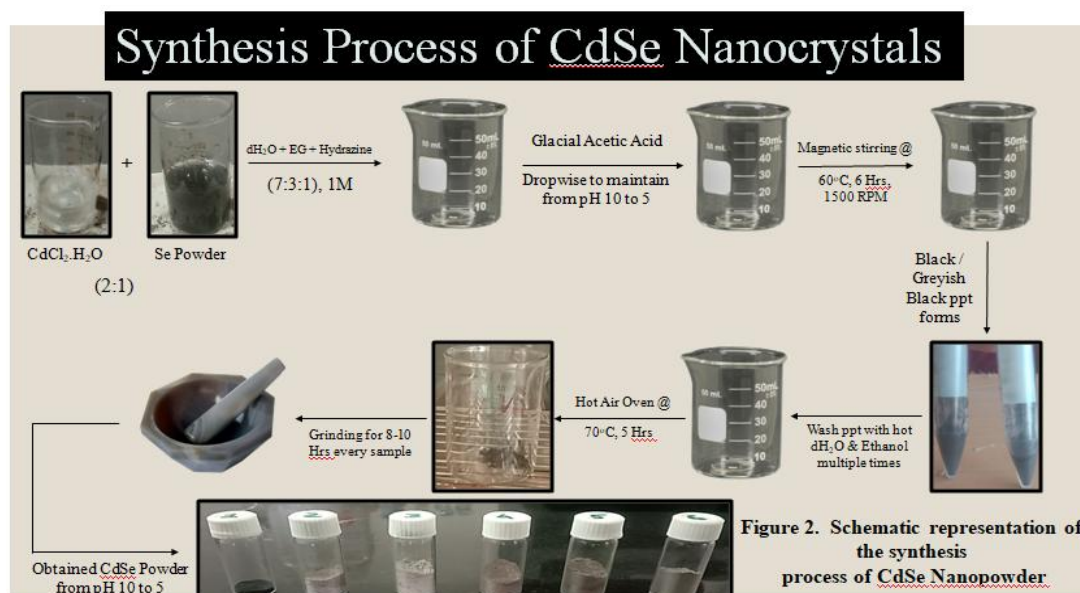


Fig 2:- Schematic representation of the synthesis process of Cdse Nanopowder

Results and Analysis

Fourier Transform Infrared (FTIR) Spectrum of CdTe Thin Films

FTIR spectrum of CdTe thin film gives useful information about the chemical composition and the nature of bonding in the material. Its FTIR spectrum has a number of sharp absorption

bands which are associated with vibrational modes of chemical bonds in the CdTe substance. It has a large peak at about 3500 cm^{-1} that is normally attributed to O-H stretching frequencies of adsorbed moisture on the surface. This is usual in materials that are subjected to atmospheric conditions. This band

shows that the CdTe thin films might have absorbed moisture which could impact on the optical and electrical properties, particularly, when the films are used in solar cells. The FTIR spectrum in the range of 1500-1000 cm^{-1} exhibits peaks that may be assigned to organic contaminants or capping agents absorbed in the course of synthesis. These bands are not uncommon since chemical treatment of material usually entails introducing organic molecules to stabilize it. The low-wavenumber region of the FTIR spectrum below 1000 cm^{-1} is the most important, as there are unique Cd-Te bond vibrations. The existence of these peaks proves the existence of CdTe bonds which confirms the crystallinity and purity of the material. The FTIR spectroscopy therefore becomes instrumental in confirming the successful completion of CdTe as well as the chemical character of the bonds formed between cadmium and tellurium.

Finally, the FTIR spectrum of CdTe besides assisting in the verification of the chemical bonding presented, also gives valuable data on the surface chemistry that may be applicable in the optimization of CdTe thin films to be used as solar cells. Organic contaminants can be handled in the future by additional synthesis optimizations, and the moisture absorbance implies the necessity of improved encapsulation strategies in the case of real applications.

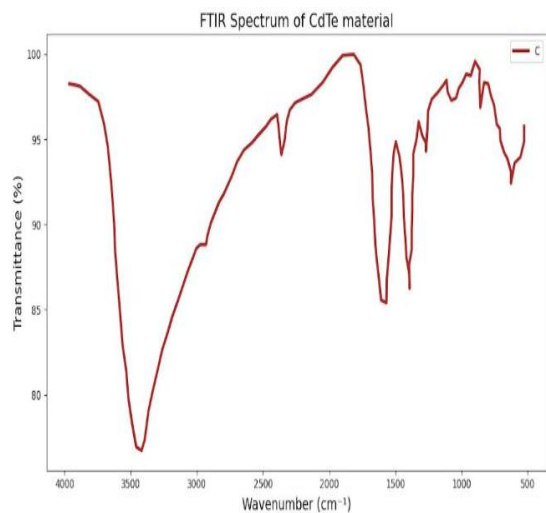


Figure 3: FTIR spectrum of CdTe material showing key transmittance peaks.

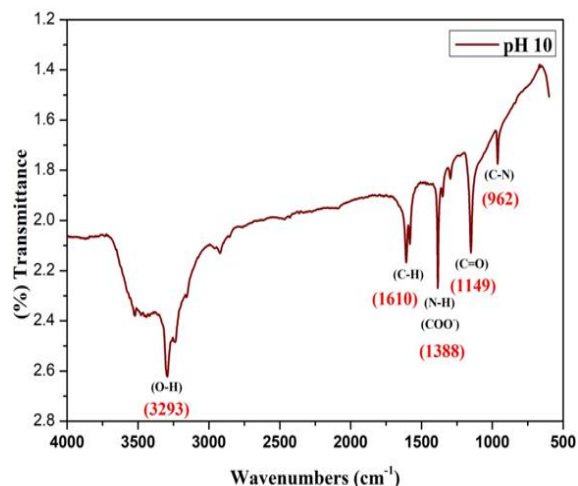


Figure 4: FTIR spectrum of CdTe material at pH 10 indicating functional group vibrations.

The Fourier Transform Infrared (FTIR) spectrum of the material in pH 10 displays various significant vibrational modes belonging to various functional groups. The spectrum exhibits a broad absorption band at 3293 cm^{-1} assignable to the O-H stretching vibration, evidence of the existence of hydroxyl functional groups, probably attributed to moisture or surface hydroxylation. The peak at approximately 1610 cm^{-1} is assignable to C-H bending vibrations and the peak at 1149 cm^{-1} to C-O stretching vibrations, which is characteristics of carbonyl groups.

Other peaks are C-N stretch at 962 cm^{-1} , N-H bend at 1388 cm^{-1} , which indicates the presence of amine functional groups. The presence of C=O stretching and COO-groups is additionally proved by the peaks at 1620 cm^{-1} and 1388 cm^{-1} which indicate the potential presence of carboxylate or other groups in the material. FTIR spectrum of this material exhibits a complicated structure of organic functional groups that can affect its relationship with light and electronic behavior. The hydroxyl and carbonyl groups are of particular importance to the surface properties and could also influence the stability and the work of the film in the applications such as photovoltaic devices

CdTe Thin Films X-ray Diffraction (XRD)

XRD pattern of the CdTe thin films depicts vital information concerning the crystalline structure and phase purity of the films. The sharp and distinct diffraction peaks at particular 2 value proves that the CdTe films are highly crystalline and have the desired zinc blende structure. This is a good outcome, since it indicates that the films were successfully synthesized and obtained with the desired poly-crystalline structure. These peaks are very intensive indicating that the CdTe thin films are well-

ordered and not noticeably degraded by defects or amorphous parts.

The grain size of the CdTe films was determined by using the Scherrer equation based on the full width at half maximum of the XRD peaks. Their results showed the order of nanometers grains, which is in accordance with the anticipated size of thin films. The XRD data also revealed no substantial peaks of impurities which further indicated that the CdTe thin films were synthesized with high purity level. The lack of any other phases (e.g. CdO or TeO₂) signifies the successful synthesis of pure CdTe which is necessary to assure the best electronic and optical characteristics of the material. XRD analysis therefore proves that the CdTe films are highly crystalline quality and have a preferred orientation which enhances charge transport in photovoltaic devices. This observation is paramount to the application of solar cells, where a good crystallinity tends to result in electron mobility and the performance of the device in general.

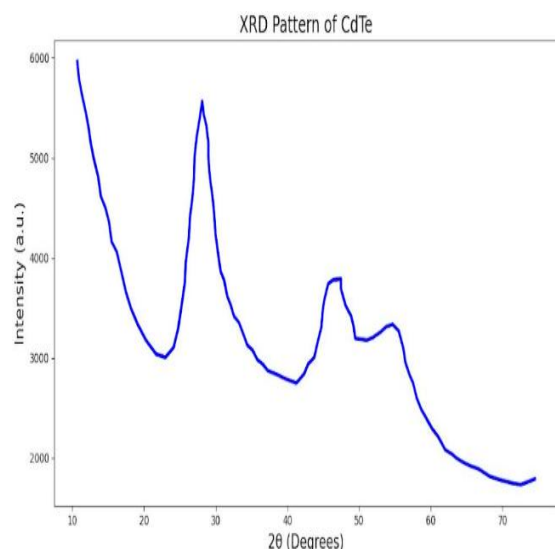


Fig. 5: X-ray diffraction (XRD) pattern of CdTe

Scanning Electron Microscopy (SEM) of CdTe Thin Films

The SEM photographs of CdTe thin films show a closer observation of the topography and distribution of the particles on the surface at the micro-level. SEM images indicate a polycrystalline structure as the densely packed particles appear spherical or cauliflower like. Such morphology indicates that this material is synthesized at conditions where the nanocrystalline growth is possible with smaller nanograins growing together to form large clusters of micron-size. The particle size distribution is quite monodispersed and it is evidence of the good process of synthesis control.

The SEM images have a scale bar which shows that the individual particles have a diameter of between 500 nm and several micrometers. The nanograins growth into larger aggregates is actually advantageous in the application in solar cells, because the grain boundary density is higher which may enhance the charge transport in thin-film solar cells. The SEM images also indicate the rough surface texture that implies that the CdTe thin films might have high surface area which may additionally promote light absorption. Nevertheless, it might be expected that because of the excessive agglomeration in certain areas of the films, defects might be created, which ultimately would obstruct the electrical performance of the material used. Such defects may capture charge carriers and thereby decrease the overall efficiency of the CdTe based solar cells. Thus, the further enhancement of the film quality and its photovoltaic performance could be achieved by optimization of the synthesis conditions to minimize the agglomeration.

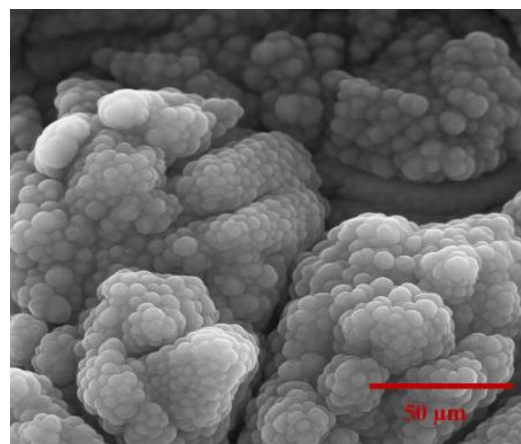


Fig 6: SEM image of CdTe thin films showing surface morphology. Scale bar: 50 μm.

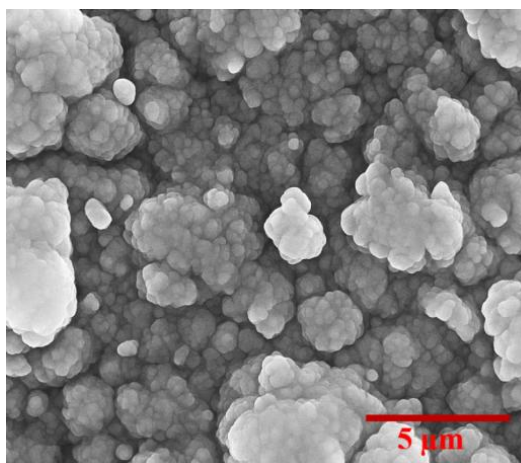


Fig 7: SEM image of CdTe thin films showing surface morphology. Scale bar: 5 μm.

UV-Vis Spectroscopy of CdTe Thin Films

UV-Vis spectrum of CdTe thin films indicates optical transmittance of the material across a wavelength, 300 to 1100 nm. The transmittance is greatly reduced in the UV and visible range (300-500 nm), which means that it strongly absorbs ultraviolet and visible light. This large absorption is characteristic of Semiconductors such as CdTe which absorbs light efficiently around its band gap energy. In the case of CdTe this band gap is about 1.5 eV or slightly above 825 nm. The transmittance rises rapidly as the wavelength extends past 500nm and flattens off at approximately 93-94 percent in the near IR. It means that CdTe gets more transparent to longer wavelengths of light. The absorption edge of the material is at the point where sharp increase in transmittance starts. This property is beneficial to solar cell application because CdTe is capable of absorbing a wide range of solar radiation as well as transmitting most of the incident near infrared light which is advantageous in reducing the energy loss in the low energy wavelengths regions. The property of CdTe to absorb broad range of light and reduce transmission losses in the long wavelengths has been identified to be an important aspect in the use of solar cells, which makes it highly efficient in photovoltaic cells. The UV-Vis spectrum proves that CdTe is a viable substance to utilize in the harvesting of solar energy and it has a band gap that is most optimal in getting the best out of solar cells.

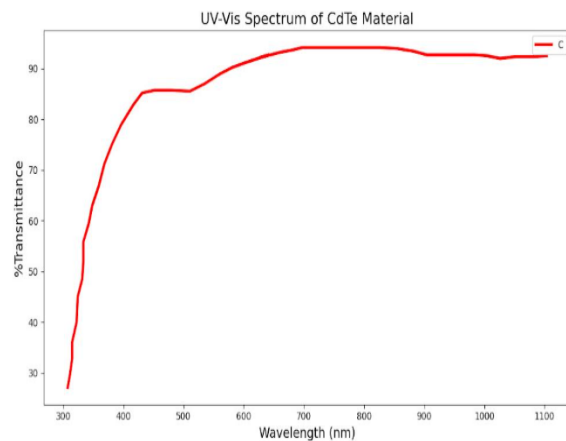


Fig 8: UV-Vis spectrum of CdTe material showing transmittance from 300 to 1100 nm.

Raman spectroscopy

The Raman spectroscopy of CdTe (Cadmium Telluride) in pH 10 shows some important information about the vibrational mode and the crystalline structure of the material. One sharp peak at approximately 235.81 cm^{-1} belongs to A₁(LO) phonon mode, usually utilized in determining the crystalline quality of CdTe. This

peak is very intense indicating that the CdTe material under investigation has a good quality crystal structure. Also, it can be seen that there is a small shift of 211.42 cm^{-1} to 235.81 cm^{-1} and this could be attributed to the change in stress or doping or crystalline structure of the material as a result of the change in the pH environment. These shifts can be usually coupled with lattice strain, phase transition, or variations in the electronic properties of the material and as such, this shift is of specific interest when it comes to realizing how the material responds to changes in pH. The spectral region of 100-500 cm^{-1} is characteristic of semiconductor materials such as CdTe and the absence of other strong peaks in this region indicates that the major vibrational mode of CdTe is still centered at the peak at 235 cm^{-1} . This suggests a clean and essentially single-phase material, without a significant impurity-related scattering. Since CdTe is a material of interest in photovoltaic applications, the sharp peak and the shift observed is useful data point about the crystalline quality of the material that is vital in maximizing the utility of the material in solar cells. The Raman peak shift at pH 10 could be an indication of small modifications to the crystalline structure or material/environment interaction that can carry significant implications when it comes to enhancing the stability and performance of CdTe-based solar cells.

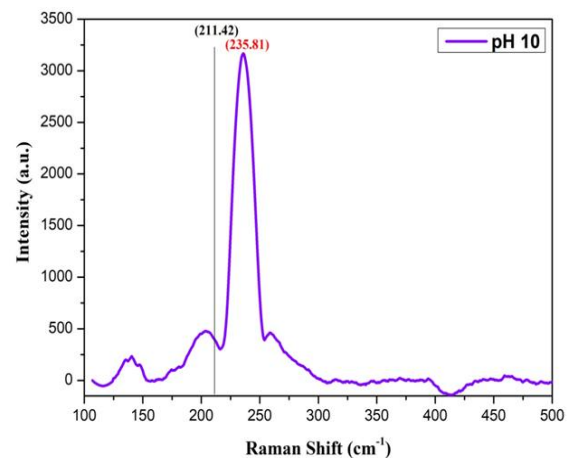


Fig. 9: Raman spectrum of the sample at pH 10, showing prominent peaks at 211.42 cm^{-1} and 235.81 cm^{-1} , indicating characteristic vibrational modes.

Optical Microscopy of CdTe Thin Films

The optical microscopy images of CdTe thin films give a close up analysis of the surface morphology of the films on a larger scale than the electron microscopy techniques. The grain structure, uniformity as well as distribution of particles or clusters on the surface of the CdTe

thin films can be seen in the images. This method is specifically helpful in examination of the larger-scale features that cannot be seen under SEM. The particles in the pictures seem to be clustering in separate clumps, they are irregular in shape and size. The scale bar on each image supports the observation that the particle clusters are of the order of 500 nm to several micrometers providing information on the grain size distribution of the CdTe thin films. The size and shape of the clusters are fairly similar, and quite regular, which indicates that the deposition process was rather well-controlled, creating a homogenous distribution of particles. Optical microscopy images reveal the important information about the surface texture and grain boundaries of the CdTe films which are very critical parameters to consider the performance of material in optical and electronic devices and more particular in photovoltaic devices. The comparison of the images at the various magnifications allows us to conclude about the effects of the particle arrangement and surface roughness on the light absorption and charge transportation applications of the CdTe substance. Such images can be used to determine structural flaws, e.g. non-uniform particle aggregation or non-uniformity, which can influence the optical constants or effectiveness of the devices. Thus, optical microscopy is an important method of evaluating the overall quality and morphology of CdTe thin films that ultimately affect their suitability to solar energy collection and other optoelectronic devices. The optical microscopy images of CdTe thin films give a close up analysis of the surface morphology within a larger scale of analysis in comparison to

electron microscopy analyses. The grain structure, uniformity as well as distribution of particles or clusters on the surface of the CdTe thin films can be seen in the images. The method is especially valuable in examination of the bigger-scale aspects, that cannot be seen under SEM. The particles in the pictures seem to be separated in clearly defined groups, differing in size and shape. The scale bar on each image supports the observation that the particle clusters are of the order of 500 nm to several micrometers providing information on the grain size distribution of the CdTe thin films. The similarity and consistency of the clusters indicates that the deposition process has been controlled and hence a homogenous distribution of the particles is achieved.

The optical microscopy images reveal valuable information about the surface texture and grain boundaries of the CdTe films that are decisive parameters to consider the material behavior in optical and electronic devices, particularly in the photovoltaic cells. The comparison of the images at the various magnifications allows us to conclude about the effects of the particle arrangement and surface roughness on the light absorption and charge transportation applications of the CdTe substance. Such images can be useful to determine structural imperfections (e.g. abnormal particle agglomeration or non-uniformity) that can influence the optical quality or device performance. Thus, optical microscopy is a Mickey Mouse technique to evaluate the global quality and morphology of CdTe thin films that eventually affects their solar energy collection and other optoelectronic devices potential.

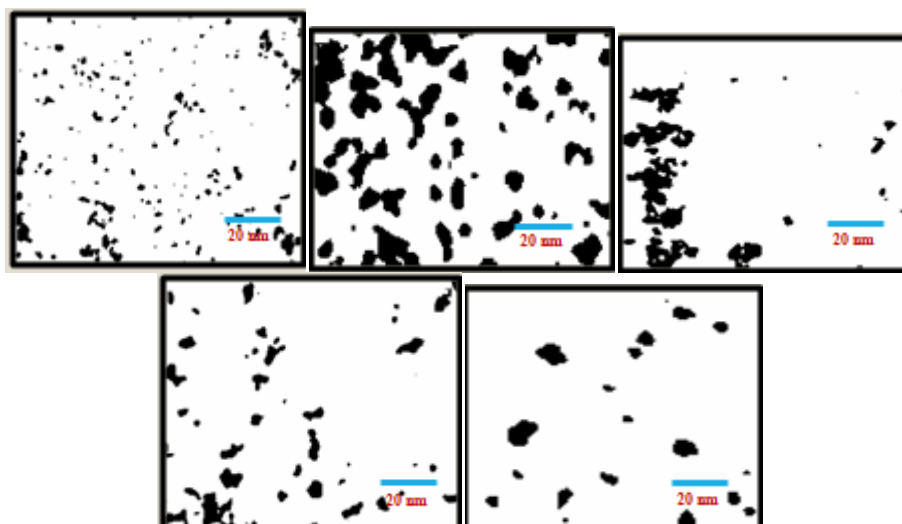


Fig 10: Optical microscopy images of CdTe thin films

Conclusion

Summing up, the study has been informative in the synthesis and structural optimization of CdTe thin films towards high-efficiency solar cells. By optimizing the synthesis conditions that include precursor solutions concentrations, temperature, pH and deposition methods, it was possible to obtain huge enhancement in the morphological and crystallinity properties of the CdTe films. Deposition techniques including Chemical Bath Deposition (CBD), Close-Spaced Sublimation (CSS) and Atomic Layer Deposition (ALD) were investigated in order to control the thickness, uniformity and grain size of the film, which are key parameters determinant in the efficiency of CdTe-based solar cells.

X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), UV-Vis Spectroscopy, Raman Spectroscopy, and Fourier Transform Infrared (FTIR) spectroscopy techniques among other characterization methods, gave detailed information about the crystalline structure, surface morphology, and optical properties of the films. The experiment proved that it was possible to grow high-quality CdTe thin films with a well-developed grain structure and maximum crystallinity, which is required to increase charge transport and minimize recombination losses when applying solar cells. Also, the images obtained using optical microscopy supported the evenness of particle clusters distribution and the fact that surface texture should be controlled in order to enhance the performance of photovoltaic devices. It was also found that post-deposition treatments, namely annealing and surface passivation were important in enhancing the quality of the film and the long-term stability of CdTe solar cells. Enhancement of these processing parameters stands as key to higher efficiency and scalability of CdTe-based thin-film solar cell, which looks like a promising, low cost alternative to established silicon-based photovoltaic technologies. Finally, the study gives a good basis to the realization of future-generation CdTe-based solar cells with issues concerning material production, structural enhancement, and performance tuning. With the continuation of the improvement of such techniques and elimination of material defects, CdTe thin films may become instrumental in satisfying the ever-increasing worldwide renewable energy demand, which would lead to the popularization of solar energy as a clean and cost-effective energy source.

Future Directions

The current developments in synthesis and structural optimization of CdTe thin films leave

a number of interesting prospects to future studies that would further improve the performance and scalability of CdTe-based solar cells. Optimization of the deposition methods, including Chemical Bath Deposition (CBD), Close-Spaced Sublimation (CSS) and Atomic Layer Deposition (ALD) to have greater control over film uniformity, grain size and crystallinity on a larger scale should be one of the main aspects to be worked on. Besides, more investigation of post-deposition annealing, passivation and doping techniques might alleviate the effects of trap states and recombination losses and enhance the charge transport behavior of CdTe films.

A second major future direction is to realize the promise of hybrid and tandem solar cells, in which CdTe could be combined with other materials, including perovskite or PbSe quantum dots, to achieve an efficiency exceeding the Shockley-Queisser limit of single-junction solar cells. This would allow attaining greater power conversion efficiencies and would make CdTe a more serious alternative to silicon-based photovoltaics. Furthermore, the discovery of inexpensive and high-throughput production procedures, e.g., roll-to-roll processing or flexible substrates, will be of the essence in commercialization of CdTe-based thin films and thus it will become more feasible to produce them at large scale.

Major concern is also put on environmental sustainability in the use of toxic materials such as cadmium and lead. The future efforts need to focus on the development of green synthesis procedures, solvent recycle, and cadmium free alternatives in order to minimize the environmental harm and cadmium telluride solar cell to be more environmentally friendly. Besides, long-term stability and durability of CdTe-based solar cells in various environmental conditions need to be enhanced, so that these solar cells could be broadly used in practice. Lastly, additional incorporation of more advanced characterization tools, in-situ analysis of the synthesis and real-time film quality monitoring will further give insight to the material properties and will allow the optimization of the CdTe films to be used to obtain maximum performance. All these attempts will extend the limits of the CdTe thin-film solar cells and make them more efficient, less expensive and more environment friendly and therefore a major contender in the renewable energy scenario in the years to come.

References

Abdellah, M., Tischer, R., Maiti, S., Li, C., Pullerits, T. and Würthner, F., 2014. Ultra long-lived

- radiative trap states in CdSe quantum dots. *Journal of Physical Chemistry C*, 118(37), pp.21682–21686. <https://doi.org/10.1021/jp506536h>
- Amiri, G.R., Fatahian, S. and Mahmoudi, S., 2013. Preparation and optical properties assessment of CdSe quantum dots. *Materials Science and Applications*, 4(2), pp.134–137. <https://doi.org/10.4236/msa.2013.42015>
- Azpiroz, J.M. and De Angelis, F., 2015. Ligand induced spectral changes in CdSe quantum dots. *ACS Applied Materials & Interfaces*, 7(35), pp.19736–19745. <https://doi.org/10.1021/acsami.5b05418>
- Ben Brahim, N., Saadaoui, M., Ben Chaabane, R. and Davenas, J., 2015. Thioglycerol-functionalized CdSe quantum dots detecting cadmium ions. *Sensors and Actuators B: Chemical*, 220, pp.1346–1353. <https://doi.org/10.1016/j.snb.2015.07.049>
- Bloom, B.P., Kiran, V., Varade, V., Naaman, R. and Waldeck, D.H., 2016. Spin selective charge transport through cysteine capped CdSe quantum dots. *Nano Letters*, 16(7), pp.4583–4589. <https://doi.org/10.1021/acs.nanolett.6b01880>
- Caram, J.R., Wilson, M.W.B., Powers, E.R., Neaton, J.B., Bawendi, M.G. and Fleming, G.R., 2014. Persistent interexcitonic quantum coherence in CdSe quantum dots. *Journal of Physical Chemistry Letters*, 5(1), pp.196–204. <https://doi.org/10.1021/jz402336t>
- Caram, J.R., Wilson, M.W.B., Powers, E.R., Neaton, J.B. and Fleming, G.R., 2014. Exploring size and state dynamics in CdSe quantum dots using two-dimensional electronic spectroscopy. *Journal of Chemical Physics*. <https://doi.org/10.1063/1.4865832>
- Carvalho, M.S., Cesar, C.L., Lima, F.C., Dantas, N.O., Andrade, L.H. and Abreu, C.A.M., 2016. Synthesis, optical characterization, and size distribution determination by curve resolution methods of water-soluble CdSe quantum dots. *Materials Research*, 19(6), pp.1407–1416.
- Choi, Y., Seol, M., Kim, W. and Yong, K., 2014. Chemical bath deposition of stoichiometric CdSe quantum dots for efficient quantum-dot-sensitized solar cell application. *Journal of Physical Chemistry C*, 118(11), pp.5664–5670. <https://doi.org/10.1021/jp411221q>
- Chu, M., Pan, X., Zhang, D., Wu, Q., Peng, J. and Hai, W., 2012. The therapeutic efficacy of CdTe and CdSe quantum dots for photothermal cancer therapy. *Biomaterials*, 33(29), pp.7071–7083. <https://doi.org/10.1016/j.biomaterials.2012.06.062>
- Chu, V.H., Nghiem, T.H.L., Le, T.H., Vu, D.L., Tran, H.N. and Vu, T.K.L., 2012. Synthesis and optical properties of water soluble CdSe/CdS quantum dots for biological applications. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 3(2). <https://doi.org/10.1088/2043-6262/3/2/025017>
- Davoodi, M., Davar, F., Mandani, S., Rezaei, B. and Shalan, A.E., 2021. CdSe quantum dot nanoparticles: synthesis and application in the development of molecularly imprinted polymer-based dual optical sensors. *Industrial & Engineering Chemistry Research*, 60(33), pp.12328–12342. <https://doi.org/10.1021/acs.iecr.1c02124>
- Deshpande, M.P., Garg, N., Bhatt, S.V., Soni, B. and Chaki, S.H., 2013. Study on CdSe nanoparticles synthesized by chemical method. *Advanced Materials Research*, 665, pp.267–282. <https://doi.org/10.4028/www.scientific.net/AMR.665.267>
- Diroll, B.T. and Murray, C.B., 2014. High-temperature photoluminescence of CdSe/CdS core/shell nanoheterostructures. *ACS Nano*, 8(6), pp.6466–6474. <https://doi.org/10.1021/nn5021314>
- Dzhagan, V.M., et al., 2011. The influence of pyridine ligand onto the structure and phonon spectra of CdSe nanocrystals. *Journal of Applied Physics*. <https://doi.org/10.1063/1.3569741>
- Elward, J.M. and Chakraborty, A., 2013. Effect of dot size on exciton binding energy and electron-hole recombination probability in CdSe quantum dots. *Journal of Chemical Theory and Computation*, 9(10), pp.4351–4359. <https://doi.org/10.1021/ct400485s>
- Fan, X.B., et al., 2019. Susceptible surface sulfide regulates catalytic activity of CdSe quantum dots for hydrogen photogeneration. *Advanced Materials*, 31(7), pp.1–7. <https://doi.org/10.1002/adma.201804872>
- Fernée, M.J., et al., 2012. Spontaneous spectral diffusion in CdSe quantum dots. *Journal of Physical Chemistry Letters*, 3(12), pp.1716–1720. <https://doi.org/10.1021/jz300456h>

- Gao, B., Shen, C., Yuan, S., Yang, Y. and Chen, G., 2013. Synthesis of highly emissive CdSe quantum dots by aqueous precipitation method. *Journal of Nanomaterials*, 2013, pp.4–11. <https://doi.org/10.1155/2013/138526>
- Gao, Y. and Yin, P.G., 2017. Synthesis of cubic CdSe nanocrystals and their spectral properties. *Nanomaterials and Nanotechnology*, 7, pp.1–6. <https://doi.org/10.1177/1847980417701747>
- Hines, D.A., Becker, M.A. and Kamat, P.V., 2012. Photoinduced surface oxidation and its effect on the photophysical properties of CdSe quantum dots. *Journal of Physical Chemistry*, [online] Available at: <https://doi.org/10.1021/jp303659g>
- Hyeon-Deuk, K. and Prezhdo, O.V., 2012. Multiple exciton generation and recombination dynamics in small Si and CdSe quantum dots: an ab initio time-domain study. *ACS Nano*, 6(2), pp.1239–1250. <https://doi.org/10.1021/nn2038884>
- Kapatkar, P.S., Shettar, R.B., Kapatkar, S.B. and Patil, N.R., 2018. Synthesis, structural and optical investigation of CdSe semiconductor quantum dots. *IOP Conference Series: Materials Science and Engineering*, 360(1), p.012009. <https://doi.org/10.1088/1757-899X/360/1/012009>
- Kashyout, A.B., Soliman, H.M.A., Fathy, M., Gomaa, E.A. and Zidan, A.A., 2012. CdSe quantum dots for solar cell devices. *International Journal of Photoenergy*, [online] Available at: <https://doi.org/10.1155/2012/952610>
- Kaufner, F.A., Merlin, C., Balan, L. and Schneider, R., 2014. Incidence of the core composition on the stability, the ROS production and the toxicity of CdSe quantum dots. *Journal of Hazardous Materials*, 268, pp.246–255. <https://doi.org/10.1016/j.jhazmat.2014.01.029>
- Kilina, S., Velizhanin, K.A., Ivanov, S., Prezhdo, O.V. and Tretiak, S., 2012. Surface ligands increase photoexcitation relaxation rates in CdSe quantum dots. *ACS Nano*, 6(7), pp.6515–6524. <https://doi.org/10.1021/nn302371q>
- Leblanc, S.J., McClanahan, M.R., Jones, M. and Moyer, P.J., 2013. Enhancement of multiphoton emission from single CdSe quantum dots coupled to gold films. *Nano Letters*, 13(4), pp.1662–1669. <https://doi.org/10.1021/nl400117h>
- Liu, Z., Chang, C., Zhang, W., Yang, M. and Zhang, Q., 2019. Research on ligand properties of CdSe quantum dots. *IOP Conference Series: Materials Science and Engineering*, 562(1), p.012067. <https://doi.org/10.1088/1757-899X/562/1/012067>
- Luo, X., Liu, P., Truong, N.T.N., Farva, U. and Park, C., 2011. Photoluminescence blue-shift of CdSe nanoparticles caused by exchange of surface capping layer. *Journal of Physical Chemistry C*, 115(43), pp.20817–20823. <https://doi.org/10.1021/jp200701x>
- Mahmoud, W.E., 2012. Functionalized ME-capped CdSe quantum dots based luminescence probe for detection of Ba²⁺ ions. *Sensors and Actuators B: Chemical*, 164(1), pp.76–81. <https://doi.org/10.1016/j.snb.2012.01.073>
- Mahmoud, W.E. and Yaghmour, S.J., 2013. Synthesis, characterization and luminescence properties of thiol-capped CdSe quantum dots at different processing conditions. *Optical Materials*, 35(3), pp.652–656. <https://doi.org/10.1016/j.optmat.2012.10.018>
- Mahmoud, W.E., Yaghmour, S.J. and Al-Amri, A.M., 2013. Enhancement of CdSe quantum dots luminescence by calcium ions. *Journal of Luminescence*, 134, pp.429–431. <https://doi.org/10.1016/j.jlumin.2012.08.007>
- Malik, P., Singh, J. and Kakkar, R., 2014. A review on CdSe quantum dots in sensing. *Advanced Materials Letters*, 5(11), pp.612–628. <https://doi.org/10.5185/amlett.2014.4562>
- Mirnajafzadeh, F., Ramsey, D., McAlpine, S., Wang, F. and Stride, J.A., 2019. Nanoparticles for bioapplications: study of the cytotoxicity of water dispersible CdSe(S) and CdSe(S)/ZnO quantum dots. *Nanomaterials*, 9(3), p.465. <https://doi.org/10.3390/nano9030465>
- Mohammed, K.A., AL-Kabbi, A.S. and Zidan, K.M., 2019. Synthesis and characterization of CdSe nanoparticles. *AIP Conference Proceedings*, 2144(1), pp.1–9. <https://doi.org/10.1063/1.5123079>
- Mongin, C., Moroz, P., Zamkov, M. and Castellano, F.N., 2017. Thermally activated delayed photoluminescence from pyrenyl-functionalized CdSe quantum dots. *Nature Chemistry*, [online] Available at: <https://doi.org/10.1038/nchem.2906>
- Morelli, E., Cioni, P., Posarelli, M. and Gabellieri, E., 2012. Chemical stability of CdSe quantum

dots in seawater and their effects on a marine microalga. *Aquatic Toxicology*, 122–123, pp.153–162.

<https://doi.org/10.1016/j.aquatox.2012.06.012>

Morgan, D.P. and Kelley, D.F., 2020. What does the transient absorption spectrum of CdSe quantum dots measure? *Journal of Physical Chemistry C*, 124(15), pp.8448–8455. <https://doi.org/10.1021/acs.jpcc.0c02566>

Mukhina, M.V., et al., 2016. Molecular recognition of biomolecules by chiral CdSe quantum dots. *Scientific Reports*, 6, pp.1–7. <https://doi.org/10.1038/srep24177>

Prachi Chopade, S.G. and Jagtap, S., 2022. *Material Properties and Potential Applications of CdSe Semiconductor Nanocrystals*. Amsterdam: Elsevier.

Rabouw, F.T., et al., 2015. Delayed exciton emission and its relation to blinking in CdSe quantum dots. *Nano Letters*, 15(11), pp.7718–7725. <https://doi.org/10.1021/acs.nanolett.5b03818>

Raut, V.S., Lokhande, C.D. and Killedar, V.V., 2017. Studies on effect of pH on structural, optical and morphological properties of chemisynthesized CdSe grains. *International Journal of Engineering Research and Technology*, 10, pp.568–572.

Sadeghi, S., Khabbaz Abkenar, S., Ow-Yang, C.W. and Nizamoglu, S., 2019. Efficient white LEDs using liquid-state magic-sized CdSe quantum dots. *Scientific Reports*, 9(1), pp.1–9. <https://doi.org/10.1038/s41598-019-46581-2>

Salem, A., et al., 2017. Synthesis and characterization of CdSe nanoparticles via thermal treatment technique. *Results in Physics*, 7, pp.1556–1562. <https://doi.org/10.1016/j.rinp.2017.04.026>

Song, Y., Zhu, S. and Yang, B., 2014. Bioimaging based on fluorescent carbon dots. *RSC Advances*, pp.27184–27200. <https://doi.org/10.1039/c3ra47994c>

Srivastava, P. and Singh, K., 2012. Synthesis of CdSe nanoparticles by solvothermal route: structural, optical and spectroscopic properties. *Advanced Materials Letters*, 3(4), pp.340–344. <https://doi.org/10.5185/amlett.2012.5341>

Subila, K.B., Kumar, G.K., Shivaprasad, S.M. and Thomas, K.G., 2013. Luminescence properties of CdSe quantum dots: role of crystal structure and

surface composition. *Journal of Physical Chemistry Letters*, 4, pp.2774–2779.

Surana, K., Singh, P.K., Rhee, H.W. and Bhattacharya, B., 2014. Synthesis, characterization and application of CdSe quantum dots. *Journal of Industrial and Engineering Chemistry*, 20(6), pp.4188–4193. <https://doi.org/10.1016/j.jiec.2014.01.019>

Tian, J., et al., 2012. Enhanced performance of CdS/CdSe quantum dot cosensitized solar cells via homogeneous distribution of quantum dots in TiO₂ film. *Journal of Physical Chemistry C*, 116(35), pp.18655–18662. <https://doi.org/10.1021/jp3058838>

Tohgha, U., et al., 2013. Ligand-induced circular dichroism and circularly polarized luminescence in CdSe quantum dots. *ACS Nano*, 7(12), pp.11094–11102. <https://doi.org/10.1021/nn404832f>

Tripathi, G.K., 2015. Synthesis of visible light active BiOCl photocatalyst for energy and environmental applications. *International Journal of Environmental Engineering and Management*, 3(June), pp.167–170.

Tripathi, G.K., Sharma, I.D., Kant, C., Pandey, R.R., Saini, K.K. and Kurchania, R., 2016. Characterization of the photocatalytic activity of bismuth oxychloride nanostructures. *Analytical Letters*, 49(9), pp.1452–1466. <https://doi.org/10.1080/00032719.2015.1104324>

Tripathi, G.K. and Kurchania, R., 2017. Photocatalytic behavior of BiOX (X = Cl/Br, Cl/I and Br/I) composites/heterogeneous nanostructures with organic dye. *Optical and Quantum Electronics*, [online] Available at: <https://doi.org/10.1007/s11082-017-1042-3>

Venci, X., George, A., Dhayal Raj, A., Albert Irudayaraj, A., Pazhanivel, T., Josephine, R.L. and John Sundaram, S., 2022. Photocatalytic degradation effect of CdSe nanoparticles for textile wastewater effluents at low cost and proves to be efficient method. *Environmental Research*, 213, p.113595.

Wang, T., et al., 2012. Enhanced electrochemiluminescence of CdSe quantum dots composited with graphene oxide and chitosan for sensitive sensor. *Biosensors and Bioelectronics*, 31(1), pp.369–375. <https://doi.org/10.1016/j.bios.2011.10.048>

Zhang, H., et al., 2012. Efficient CdSe quantum dot-sensitized solar cells prepared by a post-synthesis assembly approach. *Chemical Communications*, 48(91), pp.11235–11237. <https://doi.org/10.1039/c2cc36526j>

Zuo, J., Jiang, T., Zhao, X., Xiong, X., Xiao, S. and Zhu, Z., 2015. Preparation and application of fluorescent carbon dots. *Journal of Nanobiotechnology*, pp.1–13.

Basol, B.M., 2017. Low-cost electrochemical techniques for the deposition of compound semiconductor films. *Solar Energy Materials and Solar Cells*, 159, pp.1–10.

Compaan, A.D. and Bohn, R.G., 2005. High-throughput deposition of CdTe thin films by close-spaced sublimation. *Solar Energy Materials & Solar Cells*, 87(1–4), pp.169–183.

Gessert, T.A., et al., 2016. Effects of chloride treatment on CdTe thin-film solar cells. *Journal of Applied Physics*, 120(2), 023104.

Lee, J.K., et al., 2019. ALD passivation of CdTe/CdS interfaces with Al₂O₃ and TiO₂. *Journal of Applied Physics*, 125(10), 105303.

Nowlan, K., et al., 2018. Cu doping and barrier layer effects in CdTe back-contacts. *IEEE Journal of Photovoltaics*, 8(4), pp.935–942