Structural, Optical, Electrical and Surface Morphological Studies of Electrodeposited Mn-Doped CdTe Thin Films

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ORIGINAL RESEARCH

Abstract— Cadmium telluride (CdTe) is one of the most promising thin-film semiconductor materials for photovoltaic and optoelectronic applications because of its direct bandgap and high optical absorption coefficient. In this study, Mn-doped CdTe ($Cd_{1-x}Mn_xTe$) thin films with Mn concentrations of 0.00–0.03 were successfully synthesized on fluorine-doped tin oxide (FTO) coated glass substrates by the electrodeposition technique. The deposited films were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), UV–Visible spectroscopy, and electrical measurements to investigate the influence of Mn incorporation on their structural, optical, electrical, and surface morphological properties. The results revealed that increasing Mn concentration produced thinner and more compact films with improved grain refinement and enhanced surface roughness. Optical analysis showed a systematic increase in bandgap energy from 1.51 eV for undoped CdTe to 2.92 eV at 3% Mn incorporation, indicating pronounced bandgap widening associated with sp–d exchange interactions in the CdMnTe alloy system. Electrical measurements demonstrated a progressive reduction in resistivity accompanied by increased electrical conductivity, suggesting enhanced charge transport arising from improved grain connectivity and defect-assisted conduction. XRD and SEM analyses further confirmed modifications in crystallinity, lattice structure, and surface morphology with increasing Mn concentration, while EDX spectra verified successful incorporation of Mn without detectable secondary phases. The study establishes a comprehensive correlation between Mn concentration and the resulting structural, optical, electrical, and morphological evolution of electrodeposited CdTe thin films, demonstrating that controlled Mn incorporation provides an effective strategy for tailoring CdTe from a conventional photovoltaic absorber into a wide-bandgap semiconductor suitable for advanced optoelectronic devices, window layers, and tandem solar-cell applications.

Keywords— Bandgap engineering, CdTe thin films, Electrodeposition, Mn doping, Optical characterization, Thin-film photovoltaics.

1 INTRODUCTION

Cadmium telluride (CdTe) is one of the most promising II–VI semiconductor materials for thin-film photovoltaic and optoelectronic applications owing to its direct energy bandgap, high optical absorption coefficient, and excellent photoelectric conversion efficiency (Ahmed et al., 2022). These outstanding properties have made CdTe one of the leading absorber materials in commercial thin-film solar-cell technology and have stimulated extensive research into improving its structural, optical, and electrical performance (Green and Bremner, 2020). Several techniques have been employed for the fabrication of CdTe thin films, including chemical bath deposition, close-spaced sublimation, sputtering, thermal evaporation, and electrodeposition. Among these techniques, electrodeposition has attracted considerable attention because of its simplicity, low production cost, low processing temperature, ease of large-area deposition, and excellent control of film thickness and composition (Ling et al., 2024). Furthermore, electrodeposition offers a scalable route for fabricating semiconductor thin films suitable for photovoltaic and optoelectronic applications Green and Bremner (2020) and Wu et al. (2021). Recent advances in semiconductor engineering have demonstrated that the physical properties of CdTe can be significantly modified through controlled incorporation of suitable dopants (Rahman et al., 2024). Doping provides an effective approach for tailoring the crystal structure, carrier concentration, electrical conductivity, optical response, and defect chemistry of semiconductor materials to satisfy the requirements of modern electronic and photovoltaic devices (Wu et al., 2021). Among the various transition-metal dopants, manganese (Mn) has received considerable attention because of its ability to substitute Cd atoms within the CdTe lattice while maintaining the host crystal structure over an appropriate compositional range (Shah et al., 2024). The incorporation of Mn introduces localized 3d electronic states into the CdTe matrix, resulting in strong sp–d exchange interactions that modify both the electronic band structure and charge transport behaviour (Li et al., 2022).

Unlike many conventional dopants that reduce the bandgap of semiconductor materials, Mn incorporation in CdTe generally produces bandgap widening, thereby transforming CdTe from a conventional absorber material into a wide-bandgap semiconductor (Zhang et al., 2023; Kumar et al., 2023; Nnamani & Okoli, 2026). Such bandgap engineering significantly extends the potential applications of CdTe beyond single-junction photovoltaic devices to include window layers, tandem solar cells, ultraviolet photodetectors, and other advanced optoelectronic technologies (Kumar et al., 2023).

In addition to modifying the optical band structure, Mn incorporation has been reported to influence crystallinity, grain growth, lattice strain, defect density, electrical conductivity, and carrier mobility in CdTe thin films (Beker et al., 2025). These structural modifications strongly influence charge transport mechanisms and ultimately determine the performance and reliability of semiconductor

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devices fabricated from the material (Yimamu et al., 2025). The electrodeposition conditions also play an important role in determining the structural quality and functional properties of CdTe-based thin films. Variations in deposition parameters such as deposition time, cathodic voltage, electrolyte composition, and post-deposition treatment have been shown to influence crystal growth, grain refinement, and the resulting optical and electrical characteristics of CdTe thin films (Santos et al., 2021; Adesiji, 2025). Similarly, post-deposition thermal treatment has been reported to improve crystallinity and electrical performance through defect reduction and grain growth enhancement (Ibikunle, 2025). Consequently, understanding the combined influence of Mn incorporation on the structural, optical, electrical, compositional, and surface morphological characteristics of CdTe thin films has become an important area of semiconductor materials research. Such an integrated understanding is essential for optimizing material performance and facilitating the development of high-efficiency photovoltaic and advanced optoelectronic devices.

Although previous investigations have demonstrated that Mn-doped CdTe thin films possess promising structural, optical, and electrical characteristics for photovoltaic applications, many of these studies have focused primarily on individual material properties rather than establishing an integrated relationship between structural evolution, optical behaviour, electrical transport, elemental composition, and surface morphology under identical electrodeposition conditions (Chander and Tripathi, 2023). The novelty of the present study lies in providing a comprehensive structure–property relationship for electrodeposited Mn-doped CdTe thin films by integrating X-ray diffraction (XRD), ultraviolet–visible spectroscopy, electrical measurements, energy-dispersive X-ray spectroscopy (EDX), and scanning electron microscopy (SEM) within a single experimental framework. This integrated characterization enables a clearer understanding of how Mn incorporation simultaneously modifies crystallinity, optical bandgap, electrical conductivity, elemental composition, and surface morphology. Therefore, this study aims to systematically investigate the influence of Mn incorporation on the structural, optical, electrical, compositional, and surface morphological properties of electrodeposited $Cd_{1-x}Mn_xTe$ thin films. The findings provide valuable insight into the engineering of CdTe-based wide-bandgap semiconductors for advanced photovoltaic and optoelectronic applications.

2 MATERIALS AND METHODS

2.1 PREPARATION OF Mn-DOPED CdTe THIN FILMS

Manganese-doped cadmium telluride ($Cd_{1-x}Mn_xTe$) thin films were deposited on fluorine-doped tin oxide (FTO)-coated glass substrates using the electrodeposition technique at the Nano Physics Laboratory, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria. Analytical-grade cadmium nitrate hexahydrate ($Cd(NO_3)_2{\cdot}6H_2O$), manganese nitrate hexahydrate ($Mn(NO_3)_2{\cdot}6H_2O$), tellurium dioxide (TeO_2), hydrochloric acid (HCl), and distilled water were used as precursor materials without further purification.

Prior to deposition, the FTO-coated glass substrates were thoroughly cleaned with detergent solution, rinsed with distilled water, ultrasonically cleaned in acetone, etched in 5% hydrochloric acid, and finally rinsed with distilled water before being air-dried. This cleaning procedure was adopted to remove surface contaminants and enhance film adhesion during deposition.

The electrolyte solutions were prepared by dissolving the required quantities of cadmium nitrate hexahydrate ($Cd(NO_3)_2{\cdot}6H_2O$), manganese nitrate hexahydrate ($Mn(NO_3)_2{\cdot}6H_2O$), and tellurium dioxide (TeO_2) in distilled water under continuous magnetic stirring using a digital magnetic hot-plate stirrer. The Mn concentration was varied from 0.01 to 0.03 to obtain the different $Cd_{1-x}Mn_xTe$ compositions. Hydrochloric acid (HCl) was added to adjust the electrolyte to a pH of 4.5.

The precursor quantities used for the preparation of the Mn-doped CdTe thin films were varied according to the intended Mn concentration. For $Mn_{0.01}CdTe$, 0.2099 g of $Cd(NO_3)_2{\cdot}6H_2O$, 0.00177 g of $Mn(NO_3)_2{\cdot}6H_2O$, and 0.0983 g of TeO_2 were used. For $Mn_{0.02}CdTe$, 0.2085 g of $Cd(NO_3)_2{\cdot}6H_2O$, 0.00352 g of $Mn(NO_3)_2{\cdot}6H_2O$, and 0.0986 g of TeO_2 were used, while 0.2071 g of $Cd(NO_3)_2{\cdot}6H_2O$, 0.00533 g of $Mn(NO_3)_2{\cdot}6H_2O$, and 0.0988 g of TeO_2 were used for $Mn_{0.03}CdTe$.

Table 1. Quantities of precursor materials used for preparation of Mn-doped CdTe thin films

Sample	$Cd(NO_3)_2{\cdot}6H_2O$ (g)	$Mn(NO_3)_2{\cdot}6H_2O$ (g)	TeO_2 (g)
$Mn_{0.01}CdTe$	0.2099	0.00177	0.0983
$Mn_{0.02}CdTe$	0.2085	0.00352	0.0986
$Mn_{0.03}CdTe$	0.2071	0.00533	0.0988

Electrodeposition was carried out using a conventional three-electrode electrochemical cell comprising an FTO-coated glass working electrode, a graphite counter electrode, and a reference electrode connected to a regulated DC power supply. The deposition was performed at room temperature at an applied voltage of 10 V for 60 s, while the electrolyte was continuously stirred throughout the process to ensure uniform deposition (Shah et al., 2024; Zhang et al., 2023). The electrochemical deposition reactions responsible for the formation of $Cd_{1-x}Mn_xTe$ thin films are represented as follows:

$$Cd^{2+} + 2e^- \rightarrow Cd(s) \quad (1)$$

$$Mn^{2+} + 2e^- \rightarrow Mn(s) \quad (2)$$

$$TeO_2 + 4H^+ + 4e^- \rightarrow Te(s) + 2H_2O \quad (3)$$

$$Cd(s) + Te(s) \rightarrow CdTe(s) \quad (4)$$

$$CdTe + xMn \rightarrow Cd_{1-x}Mn_xTe(s) \quad (5)$$

Overall reaction:

$$(1-x)Cd^{2+} + xMn^{2+} + TeO_2 + 4H^+ + 6e^- \rightarrow Cd_{1-x}Mn_xTe + 2H_2O \quad (6)$$

Following electrodeposition, the deposited films were thoroughly rinsed with distilled water to remove residual electrolyte and subsequently annealed in an electrically heated thermostatic blast dry box (Model DHG-9101) at 100 °C for 40 min before characterization. The annealing

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treatment was carried out to improve crystallinity, reduce internal defects, and enhance film adhesion and structural stability (Green and Bremner, 2020).

2.2 STRUCTURAL CHARACTERIZATION

The crystal structure and phase composition of the deposited $Cd_{1-x}Mn_xTe$ thin films were investigated using a Bruker D8 Advance X-ray diffractometer (Bruker AXS GmbH, Germany) employing Cu Kα radiation (λ = 1.5406 Å). The diffraction patterns were recorded over an appropriate 2θ scanning range under standard operating conditions to identify the crystalline phases, preferred orientation, crystallite size, and structural modifications induced by Mn incorporation (Kumar et al., 2023).

2.3 OPTICAL CHARACTERIZATION

The optical properties of the deposited thin films were investigated using a UV–1800 UV–Visible spectrophotometer over the wavelength range of 300–1100 nm at the Nano Physics Laboratory, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria. The absorbance and transmittance spectra obtained from the measurements were subsequently used to determine the reflectance, absorption coefficient, refractive index, extinction coefficient, and optical bandgap energy using established optical relationships for semiconductor thin films (Chander and Tripathi, 2023).

2.4 ELECTRICAL CHARACTERIZATION

The electrical properties of the deposited thin films were evaluated at room temperature. The electrical resistance of each sample was measured using the electrical measurement system available at the Nano Physics Laboratory, University of Nigeria, Nsukka. The measured resistance and film thickness were used to determine the electrical resistivity using the thin-film electrical transport relation. The electrical conductivity was subsequently calculated as the reciprocal of the resistivity, $\sigma = 1/\rho$. The same measurement procedure was applied to all deposited films to ensure consistent comparison of their electrical properties.

2.5 SURFACE MORPHOLOGY AND ELEMENTAL COMPOSITION

The surface morphology and elemental composition of the deposited thin films were investigated using an Axia ChemiSEM Scanning Electron Microscope (Thermo Fisher Scientific, USA) equipped with an integrated Energy-Dispersive X-ray Spectroscopy (EDS) detector. The SEM analysis was performed at an accelerating voltage of 5.0 kV and a magnification of 100.0 kX. The SEM micrographs were used to evaluate the surface morphology of the deposited films, while the EDS spectra were used to determine their elemental composition and confirm Mn incorporation into the CdTe matrix.

3 RESULTS AND DISCUSSION

The results are presented to examine the effects of Mn incorporation on the properties of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films. Particular attention is given to the changes in crystal structure, optical response, electrical behaviour, elemental composition, and surface morphology as the Mn concentration increases.

3.1 OPTICAL PROPERTIES

The optical properties of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films were investigated using UV–Visible spectroscopy to evaluate the influence of Mn incorporation on light absorption and optical constants. The measured spectra were used to determine the absorbance, transmittance, reflectance, refractive index, extinction coefficient, absorption coefficient, and optical bandgap of the deposited thin films.

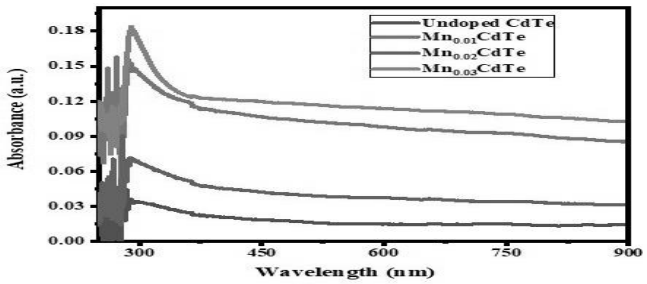

Fig. 1. Absorbance Spectra

Figure 1 presents the absorbance spectra of undoped CdTe and Mn-doped CdTe thin films deposited by the electrodeposition technique. All the films exhibit strong optical absorption within the visible region of the electromagnetic spectrum, indicating their potential relevance for photovoltaic applications. With Mn incorporation, the absorption behaviour of the CdTe films is modified, with the absorption edge showing a tendency toward shorter wavelengths. Such modification of the optical response has been reported for Mn-doped CdTe thin films and is associated with Mn-induced changes in the electronic structure of the CdTe matrix (Kumar et al., 2023). The variation is not strictly monotonic with Mn concentration, as $Mn_{0.01}CdTe$ exhibits higher absorbance than $Mn_{0.02}CdTe$ over part of the investigated wavelength range, while $Mn_{0.03}CdTe$ shows the highest absorbance. This concentration-dependent variation may reflect differences in the structural and electronic characteristics of the films resulting from Mn incorporation (Kumar et al., 2023).

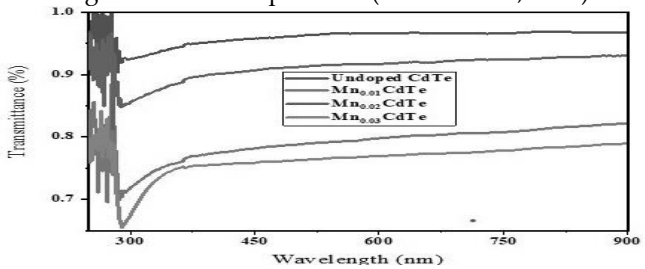

Fig. 2. Transmittance Spectra

Figure 2 illustrates the transmittance spectra of the deposited $Cd_{1-x}Mn_xTe$ thin films. The transmittance of the films varies with Mn concentration across the investigated wavelength range, indicating that Mn incorporation modifies the optical response of the CdTe matrix. The variation is not strictly monotonic, as the $Mn_{0.01}CdTe$ film exhibits higher transmittance than $Mn_{0.02}CdTe$ over much of the visible and near-infrared regions, while $Mn_{0.03}CdTe$ exhibits lower transmittance than $Mn_{0.01}CdTe$. Such concentration-dependent variations in the optical response of Mn-doped CdTe films have been reported in the literature and may arise from changes in the electronic and structural

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characteristics associated with Mn incorporation (Kumar et al., 2023). The observed transmittance behaviour is therefore consistent with a concentration-dependent modification of the optical properties rather than a strictly progressive increase with Mn concentration.

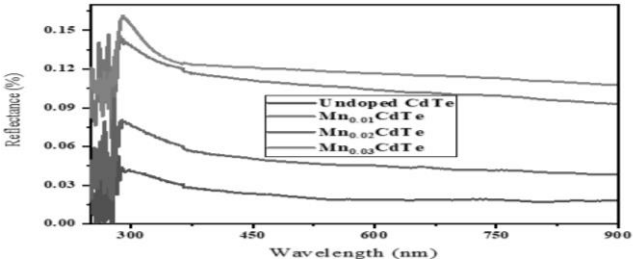

Fig. 3. Reflectance Spectra

Figure 3 shows the reflectance spectra of the prepared thin films. The reflectance generally increases with Mn incorporation, particularly at shorter wavelengths, with the $Mn_{0.03}CdTe$ film exhibiting the highest reflectance among the investigated samples. The observed increase in reflectance indicates that Mn incorporation modifies the optical response of the CdTe matrix. Similar modifications of the optical properties of Mn-doped CdTe thin films have been reported in the literature and have been associated with changes in the electronic and structural characteristics of the films following Mn incorporation (Kumar et al., 2023; Li et al., 2022). The concentration-dependent reflectance behaviour may also be influenced by changes in the refractive index and surface characteristics of the deposited films (Kumar et al., 2023).

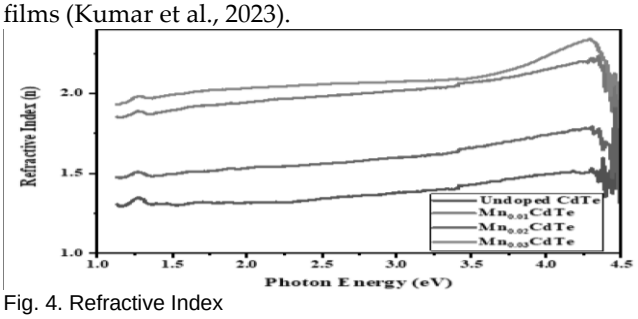

Fig. 4. Refractive Index

Figure 4 presents the variation of refractive index with photon energy for the deposited $Cd_{1-x}Mn_xTe$ thin films. The refractive index varies with photon energy for all the investigated films, with noticeable differences among the samples at different Mn concentrations. The variation is not strictly monotonic with Mn concentration, as the $Mn_{0.02}CdTe$ film exhibits a comparatively higher refractive index over much of the investigated photon-energy range. This concentration-dependent modification of the refractive index is consistent with changes in the optical response of CdTe associated with Mn incorporation, as reported for Mn-doped CdTe and related CdTe-based alloys (Kumar et al., 2023; Li et al., 2022). The observed variation indicates that Mn incorporation modifies the optical response of the CdTe matrix, although the specific dependence on Mn concentration is not strictly progressive.

Figure 5 presents the extinction coefficient of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films as a function of wavelength. The extinction coefficient varies among the films following Mn incorporation, with the $Mn_{0.03}CdTe$ film exhibiting the highest values over most of the investigated wavelength range, while the undoped CdTe film shows the lowest values. The variation is not strictly monotonic with

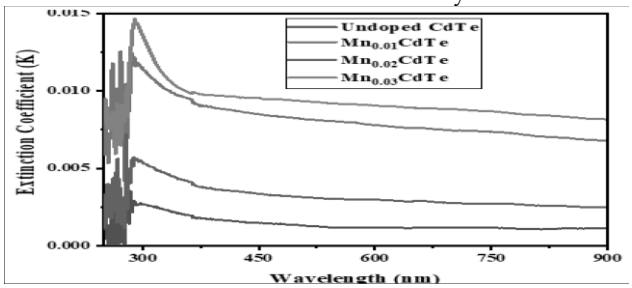

Fig. 5. Extinction Coefficient

Mn concentration, as the $Mn_{0.01}CdTe$ film exhibits higher extinction coefficients than the $Mn_{0.02}CdTe$ film over much of the investigated range. The observed modification of the extinction coefficient indicates changes in the optical interaction and attenuation of electromagnetic radiation following Mn incorporation. Similar concentration-dependent modifications of the optical properties of Mn-doped CdTe thin films have been reported in the literature (Kumar et al., 2023; Li et al., 2022).

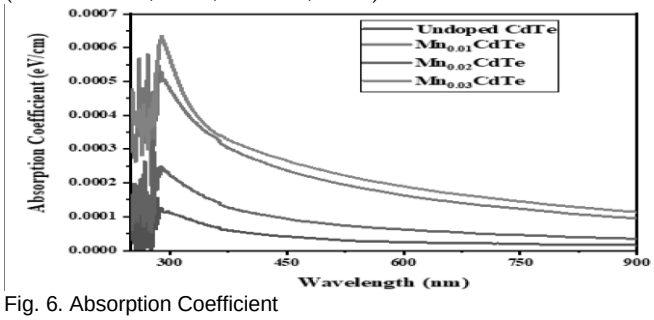

Fig. 6. Absorption Coefficient

Figure 6 illustrates the absorption coefficient of the prepared $Cd_{1-x}Mn_xTe$ thin films as a function of wavelength. The absorption coefficient is higher for the Mn-doped films than for the undoped CdTe film over much of the investigated wavelength range, with $Mn_{0.03}CdTe$ exhibiting the highest absorption coefficient among the deposited films. The observed differences indicate that Mn incorporation modifies the optical absorption characteristics of the CdTe matrix. Similar modifications of the optical properties of Mn-doped CdTe thin films associated with Mn incorporation have been reported in the literature (Kumar et al., 2023; Li et al., 2022). The variation in absorption coefficient with Mn concentration is therefore consistent with concentration-dependent modification of the optical response of the $Cd_{1-x}Mn_xTe$ films.

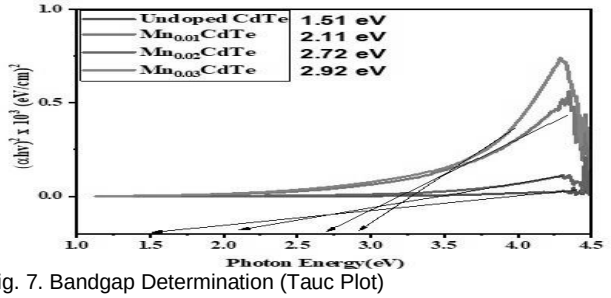

Fig. 7. Bandgap Determination (Tauc Plot)

Figure 7 presents the Tauc plots used to determine the optical bandgap energies of the deposited $Cd_{1-x}Mn_xTe$ thin films. The estimated optical bandgap increases from 1.51 eV for undoped CdTe to 2.11, 2.72, and 2.92 eV for $Mn_{0.01}CdTe$, $Mn_{0.02}CdTe$, and $Mn_{0.03}CdTe$, respectively. The results therefore indicate a systematic widening of the optical bandgap with increasing Mn concentration. The

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corresponding shift of the absorption edge toward higher photon energies is consistent with modification of the electronic structure of CdTe following Mn incorporation. Such bandgap tuning in Mn-doped CdTe and related CdTe-based ternary systems has been reported in previous studies (Zhang et al., 2023; Kumar et al., 2023). The observed increase in bandgap demonstrates that Mn incorporation provides a means of modifying the optical response of CdTe thin films over the investigated composition range.

3.2 STRUCTURAL PROPERTIES

The structural characteristics of the deposited $Cd_{1-x}Mn_xTe$ thin films were examined using X-ray diffraction (XRD) to determine the crystal structure, phase composition, crystallinity, and the effect of Mn incorporation on the lattice structure.

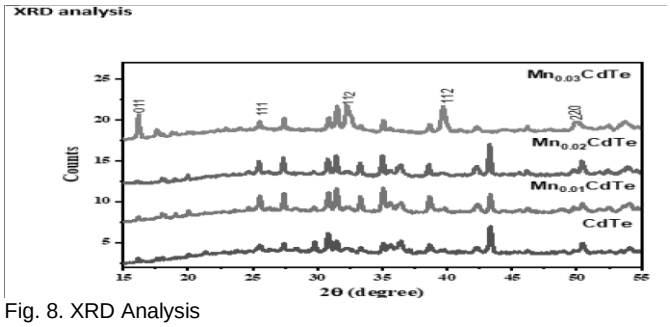

Fig. 8. XRD Analysis

Figure 8 presents the X-ray diffraction (XRD) patterns of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films with varying Mn concentrations. The diffraction patterns of the undoped CdTe and Mn-doped CdTe films exhibit the characteristic CdTe-related reflections, with the indexed features including the (011), (111), (112), and (220) planes. These principal diffraction features are retained after Mn incorporation, indicating that the basic crystalline structure of the CdTe host is preserved over the investigated Mn concentration range. No additional dominant diffraction peaks attributable to a distinct crystalline secondary phase are evident in the patterns, suggesting that Mn incorporation does not produce a prominent separate crystalline phase under the deposition conditions used. With increasing Mn concentration, variations in the relative peak intensities and peak widths are observed, indicating changes in crystallinity and lattice disorder. The changes in the diffraction profiles are consistent with the incorporation of Mn into the CdTe matrix and the resulting modification of the crystal structure. Thus, the XRD results demonstrate that Mn addition modifies the structural characteristics of the CdTe films while retaining the principal CdTe crystalline framework.

3.3 ELECTRICAL PROPERTIES

The electrical behaviour of the deposited thin films was investigated by evaluating the variation in film thickness, electrical resistivity, and conductivity with increasing Mn concentration. These parameters provide useful information on the influence of Mn incorporation on charge transport within the CdTe matrix.

Figure 9 presents the variation of electrical resistivity and conductivity of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films, while the corresponding numerical values together with the measured film thicknesses are summarized in Table 2.

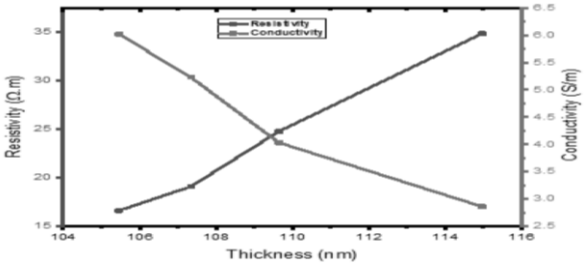

Fig. 9. Electrical Properties (Resistivity and Conductivity)

The results show that the film thickness decreases systematically from 114.97 nm for undoped CdTe to 105.46 nm for the film containing 3% Mn. This reduction in thickness may be associated with changes in the growth process following Mn incorporation, including differences in nucleation, surface diffusion, and the compactness of the deposited layer. The observed trend indicates that Mn incorporation affects the deposition and resulting film thickness of the $Cd_{1-x}Mn_xTe$ films.

The electrical resistivity decreases from 34.87×10^{-7} Ω·m for undoped CdTe to 16.60×10^{-7} Ω·m for the film containing 3% Mn, while the corresponding conductivity increases from 2.87×10^{5} S·m^{-1} to 6.02×10^{5} S·m^{-1}. The reduction in resistivity and corresponding increase in conductivity indicate enhanced electrical transport with Mn incorporation. The observed variation may be associated with changes in the microstructure and charge-transport characteristics of the deposited films, consistent with reported electrical-property modifications in electrodeposited CdMnTe thin films (Adesiji, 2025; Ibikunle, 2025).

Table 2. Electrical Properties of the Deposited CdMnTe Thin Films

Material	Thickness (nm)	Resistivity, ϱ (×10⁻⁷ Ω·m)	Conductivity, σ (×10⁵ S·m⁻¹)
Undoped CdTe	114.97	34.87	2.87
$Mn_{0.01}CdTe$	109.65	24.78	4.04
$Mn_{0.02}CdTe$	107.34	19.09	5.24
$Mn_{0.03}CdTe$	105.46	16.60	6.02

3.4 ELEMENTAL COMPOSITION

The elemental composition of the deposited thin films was analysed using Energy-Dispersive X-ray Spectroscopy (EDX) to verify the successful incorporation of Mn into the CdTe lattice and to assess the chemical purity of the deposited films.

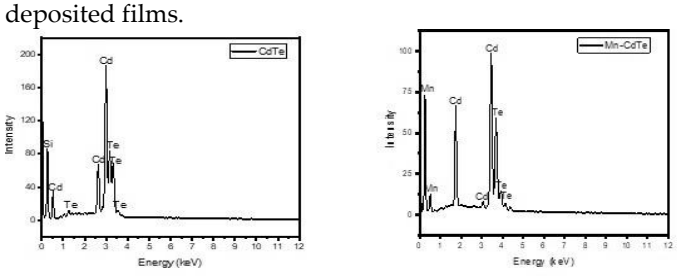

Fig. 10. EDX Analysis

Figure 10 presents the EDX spectra of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films. The spectrum of the undoped CdTe film shows the characteristic signals associated with Cd and

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Te, while the Mn–CdTe spectrum additionally exhibits Mn signals, providing direct evidence for the presence of Mn in the Mn-containing deposited film. The simultaneous detection of Cd, Te, and Mn is consistent with the formation of a Mn-containing CdTe-based thin film. No additional prominent elemental signals attributable to obvious foreign phases are observed in the displayed spectra within the detection capability of the EDX measurement.

The EDX results therefore provide compositional evidence for Mn incorporation into the deposited CdTe film. However, because the displayed EDX analysis does not provide separate spectra for each Mn concentration, the present data do not establish a progressive increase in Mn content with nominal Mn concentration. The compositional observation is consistent with previous reports of Mn incorporation in electrodeposited CdTe-based thin films (Ahmed et al., 2022). The EDX results complement the structural and optical analyses by providing direct elemental evidence for the presence of Mn in the Mn-containing film.

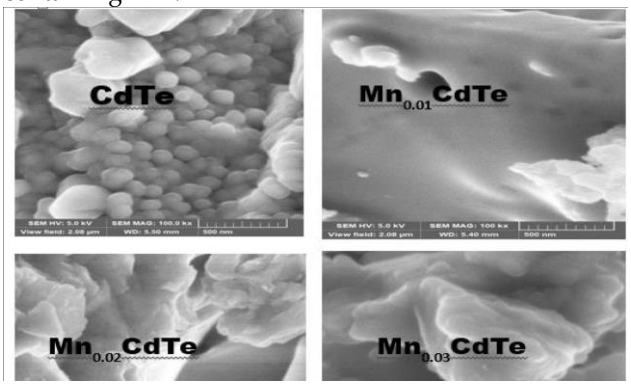

Fig. 11. Surface Morphology (SEM Images)

Figure 11 presents the scanning electron microscopy (SEM) micrographs of the electrodeposited $Cd_{1-x}Mn_xTe$ thin films deposited at different Mn concentrations. The micrographs reveal a clear evolution in surface morphology with increasing Mn incorporation, indicating that Mn significantly influences the nucleation and growth mechanisms during electrodeposition. The undoped CdTe film exhibits relatively large, compact, and uniformly distributed grains with good surface coverage, indicating successful formation of continuous polycrystalline CdTe thin films. The compact morphology suggests effective grain growth during electrodeposition, which is beneficial for reducing grain-boundary defects and improving charge transport. Upon Mn incorporation, the surface morphology changes progressively, with noticeable grain refinement and increased grain density. The reduction in grain size is attributed to the substitution of Cd^{2+} ions by the smaller Mn^{2+} ions, which increases the nucleation rate during film growth and suppresses excessive grain coarsening.

Similar grain refinement and microstructural evolution following Mn incorporation have been reported by Shah et al. (2024). Consequently, the films become more compact, with reduced intergranular voids and improved surface uniformity. At moderate Mn concentrations, the SEM images indicate improved grain connectivity and better surface homogeneity, suggesting enhanced structural compactness. Such morphological improvement is expected to reduce grain-boundary scattering and facilitate charge transport across the deposited films, consistent with the observed decrease in electrical resistivity and increase in electrical conductivity.

However, at the highest Mn concentration, slight surface irregularities and increased roughness become apparent, indicating that excessive Mn incorporation introduces lattice strain and localized structural disorder. Excessive grain refinement may also increase the density of grain boundaries, which can serve as carrier recombination centres and partially offset the electrical improvements obtained at moderate doping levels. The SEM observations are in good agreement with the XRD analysis, which revealed changes in crystallinity and lattice structure following Mn incorporation, and with the EDX analysis confirming successful Mn incorporation into the CdTe matrix. The combined structural, compositional, and morphological results demonstrate that Mn doping effectively modifies the microstructure of electrodeposited CdTe thin films and contributes to the observed improvements in their optical and electrical properties.

Overall, the SEM analysis confirms that controlled Mn incorporation promotes the formation of dense, uniform, and well-connected $Cd_{1-x}Mn_xTe$ thin films. Among the investigated compositions, the film containing approximately 2% Mn exhibits the most favourable surface morphology, providing an optimal balance between grain refinement, structural integrity, and electrical performance, thereby making it the most promising composition for photovoltaic and optoelectronic applications (Shah et al., 2024).

4 CONCLUSION

1. Mn-doped CdTe ($Cd_{1-x}Mn_xTe$) thin films were successfully deposited by electrodeposition, and their structural, optical, electrical, compositional, and surface morphological properties were systematically investigated.
2. Mn incorporation progressively increased the optical bandgap from 1.51 eV for undoped CdTe to 2.92 eV at the highest Mn concentration, accompanied by systematic modifications in the optical response, indicating effective optical-property tuning through Mn incorporation.
3. XRD, EDX, and SEM analyses confirmed the formation of Mn-incorporated CdTe films, with Mn incorporation producing changes in lattice structure, crystallinity, elemental composition, grain morphology, and surface compactness.
4. Electrical resistivity decreased from 34.87×10^{-7} Ω·m to 16.60×10^{-7} Ω·m, while conductivity increased from 2.87×10^{5} $S \cdot m^{-1}$ to 6.02×10^{5} $S \cdot m^{-1}$ with increasing Mn concentration, demonstrating enhanced electrical transport.
5. Among the investigated compositions, the film containing approximately 2% Mn exhibited the most favourable overall balance of structural, optical, electrical, and morphological properties, identifying it as the most promising composition among those studied.
6. The results demonstrate that controlled Mn incorporation

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provides an effective route for tailoring electrodeposited CdTe thin films for photovoltaic and optoelectronic applications.

5 FUTURE WORK

Future investigations should focus on optimizing the electrodeposition potential, electrolyte composition, pH, and annealing conditions, followed by fabrication and performance evaluation of complete photovoltaic devices based on the optimized $Cd_{1-x}Mn_xTe$ films.

Conflict of interest: The author declares no conflict of interest.

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