



تأثير درجات حرارة التلدين على الخواص التركيبية والبصرية لأغشية CdTe المحضرة بطريقة

الترسيب بالاستئصال الليزري

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الخلاصة

تم في هذا البحث تقديم تحليلاً شاملاً للخصائص البنيوية والتركيبية السطحية (المورفولوجيا) لأغشية CdTe الرقيقة المحضرة بتقنية الترسيب بالاستئصال الليزري (PLA) بحجم حبيبات يتراوح بين 70 و120 نانومتراً. يشمل التحليل تأثير تغير درجة حرارة التلدين لنفس الأغشية عند درجات حرارة مختلفة (50, 150, 250, 350 °C)، متبوعاً بفحص خشونة سطحها، حيث استُخدمت عدة تقنيات رئيسية منها حيود الأشعة السينية (XRD) لتحديد الطور البلوري وتقييم اتجاهات النمو السائدة؛ مجهر القوة الذرية (AFM) لتحليل مورفولوجيا السطح وخشونته وتوزيع حبيباته، ومطيافية الأشعة فوق البنفسجية والمرئية (UV-spectrophotometer). تم توضيح تأثير تغير درجة حرارة التلدين الحراري على خصائص الأغشية، بدءاً من مرحلة النمو غير المستقرة الأولية وصولاً إلى درجة الانتظام البنيوي والمورفولوجيا العالية الملاحظة بعد التلدين. توضح هذه الدراسة تأثير درجة حرارة التلدين على جودة الفيلم، مما يوفر أساساً علمياً متيناً لتطبيقات CdTe المستقبلية في الخلايا الشمسية واشباه الموصلات.

الكلمات المفتاحية: CdTe، المورفولوجيا، الاستئصال الليزري، التلدين، الخواص البنيوية، الخواص البصرية.

Effect of Annealing Temperatures on the Structural and Optical Properties of CdTe Films Prepared by Pulsed Laser Ablation

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Abstract

In this work a comprehensive analysis of the structural and surface compositional morphological properties of cadmium telluride thin films prepared by pulse laser ablation PLA with grain sizes ranging from 70 to 120 nm the analysis includes the effect of varying the annealing temperature of the same films at different temperature 50-150-250 and 350°C followed by an examination of their surface roughness and Grain distribution main techniques were used X-ray diffraction XRD to determine the crystalline phase and evaluate the dominant growth trends atomic Force microscopy AFM to analyze the surface morphology roughness and Grain distribution in UV- visible spectrophotometry the effect of varying and kneeling temperature on film properties was elucidated from the initial unstable growth phase to the high degree of structural regularity and morphology observed after a kneeling this study demonstrates the impact of annealing temperature on film quality



providing a solid scientific foundation for future cadmium telluride applications in solar cells and semiconductor.

Keywords: CdTe; morphology; pulsed laser; annealing; structural; optical.

1. Introduction

Cadmium telluride CdTe is a prominent II-VI, semiconductor material widely recognized for its applications in photovoltaic devices particularly in thin film solar cells and X-ray detectors [1], the performance of cadmium telluride based devices critically depends on the quality of the deposited cadmium telluride films which is influenced by various processing parameters host laser ablation PLA of versatile in powerful technique for fabricating high quality semiconductor thin film offering precise control over film composition and microstructure [2], However the as deposited cadmium telluride film often exhibits suboptimal properties such as structural defects or high defect densities which can hinder their performance annealing a thermal treatment process is frequently employed as a crucial post deposition step to improve the crystallinity reduce defects and modify the electronic properties of thin films this study aims to investigate the influence of an annealing temperature on the structural and optical characteristics of cadmium telluride films prepared using the PLA method by systematically varying the annealing temperature we explore how this parameter affects the film's crystal and grain size macro strain and optical band gap providing valuable insights for optimizing cadmium telluride film quality for advanced top to electric applications.

2. Physical and Chemical Properties of CdTe

Cadmium telluride is a II-V semiconductor compound that has garnered significant attention in the fields of photovoltaic optoelectronics and sensors due to its unique physical and chemical properties this article explores the key characteristics of cadmium telluride including its crystal structure electronic properties optical properties in chemical stability providing insights into why it is a material of choice for various technological applications

2.1. Crystal Structure

Te, crystallizes in a zinc blend structure, this structure is cubic with a space group of F-43m [4]. The unit cell contains four formula units and has a lattice constant of approximately 0.6486 nm at room temperature the Zinc blend structure consists of a face centered cubic lattice of one type of atom (Cd or Te) with the other type of atom occupying half of the tetrahedral interstitial sites [5]

3. Electronic Properties

3.1. Bandgap Energy



The most notable properties of cadmium telluride is its Direct banded gap energy which is approximately 1.45 e. V at room temperature [6], this band gap makes cadmium telluride suitable for applications in the visible and near infrared regions of the electromagnetic spectrum the Direct band gap nature of cadmium telluride allows for efficient radiative recombination which is beneficial for Optical electric devices such as solar cells and light emitting diodes [7].

3.2. Carrier Mobility

Cadmium telluride exhibits relatively high carrier mobility which is crucial for its use in high performance electronic devices [8]. The electron mobility in cadmium telluride is typically around $1000 \text{ cm}^2/\text{V.s}$, while the hole mobility is around $400 \text{ cm}^2/\text{V. s}$ at room temperature[9].

3.3. Electrical Conductivity

The electrical conductivity of CdTe can be controlled by doping. n-type doping is commonly achieved using elements such as Cl, while p-type doping can be realized using oxygen (O) or copper (Cu) [10]. The ability to easily dope CdTe makes it suitable for the fabrication of various electronic devices.

4. Optical Properties

4.1. Absorption and Emission

Cadmium telluride possesses a high absorption coefficient within the visible and near infrared regions, rendering it an excellent material for photodetectors and solar cells. The material also exhibits strong luminescence, featuring a sharp emission peak at approximately 800 nm for undoped cadmium telluride [11]. This property finds application in devices such as light-emitting diodes (LEDs) and lasers.

4.2. Transparency

CdTe is transparent in the visible and near infrared regions with a transparency window that extends up to about 1100 nm [11]. This transparency makes it suitable for use in optical coatings and wave guides.

5. Chemical Properties

CdTe is relatively stable under ambient conditions but can be sensitive to moisture and oxygen. The surface of cadmium telluride can be passivated to enhance its stability [12]. Common passivation methods include the use of thin layers of silicon dioxide (SiO_2) or aluminum oxide (Al_2O_3) [13].

5.1. Reactivity



CdTe can react with certain metals to form alloys, which can modify its band gap energy [14]. This property is exploited in the fabrication of multi-junction solar cells, where different alloy compositions are used to cover a broader range of the Solar spectrum.

6. Applications

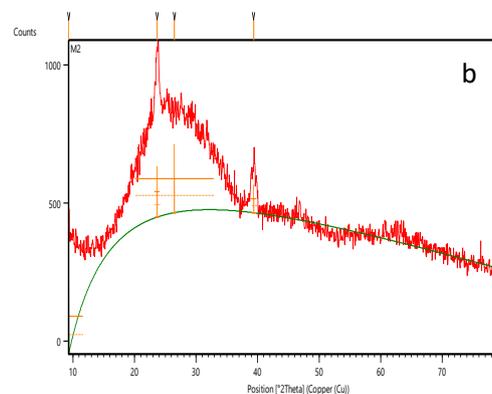
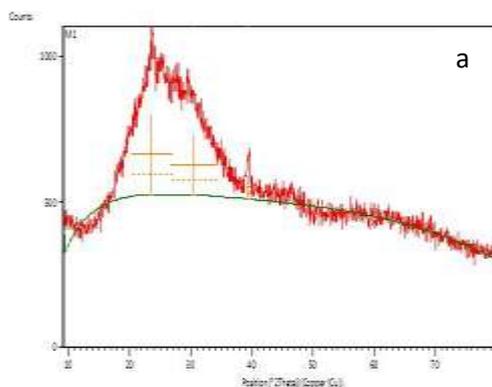
Photovoltaics: cadmium telluride is widely used in thin film solar cells due to its high absorption coefficient and Direct band gap [15] [16]. CdTe solar cells have achieved efficiencies of over 22% making them one of the most efficient thin film solar technologies available.

Optoelectronics. The optoelectronics properties of CdTe make it suitable for use in light emitting diodes (LEDs), lasers and photo detectors. Its ability to emit light in the near infrared region is particularly valuable for medical imaging and communication systems [17] [18].

Sensors: CdTe is also used in various sensor applications including gas sensors and chemical sensors its high sensitivity to environmental changes makes it an effective material for detecting trace gases and chemical species.

7. Experiments analysis

Three CdTe samples were prepared and their thermal treatments at three temperatures (50-150-250 and 350°C), as shown in Figure 1, which illustrates their XRD pattern.



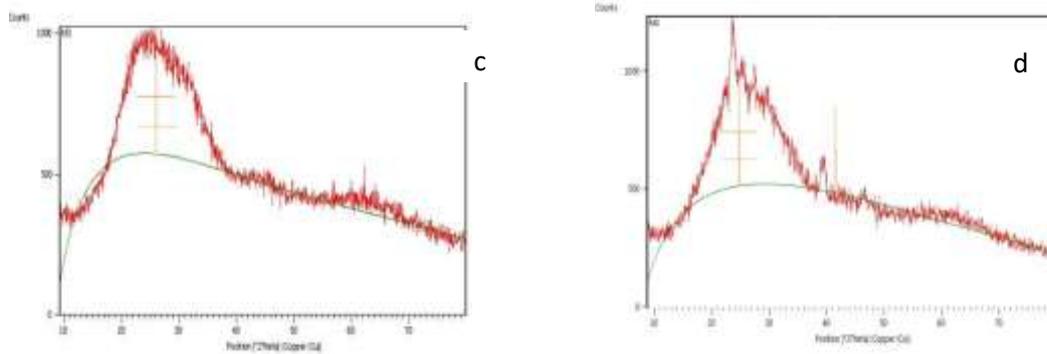
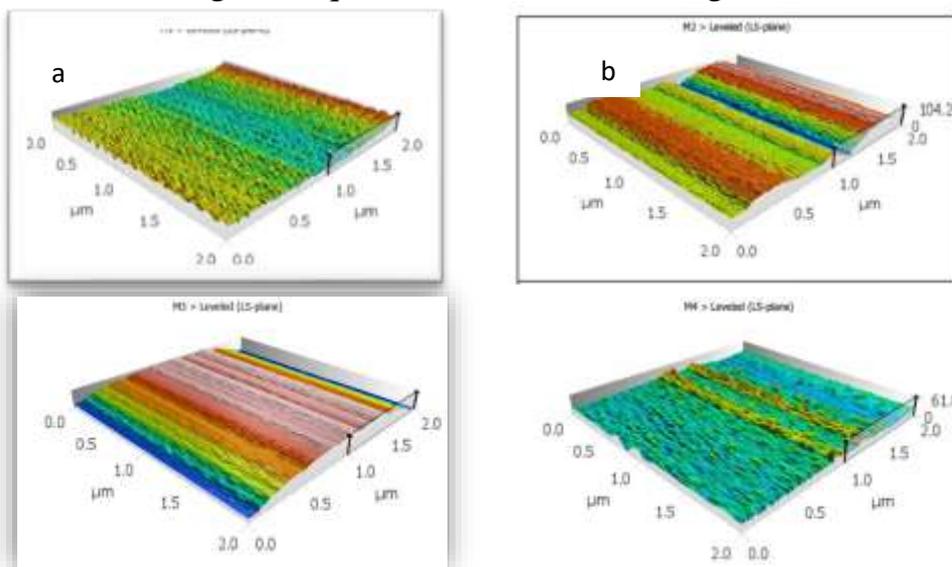


Figure 1. XRD at temperatures of a-50,b-150, C-250, and d-350°C

XRD analysis showed that all samples belong to the cubic FCC phase but the intensity clarity, and FWHM values showed a marked improvement with increasing annealing with sample (d at 350°C) achieving the highest degree of crystallinity

8. Three-dimensional topography

ASM analysis revealed a gradual morphological evolution from a very rough and irregular surface in sample 1-a to a homogeneous low roughness surface in sample (d), with a significant decrease in grain height and distribution and a shift from a random growth pattern to a highly uniform directed pattern this indicates that a kneeling at 350°C, represents the optimal temperature for improving structural regularity and homogeneity making sample d the most suitable for Optical in optical electric applications. All three techniques share the conclusion that the treatment plays a crucial role in enhancing the performance of cadmium telluride layers and developing their physical properties to meet modern technological requirements as shown in figure 2.



d

C



Figure (2) Three-dimensional topography at temperatures a-50 , b-150 , c- 250, d-350°C

9. Extended optical analysis of CdTe films using UV-Vis spectroscopy.

Optical absorption analysis using UV- vis. Spectroscopy is one of the most important techniques used in characterizing semiconductor materials and thin films as it provides a precise understanding of the electronic structure in energy transitions between valence and conduction levels this technique relies on measuring the amount of light the absorbed by the sample at different wavelengths within the range of 300 to 1100 nm which covers the ultraviolet visible and near infrared regions this makes it an effective tool for studying the optical behavior of CdTe materials used in photovoltaic applications.

The importance of this analysis lies in its ability to determine the absorption coefficient assess the materials quality in terms of the presence of electronic defects and band gaps and accurately estimate the band gap using the tauc method this directly reflects the materials of ability to absorb light and convert it into electrical energy UV-vis. Analysis also allows for comparing the effects of different treatments such as thermal annealing on the electronic structure improving crystallinity and reducing surface distortions lead to significant changes in the absorption curve both in terms of absorption intensity in the slope of the absorption curve in the infrared region this analysis is particularly important for studying cadmium telluride films as absorption capacity in the visible and near infrared ranges is crucial for maximizing solar cell efficiency therefore UV- vis. Analysis is a central step in assessing the suitability of these films for practical applications and in understanding the relationship between structural properties revealed by XRD and AFM and optical properties related to electronic transitions within the material figure 3, shows the optical absorption curves of the four cadmium telluride samples (a-d) in the 300 to 1100 nm range this analysis is essential for understanding the electronic and optical changes resulting from thermal and kneeling the spectrum clearly demonstrates the relationship between the degree of annealing and the films ability to absorb light a key property in semiconductor materials used in solar cells absorption begins at very high values in the ultraviolet region 300 to 350 nm where the phenomenon of sharp absorption occurs due to direct electronic transitions between the valence band and the conduction band sample (d), exhibits the highest absorption in this region followed by (C), then (b), and finally (a), reflecting the gradual improvement in the quality of the electronic structure with increasing a kneeling this behavior is explained by the fact that a kneeling reduces the levels of defect States within the gap and remove surface impurities that act as unwanted recombination Centers allowing the material to absorb light more efficiently



In the region 350 to 600 nm the absorption curves gradually stabilize with the appearance of the so-called (urbach tail) a part of the spectrum directly affected by lattice disturbances and spatial defects sample a exhibits a longer and steeper tail indicating your regular energy levels within the gap due to poor crystallinity and numerous structural defects the annealed samples especially C and d exhibits shorter smoother tales reflecting a marked improvement in crystal lattice regularity this aligns perfectly with the XRD results which showed a decrease in FWHM and an increase in Crystal Peak intensity with a annealing.

In the visible- infrared region 600 to 1100 nm the absorption continues to decrease gradually a behavior typical of direct semiconductors such as CdTe. The Subtle differences between the sample curves indicate important effects on the energy gap the curve with the highest absorption (d) has a relatively smaller energy gap due to reduce defects and improved grain cohesion while the lower absorption values in sample (a), indicate a larger effective energy gap resulting from the presence of local energy levels that inhibit electron transitions.

The differences between the samples demonstrate the crucial role of thermal annealing in the reorganization of atoms within the lattice. Annealing leads to[19]:

- i. Increased grain size and reduced grain boundaries.
This reduces electron scattering and improves absorption in the visible region.
- ii. Reducing crystalline distortions
This makes optical transitions more pronounced and reduces the impact of defects on absorption.
- iii. Improving internal cohesion within the layer
This reduces light scattering losses and increases the absorption coefficient.

A direct relationship can be observed between optical behavior and AFM analysis:

The more uniform the surface and grain size (as in C and d), the better the light absorption capacity, due to the reduction of random paths taken by light within the material. Furthermore, the optical improvement shown by increased absorption across the spectral range of sample d suggests that this sample possesses superior crystalline and morphological quality, making it the most efficient for solar cell applications, where high absorption in the visible-infrared range is required to capture the maximum amount of solar radiation. Overall, the UV-Vis plot provides clear evidence of:

The progressively positive effect of annealing degrees on optical properties

Increased absorbance with annealing

Improved electron transitions and reduced internal defects

The results are consistent with XRD and AFM, confirming the unity of the structural and optical conclusions as in figure 4.

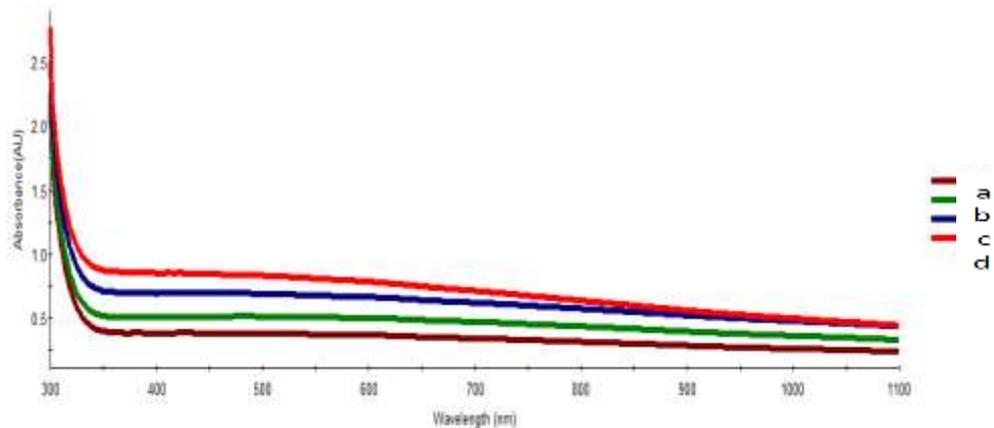


Figure (5): UV–Vis absorption curves for samples a–50, b-150, c-250, d-350°C
10. Conclusions

The results demonstrate that thermal annealing has a pivotal effect on improving the structural, chemical, and morphological properties of CdTe thin films. XRD analysis showed that all samples belonged to the cubic (FCC) phase, but the peak intensity, clarity, and FWHM values showed a marked improvement with increasing annealing degree, with sample d exhibiting the highest degree of crystallinity and lattice stability.

AFM analysis revealed a gradual morphological evolution from a very rough and irregular surface in sample (a) to a homogeneous low roughness surface in sample (d) with (a) significant decrease in grain height and distribution and a transformation from a random growth pattern to a highly uniform directed pattern thus it becomes clear that a kneeling at 350°C represents the optimal temperature for improving structural regularity and homogeneity making the (d) sample the most suitable for Optical in optical electric applications all three techniques share the conclusion that the treatment plays a crucial role in enhancing the performance of cadmium telluride layers and developing their physical properties to meet the requirements of modern technology.

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