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# Development of CdMnTe Thin Films Using Electroplating Technique for Opto-Electronic Device Applications

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## Abstract

Cathodic electrodeposition technique has been successfully used to achieve the growth of polycrystalline CdMnTe ternary compound thin films at different cathodic potentials. The choice of various cathodic potentials used in this work was made from the cyclic voltammogram results. The CdMnTe thin films were electroplated from electrolytes containing CdSO<sub>4</sub>, TeO<sub>2</sub> and MnSO<sub>4</sub> in an acidic aqueous medium. The electrodeposition was carried out on glass/fluorine-doped tin oxide {FTO} substrates. The optical, structural, morphological, and electrical properties of the CdMnTe thin films were studied using UV-Vis spectroscopy, X-ray diffraction (XRD), Scanning electron microscopy (SEM), Keithley 2401 source meter current – voltage (I-V) system and Photo-electro-chemical (PEC) cell measurements respectively. The materials investigated in this work were explored under three different conditions namely: as-deposited (AD), heat-treated ordinarily in air (HT) and heat-treated in air in the presence of CdCl<sub>2</sub> surface treatment (CC). Results from the XRD showed that the electrodeposited films are polycrystalline with the presence of CdTe<sub>x</sub>O<sub>y</sub>, CdTe and CdMnTe peaks. The electroplated films have cubic crystal structures and the preferred orientation was found to be along the (111) plane of CdTe peak. The optical energy bandgaps of the thin films were found to be deposition potential dependent. Electrical conductivity types namely p – and n – type conductivity were also obtained at different cathodic potentials using photo-electro-chemical cell measurement technique for as-deposited materials.

**Keywords:** Electroplating, CdMnTe, Deposition Potential, Surface Treatment, Electrical Conductivity Type

## 1. Introduction

CdMnTe is a ternary compound semiconductor which is most often referred to as diluted magnetic semiconductor. The magnetic properties arise from the paramagnetic nature of manganese metal and their common ions. CdMnTe finds numerous applications: in the field of nuclear detection and radiation [1–3], as magnetic diodes for photo-capacitance application [4], and for photo-voltaic device application [5].

Researchers have proven that CdMnTe thin films possess tunable bandgaps ranging from 1.70 to 2.20 eV [2]. The bandgap tunability has been reported to be one of the advantages of CdMnTe over CdZnTe as a room temperature  $\gamma$ -ray detector. The tunability can be achieved using a lower manganese content compared to the zinc content in CdZnTe [2,6]. It should be noted that changes in pre-deposition parameters such as growth temperature, time, pH, voltage can likewise lead to this bandgap variation. For most of the computerised and advanced growth techniques, parameters such as growth temperature, time and voltage are usually set on the equipment before the commencement of the growth. Likewise, post-deposition processes such as annealing of the thin films, chemical treatment of the thin films surface can also be a leading factor which can bring about these changes.

Researchers have also successfully demonstrated that CdMnTe possesses both n- and p-type electrical conduction and these have been used for different device applications. Yahia et al. [5] experimentally showed that n-CdMnTe thin films can be used as an intermediate layer between p-ZnTe and n-GaAs for photovoltaic application. The work carried out by Yahia et al. [5] is a typical example of a device with graded bandgap structure since the energy gap of CdMnTe lies-in-between that of ZnTe and GaAs. Using vertical Bridgman growth technique, Zhang et al. (2008) was able to successfully develop CdMnTe crystal with p-type electrical conductivity [7]. The authors used the developed material to fabricate electronic devices with ohmic and Schottky contacts by choosing appropriate metal contacts for the developed p-type CdMnTe material.

This paper presents a simpler technique of growing and achieving CdMnTe ternary compound semiconductors with both p- and n-type electrical conduction using the same electrolytic bath. This work further establishes that pre-deposition parameter such as growth voltage and post-deposition parameter such as surface chemical treatment influence the energy bandgap of CdMnTe layers. The electronic device qualities of the electroplated

CdMnTe ternary compound semiconductors were tested via the Schottky and ohmic contacts fabricated from the material.

## 2. Experimental Details

Using GillAC ACM potentiostat in potentiostatic configuration, CdMnTe ternary compound semiconductors were cathodically electrodeposited on glass/FTO conducting glass substrates. The conducting substrate used in this work is TEC 7 with a sheet resistance of  $7 \Omega/\text{square}$ . One vital factor which is essential in growing a uniform semiconductor material with proper adherence to the substrate is that the substrate surface must be painstakingly cleaned. To accomplish this, ultrasonic medium comprising of soap solution was used for the substrates cleaning at duration of 15 minutes. A further rinsing action using de-ionised water was carried out on the glass/FTO substrates after completing the ultrasonic cleaning. The surfaces were finally rinsed in methanol and washed in de-ionised water before being applied as the working electrode in the electrodeposition (ED) set-up.

The CdMnTe thin films were deposited from electrolyte containing 1.0 M  $\text{CdSO}_4$  (99.999% purity), 5 ml of dissolved  $\text{TeO}_2$  (99.995% purity) and 0.1 M of  $\text{MnSO}_4$  (99.996% purity) solution in 400 ml of de-ionised water. The dissolved  $\text{TeO}_2$  solution was prepared by adding 2 g of  $\text{TeO}_2$  powder to 200 ml of de-ionised water. Since  $\text{TeO}_2$  cannot dissolve completely in water, 30 ml of concentrated  $\text{H}_2\text{SO}_4$  was added to the  $\text{TeO}_2$  solution to aid its solubility. The prepared  $\text{TeO}_2$  solution was subjected to continuous stirring and heating for ~45 minutes so as to obtain a very clear  $\text{TeO}_2$  solution devoid of powder. After preparing 1 M of  $\text{CdSO}_4$  in 400 ml of de-ionised water, it was continuously stirred to ensure dissolution of the chemical. After the dissolution of  $\text{CdSO}_4$ , 5 ml of  $\text{TeO}_2$  was added to the dissolved  $\text{CdSO}_4$  solution. The Mn precursor (0.1 M  $\text{MnSO}_4$ ) was finally added to the electrolytic bath so as to form the electrolyte for the electrodeposition of CdMnTe; the ternary compound semiconductor formed is  $\text{Cd}_{0.9}\text{Mn}_{0.1}\text{Te}$ . The pH value of the deposition electrolyte was maintained at  $2.00 \pm 0.02$  by using either  $\text{NH}_4\text{OH}$  or  $\text{H}_2\text{SO}_4$ . The growth temperature of the electrolytic bath was  $\sim 80^\circ\text{C}$  and the solution was moderately stirred using a magnetic stirrer.

Before the commencement of CdMnTe layers growth, cyclic voltammetry study was carried out to determine the approximate deposition potential for CdMnTe thin films. The optical properties of the CdMnTe films were studied using Carry 50 Scan UV-Visible spectrophotometer. The ED – CdMnTe thin films were characterised for their structural properties using X-ray diffraction (XRD) technique. Scanning electron microscopy (SEM)

technique was used in investigating the surface morphology of the electrodeposited CdMnTe thin films. The SEM measurements were carried out by using FEI NOVA 200 NanoSEM equipment. The electrical conductivity type of the ED – CdMnTe thin films was determined by using photo-electro-chemical (PEC) cell measurements. The electronic properties of devices fabricated using glass/FTO/p-CdMnTe/Au and glass/FTO/p-CdMnTe/Al structures were measured by using a computerised Keithley 2401 source meter solar simulator system.

### 3. Results and Discussion

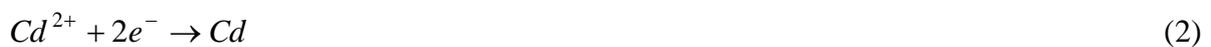
#### 3.1. Cyclic voltammetry

Cyclic voltammetry studies were performed in an aqueous solution that contains 1.0 M CdSO<sub>4</sub>, 0.10 M MnSO<sub>4</sub> and 5.0 ml of dissolved TeO<sub>2</sub> solution at a pH of 2.0±0.02 in 400 ml of de-ionised water. A FTO coated glass substrate was used as the working electrode to study the mechanism of deposition of CdMnTe thin films. A computerised GillAC potentiostat was used to carry out this voltammetric study at a sweep rate of 180 mVmin<sup>-1</sup>. In this technique, a range of cathodic potentials from 0 to 2000 mV was applied across the electrolyte through the electrodes. The potentiostat was used in monitoring the current through the electrolyte as the voltages between electrodes are varied.

The reduction – oxidation (redox) potential ( $E^o$ ) of Te, Cd and Mn with respect to the standard hydrogen electrode are ~+0.59 V, -0.40 V and -1.19 V respectively [8]. Since Te shows a more positive redox potential than Cd and Mn, it is therefore expected to deposit first according to Eqn. (1) [9].



A typical cyclic voltammogram for FTO-coated glass substrate in the prepared electrolyte is shown in Fig. 1. The forward curve illustrated at the inset of Fig. 1 shows that Tellurium (Te) begins to deposit at ~100 mV. As shown in Fig. 1, a rise was observed in the forward current density at ~1050 mV (point A), this signifies the initial deposition of Cd on the cathode according to the chemical reaction shown in Eqn. (2). Since the  $E^o$  of Cd is more positive than Mn, Cd therefore starts to deposit after Te before the deposition of Mn to form CdTe according to the chemical reaction given in Eqn. (3) [9].

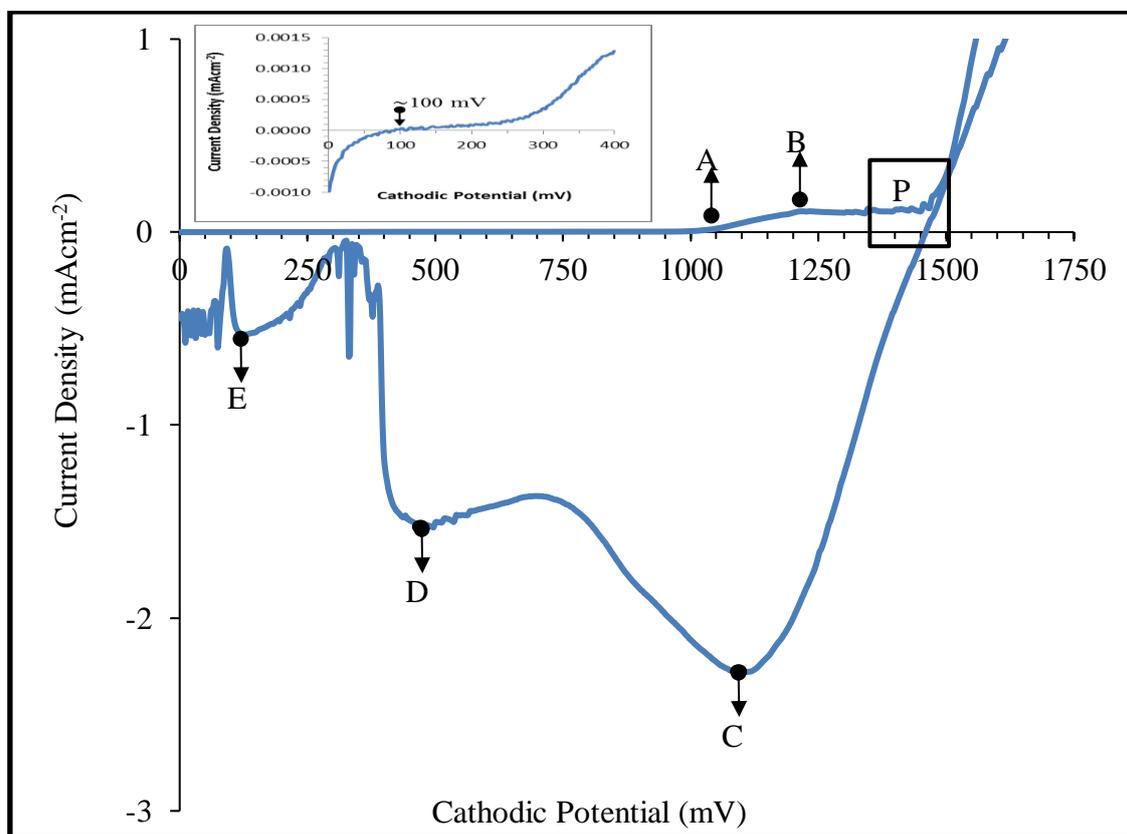




The rise in current density at ~1050 mV reaches its first peak at point B which is at ~1,200 mV. At this point, there is the deposition of Mn on the cathode according to Eqn. (4).



At a cathodic potential above ~1200 mV, there seems to be stability in the forward current density from ~1210 mV to 1450 mV. Within this voltage range, the CdMnTe semiconductor compound starts to deposit on the cathode according to the chemical reaction shown in Eqn. (5).



**Figure 1.** Cyclic voltammogram of electrolyte containing 1.0 M CdSO<sub>4</sub>, 0.10 M MnSO<sub>4</sub> and 5.0 ml of dissolved TeO<sub>2</sub> solution (pH = 2.0±0.02, T = 80°C). (Inset shows the transition voltage at which Te begins to deposit).

The rectangular box labelled ‘P’ represents the selected voltage range (between ~1350 to ~1500) mV to grow CdMnTe layers according to this experimental result. From the reverse cycle of the I-V curve shown in Figure 1, the point of transition from the positive current density axis to the negative is ~1450 mV and this point reaches its first broad peak at point C. Point C indicates the dissolution of elemental Mn and removal of Mn from CdMnTe layer formed on the cathode. The dissolution of Cd and Te from the surface of the cathode occurs at the broad peaks labelled points D and E respectively. Thus, cyclic voltammetry technique is a vital tool which helps to determine the approximate growth voltage range to grow CdMnTe thin films.

### **3.2 Optical Absorption Study**

#### **3.2.1 Effect of surface treatment on the optical properties of CdMnTe**

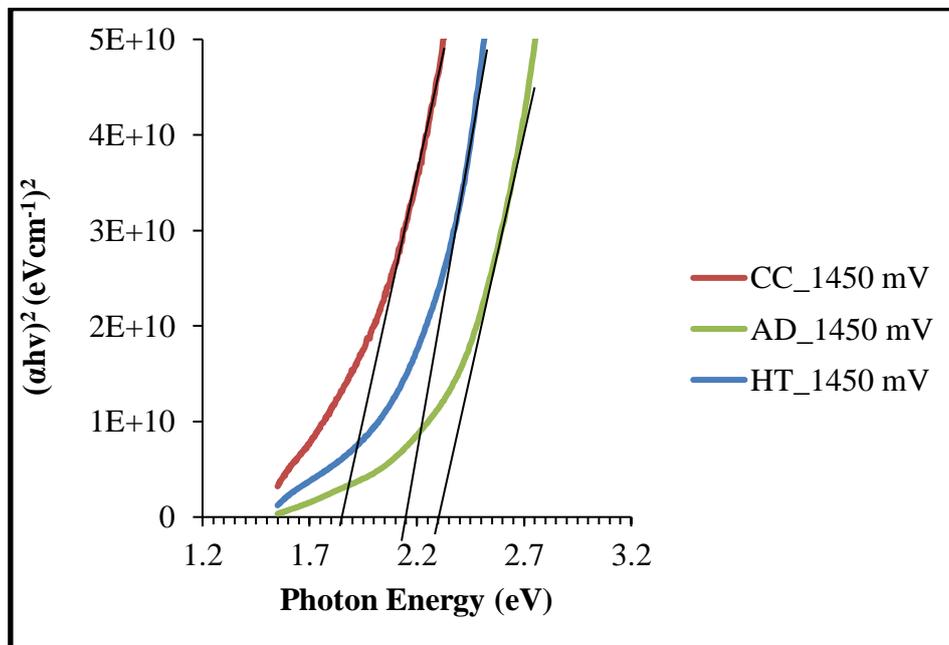
One of the main reasons of exploring CdMnTe in this work is due to the fact that the energy bandgaps are tunable and wider bandgaps than CdTe thin films can be obtained [2]. With the wide bandgap, it can serve the purpose of a back contact layer to CdTe thin films for barrier height enhancement. p-type CdMnTe layers can also be used as a p-type window material in graded bandgap solar cells. CdMnTe films of thicknesses ~230, 260 and 300 nm’s were grown at cathodic potentials of 1350, 1400 and 1450 mV’s respectively. These thin films were characterised for their optical and structural properties.

The optical characterisations were performed using UV-Visible spectrophotometer so as to find the bandgap energy of the CdMnTe in its as-deposited (AD), heat-treated (HT) and CdCl<sub>2</sub> heat-treated (CC) state. Figure 2 shows the optical absorption spectra for AD-, HT- and CC-CdMnTe thin films grown at a cathodic potential of 1450 mV. The bandgap energies were estimated by extrapolating the line of best tangent of the absorption curves to the (hv) axis when  $(\alpha hv)^2$  axis is equal to zero.

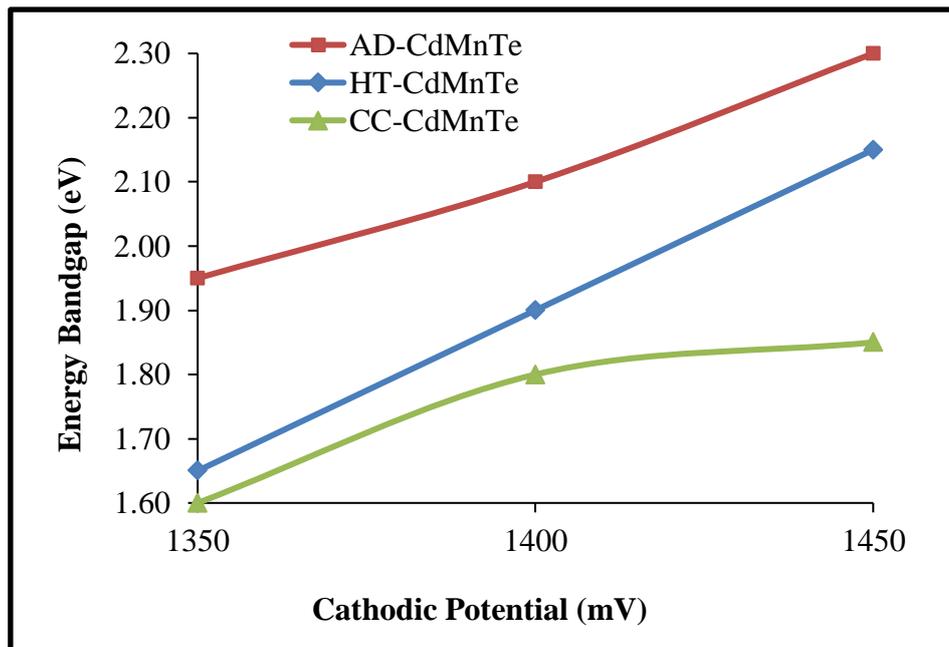
In Figure 2, the bandgap of AD-CdMnTe grown at cathodic potential of 1450 mV is ~2.30 eV; after annealing ordinarily in air, the bandgap reduced to ~2.15 eV. A further reduction in the bandgap to ~1.85 eV was observed after annealing with CdCl<sub>2</sub> treatment in air. Similar trend was observed in CdMnTe layers grown at lower cathodic potentials of 1350 and 1400 mV as illustrated in Figure 3. Generally and with respect to this experimental work, the bandgap of electroplated AD-CdMnTe semiconductors are higher in value than the bandgap of HT- and CC-CdMnTe layers. As shown in Figure 3, the bandgap of the as-deposited

CdMnTe layers are in the range 1.95-2.30 eV while those of the CC-treated CdMnTe layers are in the range 1.60-1.85 eV. Salim et al. [10] attributed the decrease in bandgap of CdTe thin films after annealing with CdCl<sub>2</sub> treatment to recrystallization and enlargement in grain sizes.

Chaure et al. attributed the larger bandgap of as-deposited materials to their having smaller grains. The authors explained that coalescence of smaller grains into bigger grains can lead to reduction in bandgap. This can be a probable reason why AD-CdMnTe have higher bandgap when compared to HT- and CC-CdMnTe layers. As later explained in section 3.4, AD-CdMnTe have the smallest grains while CC-CdMnTe have the largest grain sizes. The grain sizes of HT-CdMnTe fall in between that of AD- and CC-CdMnTe layers.



**Figure 2.** Optical absorption graphs for as-deposited (AD), heat-treated (HT) and CdCl<sub>2</sub>-heat treated CdMnTe layers grown at 1450 mV.



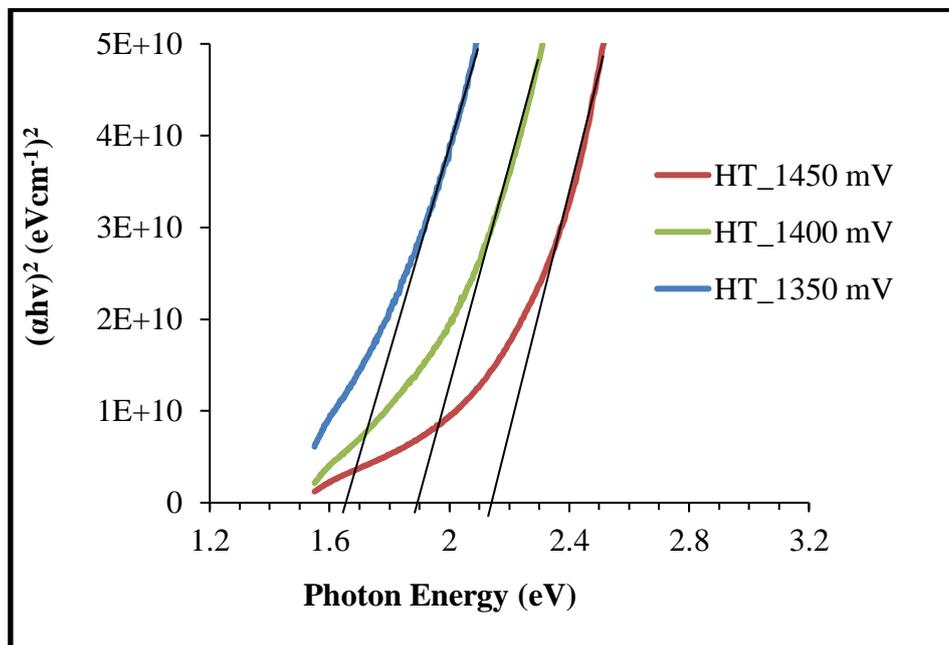
**Figure 3.** Variation of the energy bandgaps of CdMnTe layers as a function of cathodic deposition potential for as-deposited (AD), heat-treated (HT) and CdCl<sub>2</sub>-heat treated (CC) CdMnTe layers (Note: The annealing was done at a temperature of 400°C for 10 minutes in air).

### 3.2.2 Effect of Growth Voltage on the optical properties of CdMnTe

The optical absorption curves of HT-CdMnTe layers grown at different cathodic voltages from 1350-1450 mV are shown in Figure 4 with the energy gap ranging between 1.65 and 2.15 eV. It was observed that the growth voltage influence the optical parameters most especially the energy bandgap. As seen in Figure 4, lower values of energy gap were observed at lower cathodic potentials. The increase in bandgap as the cathodic deposition potential increases may be attributed to the incorporation of more Mn atom at higher growth voltage. As previously stated, the redox potential of Mn, Cd and Te have the values corresponding to ~ -1.19 V, -0.40 V and 0.59 V respectively [8]. Since the redox potential of Mn is more negative than Cd and Te, higher cathodic deposition potential will be required to favour the incorporation of more Mn atom into the CdTe thin film; the inclusion of more Mn atom into the ternary compound material in turn increases the energy bandgap. As seen in Figure 3, the energy gaps of the Cd<sub>1-x</sub>Mn<sub>x</sub>Te thin films increases with increase in deposition potential. Researchers have reported that the energy bandgaps of Cd<sub>1-x</sub>Mn<sub>x</sub>Te crystals are dependent on the contents of Mn in the Cd<sub>1-x</sub>Mn<sub>x</sub>Te ternary compound semiconductors [11]. Also, the increase in the energy bandgap as deposition potential increases could as well arise

as a result of variations in the atomic composition of the electrodeposited CdMnTe semiconductor layers.

Another possible explanation for the lower bandgap values observed at lower cathodic potential such as 1350 mV can be attributed to deposition of semi-metallic Te with a bandgap of  $\sim 0.37$  eV [12]. As later seen in section 3.3, the XRD spectrum of CdMnTe layers grown at 1350 mV exhibited Te peak along the (101) plane; this peak was not observed in the layers grown at 1400 mV and 1450 mV. The presence of the Te peak at deposition potential of 1350 mV is an indication of the growth of semi-metallic Te at lower cathodic potential.

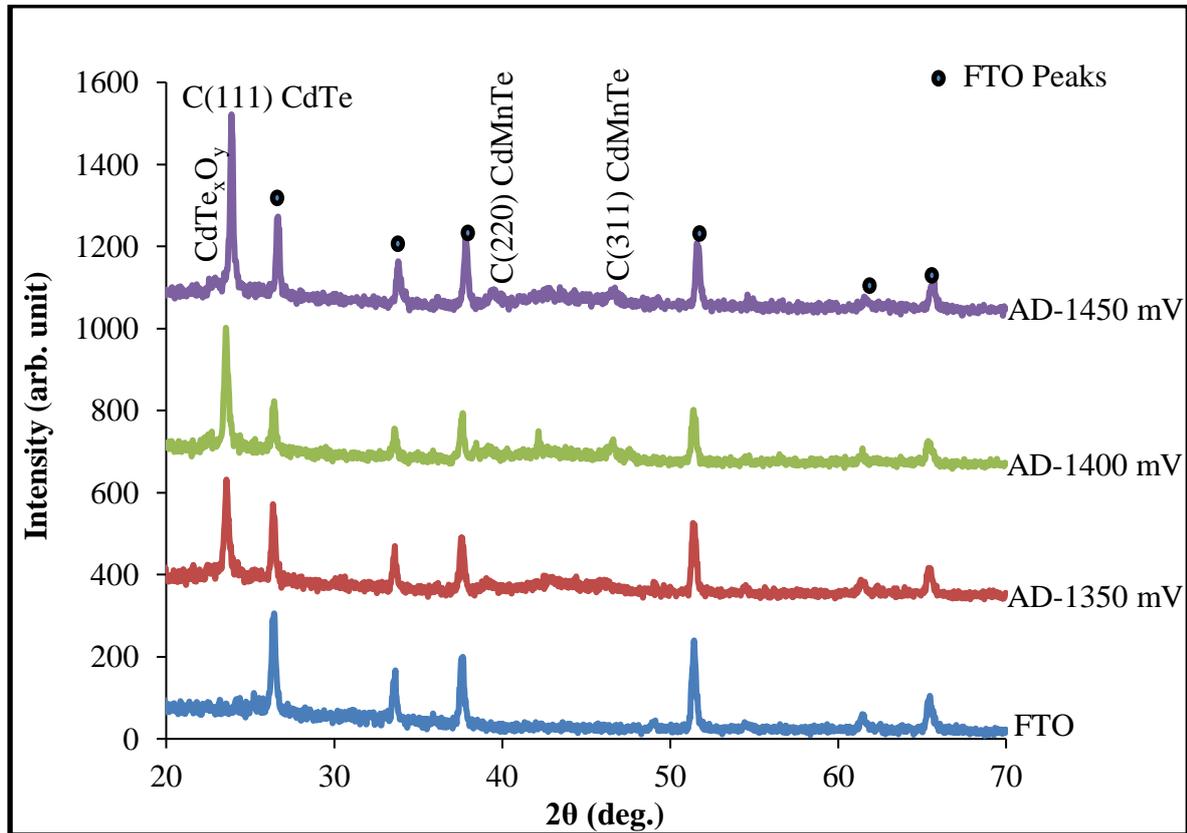


**Figure 4.** Optical absorption graphs of CdMnTe thin films grown between 1350–1450 mV for CdMnTe layers heat-treated ordinarily in air at 400°C for 10 minutes.

### 3.3. Structural Study using X-Ray Diffraction Technique

The structural properties of: as-deposited (AD) CdMnTe layers, CdMnTe layers heat-treated ordinarily in air (HT) and CdMnTe layers treated with CdCl<sub>2</sub> solution before annealing in air (CC) were investigated using X-ray diffraction technique. The heat-treatment was done in air at 400°C for 10 minutes. For the CC-CdMnTe layers, the top surface of the CdMnTe layers was first treated with CdCl<sub>2</sub> solution, allowed to dry and then heat-treated. The XRD spectra obtained for AD-, HT-, and CC-CdMnTe layers grown at different cathodic potentials are shown in Figures 5, 6 and 7 respectively.

The XRD spectra of AD-CdMnTe layers shown in Figure 5 revealed that the growth voltage has a great influence on the crystallinity and growth of CdMnTe layers. Because of the smaller proportion of Mn compared to Cd used in the electrolytic bath ( $\text{Cd}_{0.9}\text{Mn}_{0.1}\text{Te}$ ), the highest peak intensity for the CdMnTe films still occurred at the CdTe plane of preferred orientation which has been practically confirmed to be along (111) plane [13].

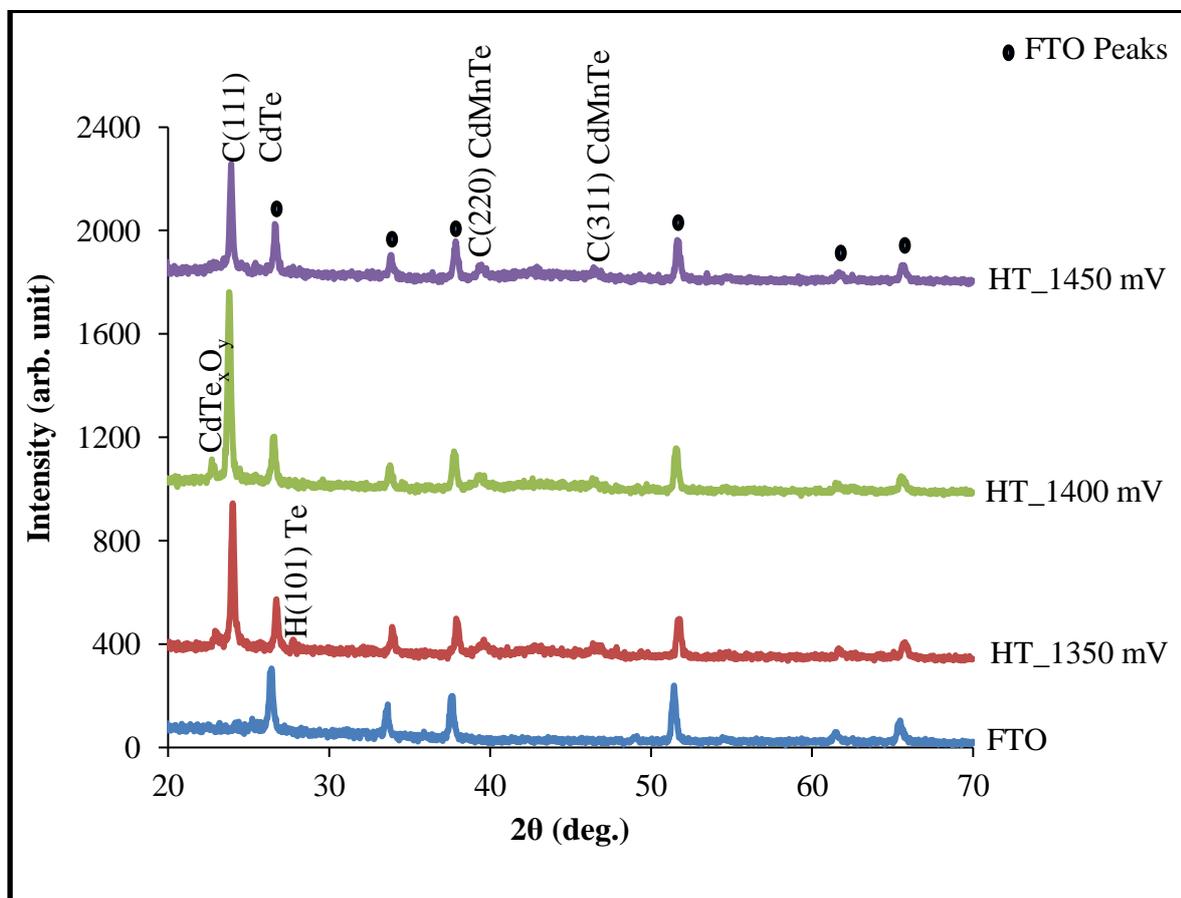


**Figure 5.** XRD spectra of as-deposited CdMnTe layers grown at cathodic potentials ranging between 1350 and 1450 mV.

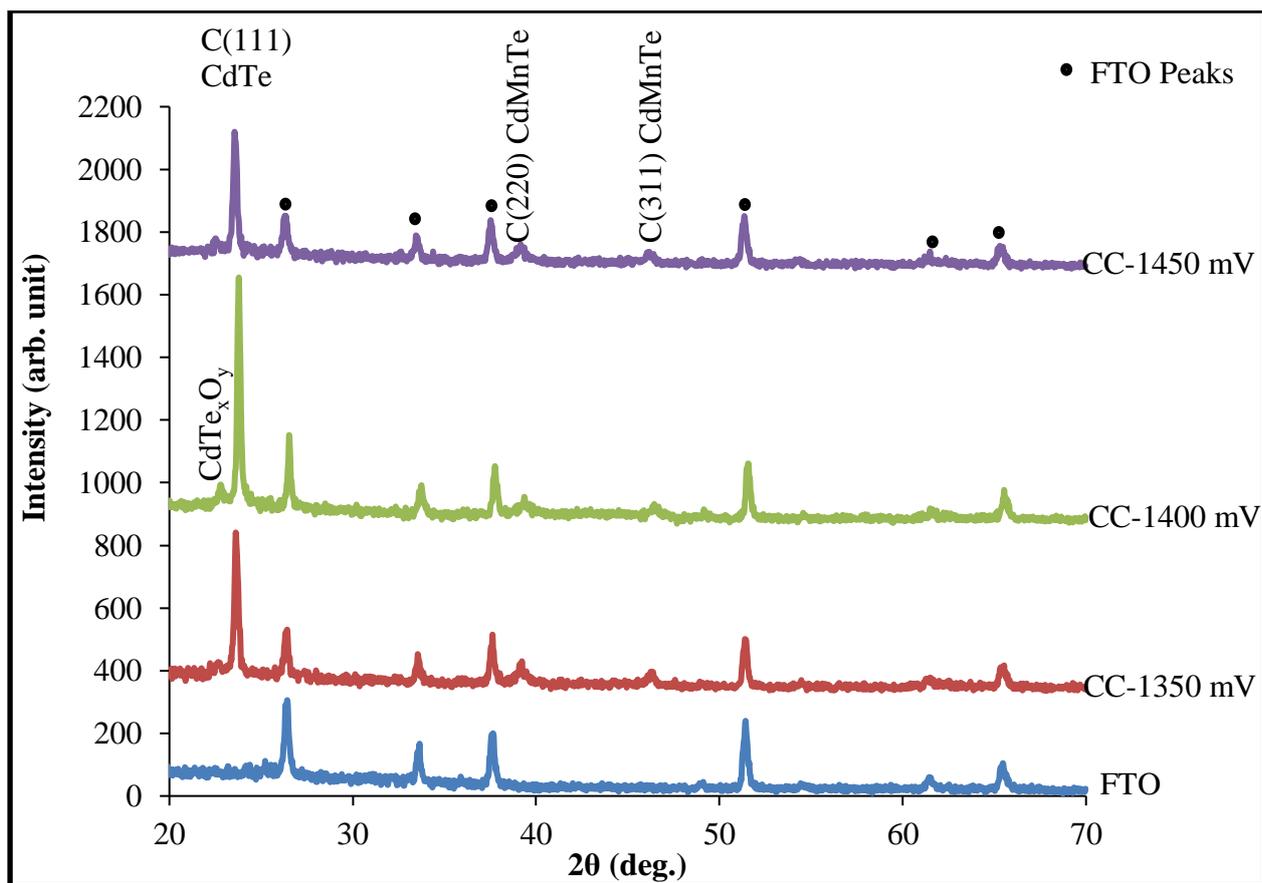
One of the probable reasons for the increase in peak intensity along (111) plane with voltage increase can be attributed to higher deposition current density observed at high voltage. The mathematical relation between thin film thickness and deposition current density shows a direct proportion according to Faraday's law of electroplating [14]. For this reasons, thin films grown at higher cathodic potentials tend to have more thicknesses than the films grown at lower potentials. The increase in thickness of thin films grown as cathodic deposition potential increases may be a likely reason for the observed higher peak intensity in thin films grown at higher potential. However, it should be noted that this statement may not be applicable to all thin films due to the different peculiarity of each semiconductors. As shown in Figure 5, the AD – CdMnTe layers grown at 1450 mV possesses better crystallinity due to

its higher (111) peak intensity. Due to the presence of high density of defects and grain boundaries in as-deposited semiconductor materials, they are not usually suitable for electronic device applications. For this reason, it becomes vital to subject the materials to annealing and surface treatment.

After annealing without and with  $\text{CdCl}_2$  surface treatment as illustrated in Figures 6 and 7 respectively, the voltage in which the highest crystallinity occurred shifted to 1400 mV. Recently, Madugu et al. [15] reported similar results and the authors ascribed the shift in voltage in which high crystallinity occurred to factors such as recrystallization and annealing out defects in the materials during heat treatment [15–17].



**Figure 6.** XRD spectra of heat treated CdMnTe layers grown at cathodic potentials ranging between 1350 and 1450 mV. Note that the heat treatment was carried out at 400°C for 10 minutes in air.



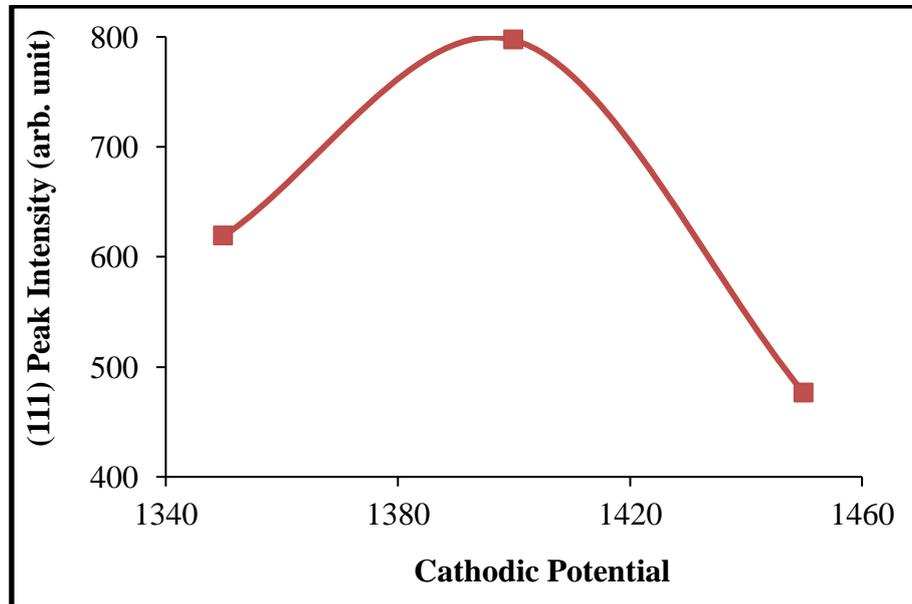
**Figure 7.** XRD spectra of CdCl<sub>2</sub> heat treated CdMnTe layers grown at cathodic potentials ranging between 1350 and 1450 mV. Note that the heat treatment was carried out at 400°C for 10 minutes in air.

The XRD spectra of AD-, HT- and CC- CdMnTe layers shown in Figures 5, 6 and 7 respectively revealed that the CdMnTe ternary compound semiconductors have a polycrystalline nature. As previously discussed under the AD – CdMnTe thin films, the preferred orientation was found to be along the (111) CdTe plane. Apart from the preferred orientation peak, emergence of CdMnTe peaks with cubic crystal structure occurred along the (220) and (311) planes at the peak positions corresponding to  $\sim 2\theta = 39.5^\circ$  and  $46.6^\circ$  respectively. These peaks which have lower intensity compared to peak along the (111) plane were seen in the three classes of CdMnTe layers (Figures 5 – 7) investigated in this work. The crystal structure of the observed peaks was found to be cubic when the acquired XRD data was compared to the JCPDS reference code: 01-086-2415 for CdMnTe.

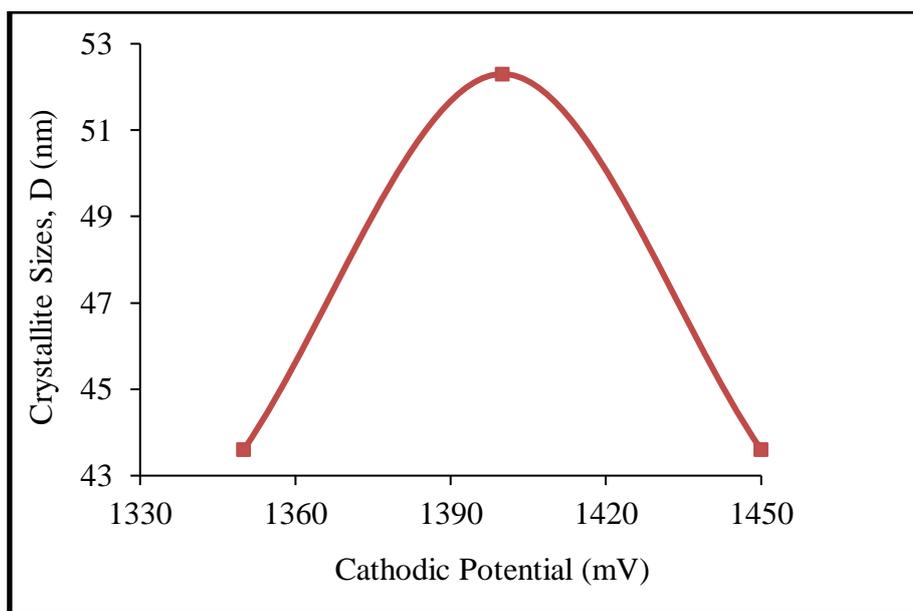
In addition to the CdTe and CdMnTe peaks observed in the materials under study, Tellurium (Te) peak having hexagonal crystal structure along the (101) plane was observed in HT – CdMnTe deposited at 1350 mV; this peak was not visible in the AD –, and CC – CdMnTe

materials grown at 1350 mV. These results explained that ordinary heat treatment can assist in the activation of dormant Te peak in the as-deposited material while annealing with  $\text{CdCl}_2$  treatment can passivate the Te peak thus improving the material. The elimination of Te peak after annealing with  $\text{CdCl}_2$  treatment has been reported by researchers as means of defects elimination and material improvement [18]. The presence of Te peak is due to occurrence of Te precipitation during deposition of CdTe. Dharmadasa et al. [18] explained that Te precipitation can happen during CdTe growth as a result of natural behaviour of Tellurium even when it is present at parts per million (ppm) level. Te precipitate when present in a material can make the material to have a reduced energy bandgap as explained in sub section 3.2.2 or become p-type in electrical conduction as later shown in sub section 3.5.1.

The variation of intensity of (111) peak for CC-CdMnTe layers as a function of cathodic potentials ranging between 1350 and 1450 mV is further illustrated in Figure 8; the result showed that the highest peak intensity occurred at 1400 mV. The estimated crystallite sizes of CC-CdMnTe layers versus the deposition potentials are given in Figure 9. The result showed that the highest crystallite sizes were attainable at deposition voltage of 1400 mV. Similar crystallite sizes were gotten for CdMnTe layers grown at 1350 and 1450 mV.



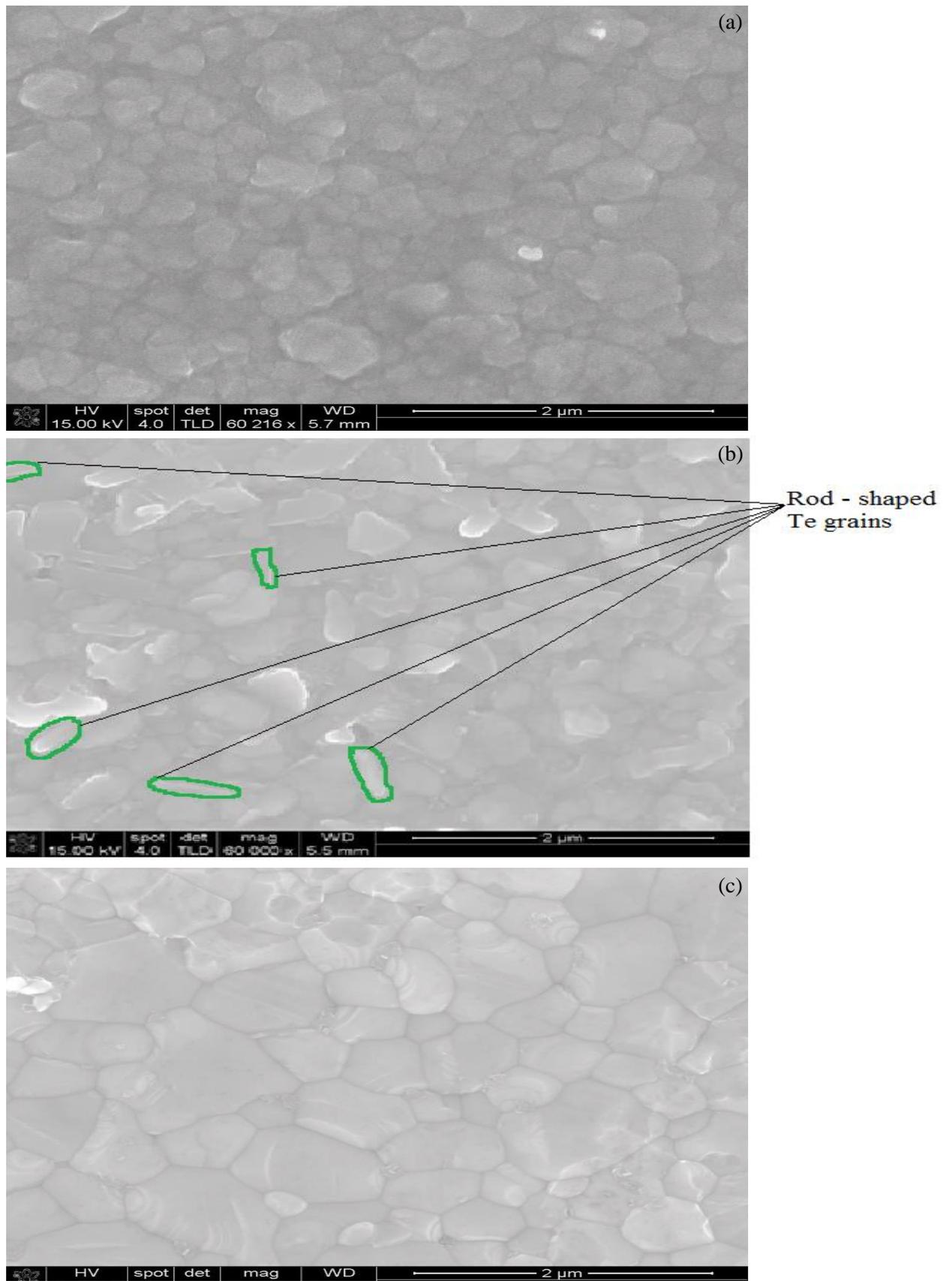
**Figure 8.** Variation of preferred orientation position along (111) plane versus cathodic potential for heat-treated CdMnTe layers grown between 1350 – 1450 mV cathodic potentials.



**Figure 9.** Crystallite sizes of CdMnTe heat-treated in air with CdCl<sub>2</sub>.

### 3.4 Morphological Study of CdMnTe Layers

Figure 10 (a) is the SEM image of as-deposited CdMnTe layers. The as-deposited layers contained small grains size when compared to the micrographs of CdCl<sub>2</sub>-heat-treated CdMnTe. Figure 10 (b) is the SEM image of heat-treated CdMnTe layers. Parts of the grains are rod-shaped which is a nature of Tellurium [19]. This further confirms the result from PEC cell measurement discussed in sub section 3.5.1 that CdMnTe when heat-treated ordinarily in air without any chemical treatment convert to p-type regardless of the cathodic potentials in which the material is grown. Figure 10 (c) is the SEM image of CdCl<sub>2</sub> heat-treated CdMnTe layers, very large grains were observed in the layers after annealing with CdCl<sub>2</sub> treatment.

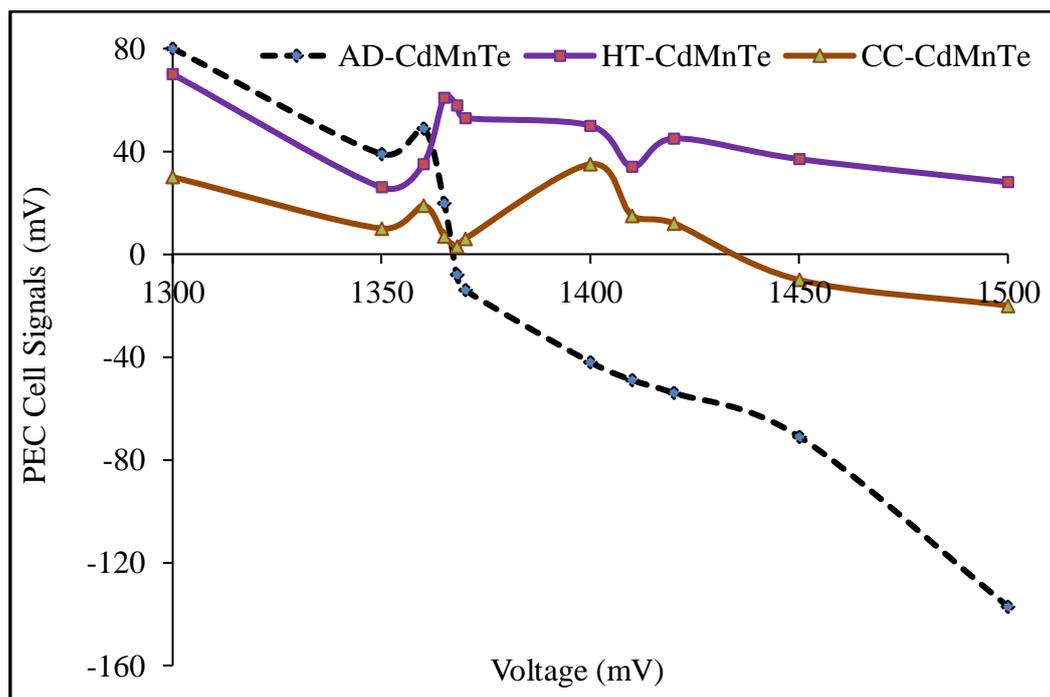


**Figure 10.** SEM micrographs of (a) AD-CdMnTe layers, (b) HT-CdMnTe layers and (c) CC-CdMnTe layers.

### 3.5 Electrical Study of CdMnTe Layers

#### 3.5.1 PEC Cell Measurement of CdMnTe Layers

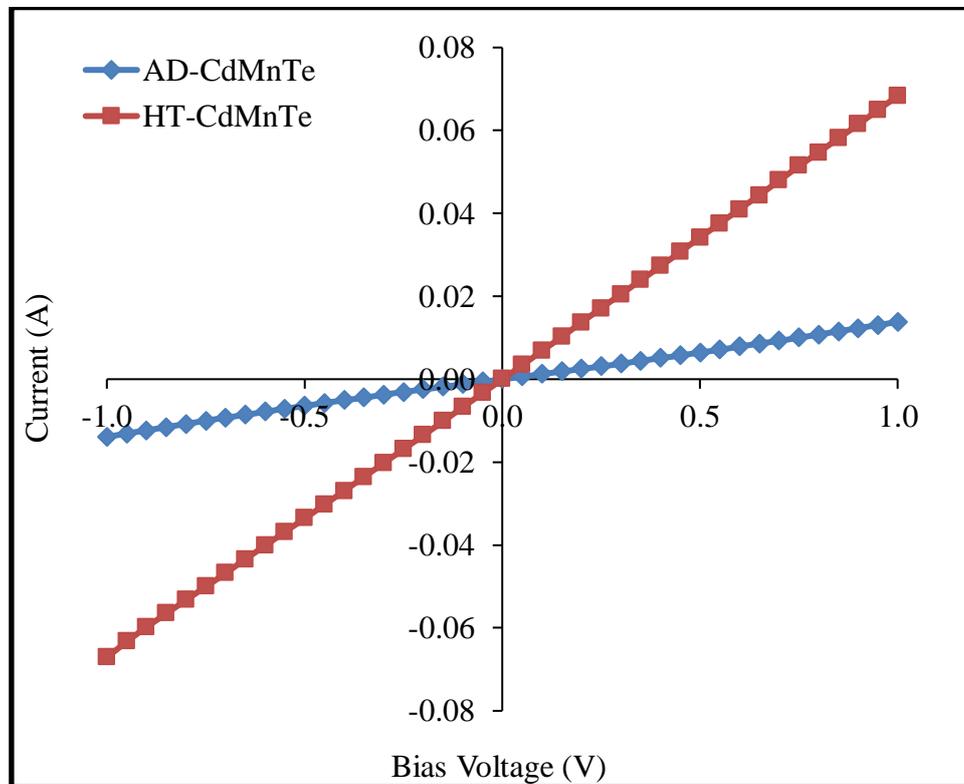
The consequence of alloying CdTe with Mn on electrical conductivity type is demonstrated in Figure 11. As revealed in Figure 11, the PEC cell signals of explored CdMnTe thin films within the n region all converted to p-type material after annealing the CdMnTe layers in air without applying CdCl<sub>2</sub> chemical treatment to the material surface. For the CdMnTe layers annealed with CdCl<sub>2</sub> surface treatment (CC – CdMnTe), the results of the PEC cell signals revealed that CdMnTe layers deposited at voltages  $\geq 1450$  mV still retain their n – type electrical conductivity when measured immediately. For the materials that were grown at a close proximity to the inversion cathodic voltage of  $\sim 1370$  mV, there was a conversion to p – type material within the +70 mV range. The results of our investigation agree with the reports given by [5,20] that CdMnTe ternary compound semiconductors can possess both p and n- type electrical conduction.



**Figure 11.** Disparity of PEC cell signals with cathodic deposition voltages for AD –, HT –, and CC – CdMnTe thin films.

### 3.5.2 DC Conductivity Measurement of CdMnTe Semiconductors

Two different electronic devices of architecture glass/FTO/p-CdMnTe/Au and glass/FTO/p-CdMnTe/Al were fabricated to test the worth of electronic devices fabricated from p-type CdMnTe thin films. Au and Al metal contacts were used in making ohmic and Schottky contacts to p – CdMnTe respectively. Au and Al metals have work functions of  $\sim 5.25$  eV [21] and  $\sim 4.10$  eV [22] respectively. The device configuration, glass/FTO/p-CdMnTe/Au was employed in testing the compound semiconductor ohmic behaviour while glass/FTO/p-CdMnTe/Al was used in testing the Schottky behaviour of the CdMnTe layers. Typical current – voltage (I – V) characteristics of as – deposited and heat – treated CdMnTe layers employed in the device configuration glass/FTO/p-CdMnTe/Au is shown in Figure 12.



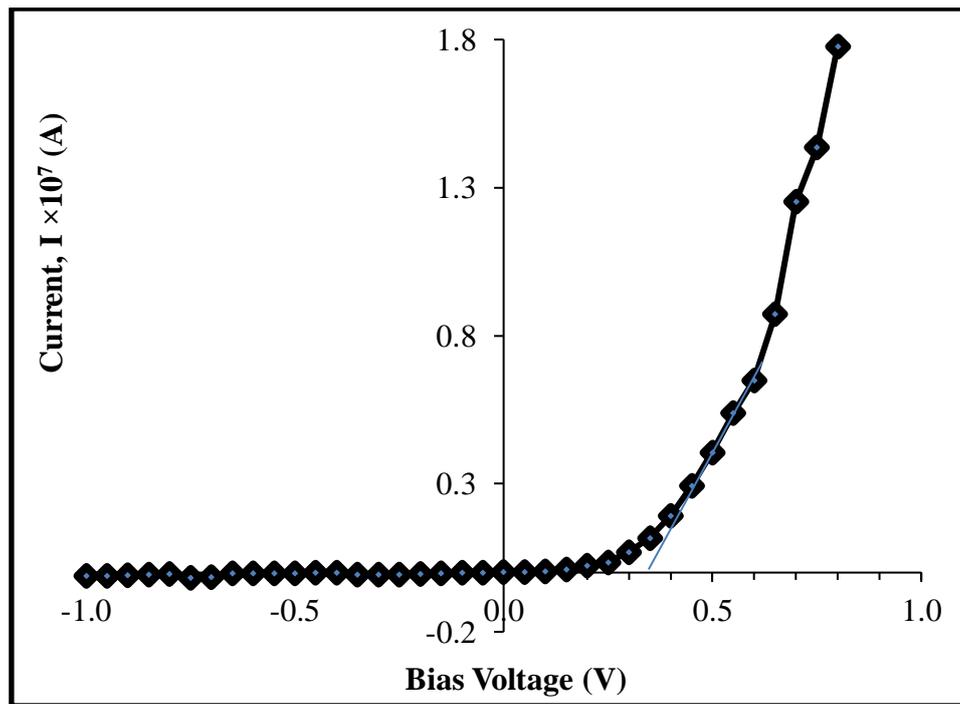
**Figure 12.** I-V characteristics of as – deposited and heat – treated CdMnTe layers with device architecture, glass/FTO/p – CdMnTe/Au.

The excellent ohmic response displayed by the fabricated devices shown in Figure 12 is an illustration of the great feature of the deposited films. It also revealed that the interface between the metal and semiconductor contains little or zero surface states [23]. As seen in Figure 12, AD – CdMnTe has the maximum resistance of  $\sim 72.49 \Omega$  and this results to a resistivity value of  $\sim 2.40 \times 10^4 \Omega\text{cm}$  while HT – CdMnTe has a reduced resistance of  $\sim 14.64$

$\Omega$  with a resistivity of  $\sim 4.84 \times 10^3 \Omega\text{cm}$ . The reduction of the material resistivity with annealing denotes the semiconducting nature of the CdMnTe thin films. The resistivity of AD – CdMnTe thin film gotten in this work agrees with the experimental investigations carried out by Yurtsenyuk et al. [11] that  $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$  grown with lower Mn content has a resistivity of the order of  $10^4 \Omega\text{cm}$ . The application of heat treatment has been able to reduce the material resistivity thereby improving its electrical conductivity.

### 3.5.3 Rectifying Behaviour of Schottky Diodes Fabricated from glass/FTO/p-CdMnTe/Al Device Structure

The Schottky behaviour of CdMnTe compound semiconductors was investigated by incorporating annealed p-CdMnTe layers into the device structure glass/FTO/p-CdMnTe/Al. The linear-linear I-V response of glass/FTO/annealed p-CdMnTe/Al Schottky diode is illustrated in Figure 13.



**Figure 13.** Linear-linear I-V characteristics of glass/FTO/p-CdMnTe/Al Schottky diodes under dark condition.

Series resistance ( $R_s$ ) of  $1.65 \times 10^6 \Omega$  and shunt resistance of  $2.11 \times 10^8 \Omega$  were gotten from Figure 13 at room temperature. The high  $R_s$  value obtained in this work is similar to the value reported by Kosyachenko et al. [6] in the fabrication of n-CdMnTe – based Schottky diodes with a graphite contact. The fabricated diodes have a turn – on voltage of  $\sim 0.35 \text{ V}$  and this

makes them suitable for use in a switching circuit. The fabricated diodes have ideality factor ( $n$ ) of  $\sim 3.74$ ; the large  $n$  value points to the fact that there are large amounts of defects in the material. The fabricated diodes have rectification factor of  $3.48 \times 10^2$ , leakage current of  $\sim 0.32$  nA and potential barrier height  $> 0.89$  eV. It is therefore possible for the large barrier height measured experimentally to emerge from the Fermi level pinning at Al/p-CdMnTe junction due to the presence of defect levels. This feature is common in thin films that have large defect concentration. The defects can be an advantage if properly managed.

## **Conclusion**

Electrodeposition of CdMnTe thin films have been successfully achieved with a two – electrode set – up. The results from XRD showed that the deposited layers are polycrystalline and cubic with the preferred orientation along the (111) CdTe plane. Optical absorption measurement results revealed that tunable energy bandgaps are obtainable within the range of cathodic potentials explored. AD – CdMnTe layers, HT – CdMnTe layers and CC – CdMnTe layers have bandgaps within the range of (1.95–2.30) eV, (1.65–2.15) eV, and (1.60–1.85) eV respectively. The optical results further revealed that annealing with and without CdCl<sub>2</sub> surface treatment have a significant effect on the materials energy bandgap. The study carried out on PEC cell measurements revealed that the CdMnTe thin films can exhibit both n – and p – type electrical conductivity depending on the cathodic potentials. Regardless of the deposition potentials used, all CdMnTe materials converted to p-type after annealing without any surface treatment. The outcome of the present experimental study provides a unique pattern to obtaining p – type CdMnTe thin films. Heat treating the AD – CdMnTe layers under the normal atmospheric condition without using chemicals for the surface treatment and annealing with surface treatment the thin films deposited near the inversion potential are two unique ways to obtaining p-type CdMnTe layers with good opto – electronic quality. The excellent current – voltage response of p – CdMnTe/Au ohmic contacts and good rectifying behaviour of the p – CdMnTe/Al Schottky contacts reveal the quality of electronic devices emerging from CdMnTe ternary compound semiconductors.

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