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Fabrication and Characterization of an *n*-CdO/*p*-Si Solar Cell by Thermal Evaporation in a Vacuum

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A CdO/Si solar cell was fabricated via deposition of a CdO thin film on *p*-type silicon substrate at room temperature by thermal evaporation technique for CdO powder in a vacuum ($\sim 2.2 \times 10^{-5}$ mbar). The synthesized thin film has a thickness of approximately 346 nm. Scanning electron microscopy revealed that the thin film had a good quality structure. X-ray diffraction and energy dispersive X-ray analysis were used to characterize the structural properties of the solar cell. The CdO thin film had a grain size of 34 nm. The solar cell yielded a minimum effective reflectance that exhibited excellent light-trapping at wavelengths ranging from 400 nm to 1000 nm. Photoluminescence spectroscopy was conducted to investigate the optical properties. The direct band gap energy of the CdO thin film was 2.46 eV. The photovoltaic properties of the CdO/Si solar cell were examined under 100 mW/cm^2 solar radiation. The cell had an open circuit voltage (V_{oc}) of 460 mV, a short-circuit current density (J_{sc}) of 18.8 mA/cm^2, a fill factor (*FF*) of 0.685, and a conversion efficiency (η) of 5.92%.

Keywords: Cadmium oxide ; Thin film ; Thermal evaporation in vacuum ; Solar cell.

1. INTRODUCTION

Energy is the most important problem facing mankind to date. Researchers have focused on transparent conductive oxide (TCO) materials because of their applications, specifically those in the field of optoelectronic devices such as photodiodes, solar cells, photo transistors, transparent electrodes, and gas sensors [1-3]. Cadmium oxide (CdO) is one of the most important TCO materials; it is an *n*-type semiconductor with a narrow direct band gap of 2.2 eV to 2.5 eV [4,5]. CdO has several attractive properties, such as its high optical transmittance in the visible region of the solar spectrum [6], low resistivity, high density (8150 Kg/m^3), high melting point (1500 °C), and has a cubic crystal structure [NaCl, face center cubic (fcc) type, and lattice constant a = 0.4695 nm] [7-10]. Different methods have been adopted to synthesize CdO thin films, such as spray pyrolysis [11], sputtering [12], chemical bath deposition [13], sol-gel method [14], vapor-liquid-solid (VLS) [15], and solid-vapor deposition method [16,17]. The objective of this study is to fabricate an *n*-CdO/*p*-Si solar cell by thermal evaporation in a vacuum. The morphological, structural, optical, and electrical (*I*–*V*) properties of the solar cell are investigated.

2. MATERIALS AND METHODOLOGY

A CdO/Si solar cell was fabricated using the thermal evaporation technique in a vacuum system of 2.2×10^{-5} mbar, with a thin film thickness of approximately 346 nm. This method was selected because of its lower cost and simplicity. The RCA (Radio Corporation of America) process was used to remove the oxide layer from a *p*-type Si wafer (1 cm × 1 cm × 283 μm) with a (111) orientation and a resistivity of 0.75 Ω cm. The Alcatel-101 evaporator system, equipped with a common diffusion and rotary pump, was used to evacuate the high vacuum chamber. The Si substrate was loaded onto the holder at the top of the vacuum chamber, whereas a tungsten boat was used to hold molten CdO for evaporation. The CdO powder (purity, 99.99%; Aldrich) as the source of CdO was loaded onto a tungsten crucible. Prior to CdO deposition, the tungsten boat was cleaned with alcohol to remove any contamination and dried using nitrogen gas. The vacuum chamber was evacuated to 2.2×10^{-5} mbar before the source was heated. The tungsten boat was then heated using 60 Amp of direct current for 10 sec to melt the CdO. The current was increased slowly to 160 Amp until all CdO evaporated. The substrate was then removed after waiting a few minutes for the chamber to cool down.

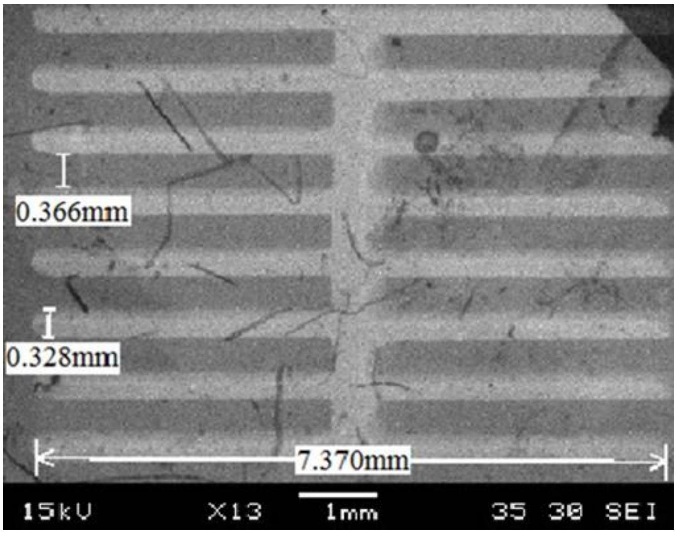


Figure 1. SEM image of Ag grid contact deposited on the CdO thin film.

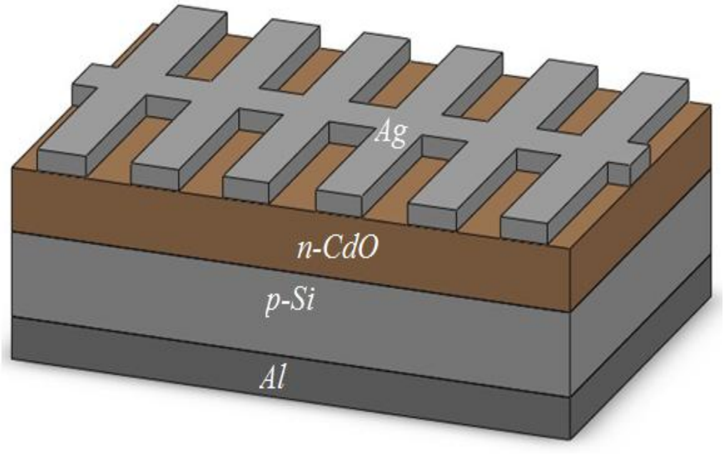


Figure 2. Schematic illustration of the (n-CdO/p-Si) solar cell.

Silver evaporation was used in front of the sample (*n*-CdO) to form metallization grid pattern as shown in Fig. 1, whereas aluminum evaporation was used at the back (*p*-Si) to form a reflector contact via thermal evaporation in a vacuum (Edwards Auto 306). The schematic illustration of the (*n*-CdO/*p*-Si) solar cell is shown in Fig. 2. Annealing was achieved at 400 °C for 20 min to ensure optimal contact.

X-ray diffraction (XRD) measurements were carried out using a high-resolution X-ray diffractometer system (X'Pert PRO MRD PW3040, PANalytical) to determine the CdO crystallite structure. Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis (JSM-6460 LV, Japan) were conducted to determine the surface morphology and composition of the CdO/Si, respectively.The photoluminescence (PL) study was carried out via a spectroscopy system (HR 800UV, Jobin Yvon, USA) at room temperature using He-Cd laser (λ = 325 nm). CdO thin film thickness and optical reflectance of the CdO/Si were measured using an optical reflectometer (Filmetrics, F20, USA). Topography of the thin film was studied using atomic force microscopy (AFM) (Dimension edge, Bruker) with tapping operation mode. Current density-Voltage (*J*–*V*) measurements were performed in forward bias with a computer-controlled Keithley 2400 Source Meter under 100 mW/cm^2 illumination from a solar simulator. A 100 W xenon lamp served as the light source, and the light intensity was calibrated using a standard silicon solar cell.

3. RESULTS AND DISCUSSION

Fig. 3 shows the XRD patterns of the CdO thin film on Si substrate. The diffraction peaks observed at diffraction 2θ angles of 33^o, 38^o, 55^o, 65^o, and 69^o corresponded to the (111), (200), (220), (311), and (222) planes. These peaks also corresponded to those observed for CdO (JCPDF File No. 03-065-2908). The spectrum obtained indicated that the studied film is polycrystalline in nature with a cubic structure (a = 0.46918 nm). The prepared film has a (111) preferred orientation. Prominent peaks were used to calculate the grain size via the Scherrer equation, which is expressed as follows [15-17]:

$$D = \frac{0.94\lambda}{\beta\, COS\theta} \quad (1)$$

Where λ is the wavelength (λ = 1.542 Å) (CuKα), β is the full width at half maximum (FWHM) of the line, and θ is the diffraction angle. The grain size of the CdO thin film was 34 nm. The strain of the CdO thin film grown on the Si substrate along the c-axis can be calculated using the following equation [18]:

$$\varepsilon_{ZZ}(\%) = \frac{C - C_O}{C_O} \quad (2)$$

Where C represents the lattice constant of the CdO thin film estimated from XRD data and C_O is the standard lattice constant for the unstrained CdO [19]. The negative value of the strain (− 0.068%) revealed the compressive strain of the CdO thin film. This low value of compressive strain suggests that the synthesized CdO thin film have high-quality crystal geometry.

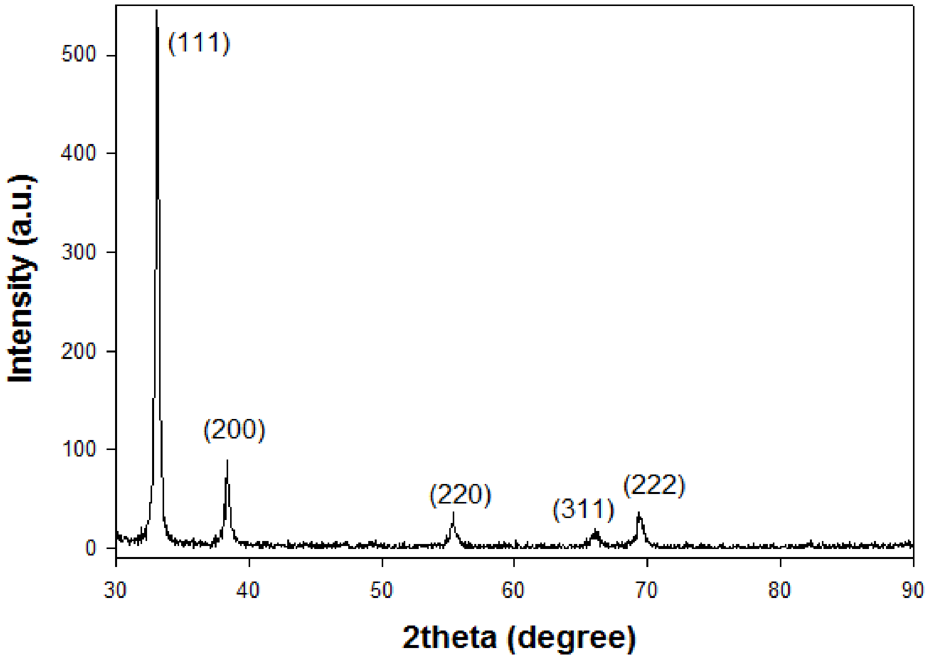
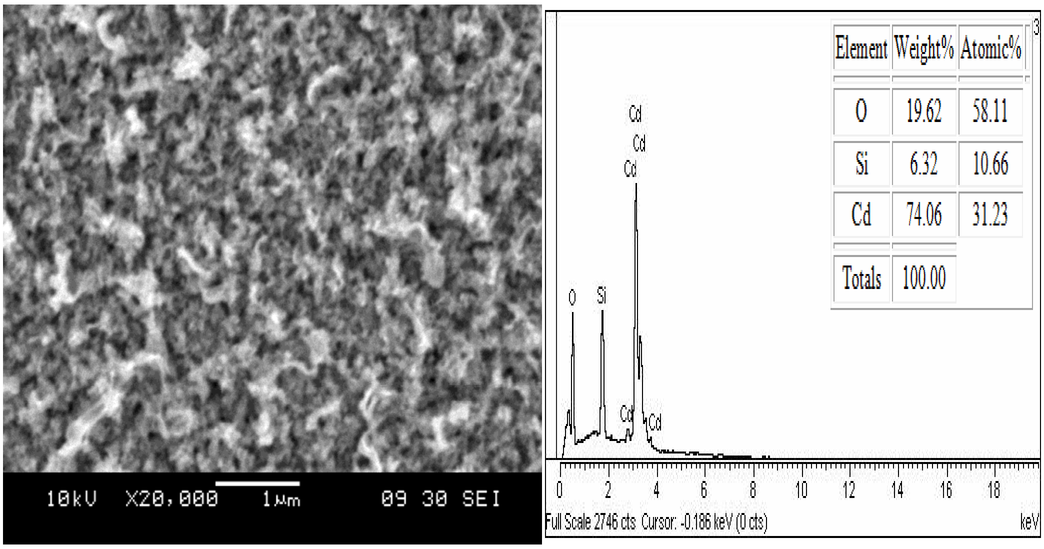


Figure 3. XRD spectrum of the CdO thin film on silicon substrate.

The surface morphology of the CdO thin film deposited on the Si substrate is observed in the SEM image shown in Fig. 4. The results showed that the thin film exhibits a uniform surface morphology over the entire substrate and that the film is of good quality. The EDX spectrum and atomic composition of the CdO/Si is shown at the right side of SEM image. The description of the atomic composition of the elements in the CdO/Si is tabulated in percentage, as shown in Fig. 4. The concentrations of these elements are indicated by the peaks, showing clearly that the elements corresponding to the peaks comprise the CdO/Si without impurities.



Element	Weight%	Atomic%
O	19.62	58.11
Si	6.32	10.66
Cd	74.06	31.23
Totals	100.00	

Figure 4. SEM image and EDX analysis of the CdO/Si.

Fig. 5 shows an SEM cross-sectional image of the CdO/Si. The CdO thin film was distinguished due to its different structure with Si substrate and has formed a uniform surface over the entire substrate. The figure also reveals the thickness of the CdO thin film was 346 nm.

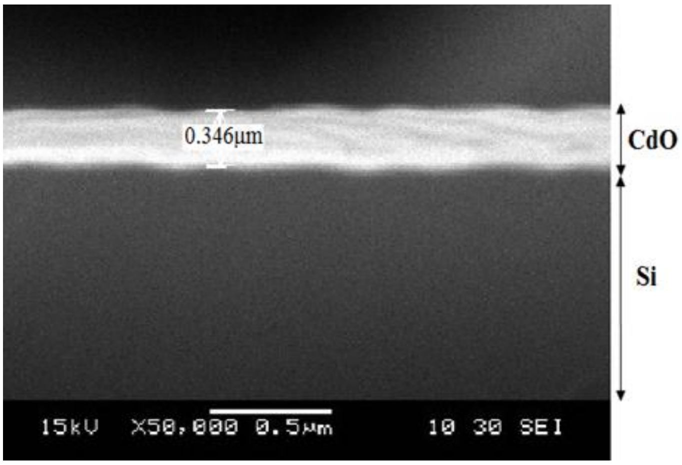


Figure 5. SEM cross-sectional image of the CdO/Si.

Fig. 6 shows the photoluminescence spectroscopy of the CdO thin film at 325 nm excitation. Based on detailed PL measurements, a strong emission peak was observed at 504 nm (2.46 eV), which is ascribable to the near-band-edge (NBE) emission of CdO with a full-width and half maximum of approximately 122 nm [15,16]. This value indicates the quantum confinement effect of the as-synthesized CdO thin film.

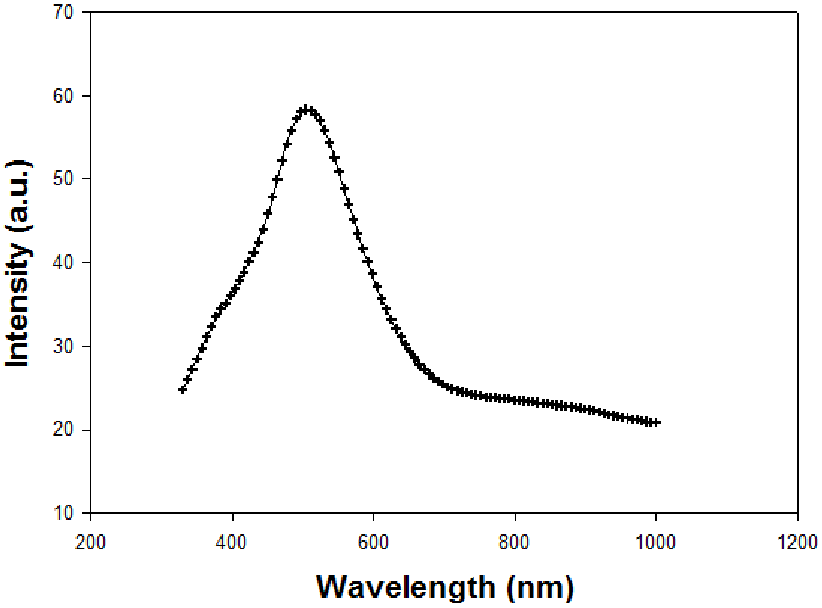


Figure 6. Photoluminescence spectroscopy of the CdO/Si.

AFM was used to characterize the topography (2D, 3D) of the CdO thin film, as shown in Fig. 7. The mean surface roughness was measured to be 65.73 nm. Therefore, the high degree of roughness of the CdO thin film reduces light reflection, but increases light absorption in the visible region of the solar spectrum in solar cells.

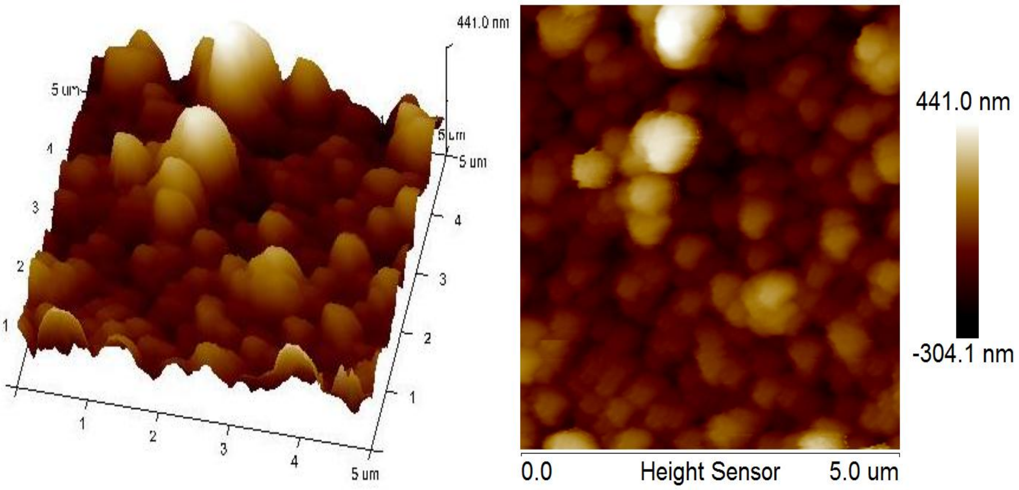


Figure 7. Atomic Force Microscope (AFM) (3D, 2D) of the CdO/Si.

Fig. 8 shows the reflection spectra of the CdO/Si. The minimum effective reflectance was obtained by deposition the *n*-CdO thin film on a *p*-type Si substrate, evidently reducing light reflection and increasing light-trapping at wavelengths ranging from 400 nm to 1000 nm because of the high degree of roughness and large thickness (346 nm) of the CdO thin film.

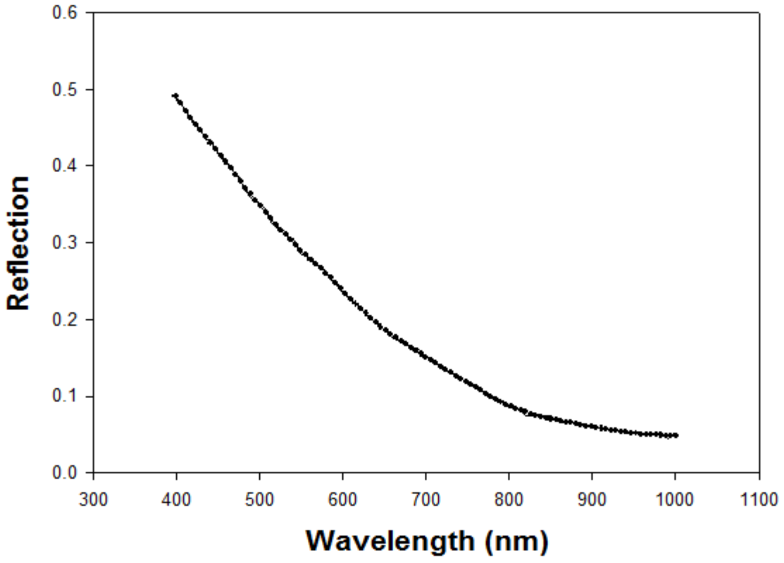


Figure 8. Reflection spectra of the CdO/Si.

Fig. 9 shows the *J–V* characteristics of the solar cell under a 100 mW/cm^2 illumination condition.

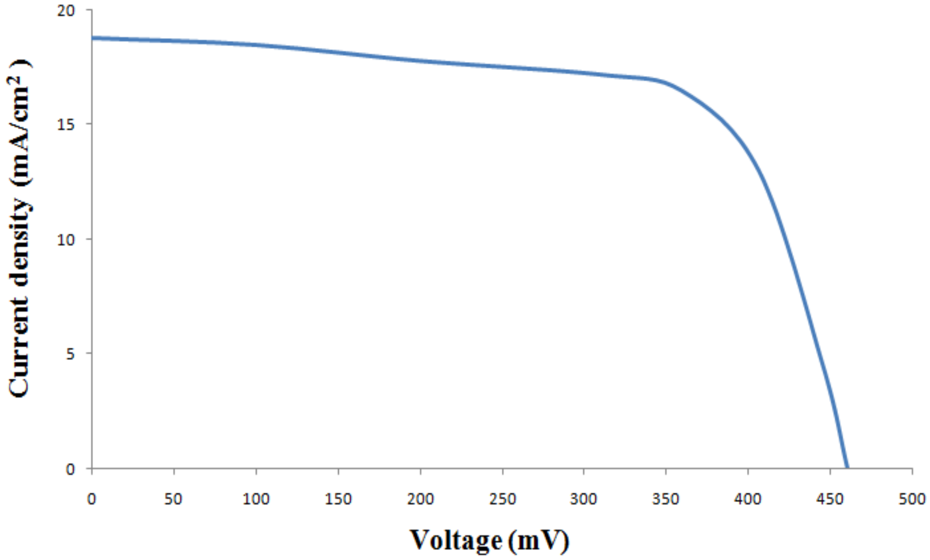


Figure 9. Current density-Voltage curves of the (*n*-CdO/*p*-Si) solar cell.

In the present study, the CdO/Si solar cell has an open-circuit voltage (V_{oc}) of 460 mV, a short-circuit current density (J_{sc}) of 18.8 mA/cm^2, a maximum voltage (V_{max}) of 359 mV, and a maximum current (J_{max}) of 16.5 mA/cm^2. The fill factor (*FF*) was calculated as follows [20,16]:

$$FF = \frac{J_{\max} \times V_{\max}}{J_{SC} \times V_{OC}} \qquad (3)$$

FF was calculated to be 0.685, and conversion efficiency (η) can be calculated as follows [20,16]:

$$\eta = \frac{FF \times J_{SC} \times V_{OC}}{P_{in}} \qquad (4)$$

The efficiency of the (*n*-CdO/*p*-Si) solar cell was 5.92% using thermal evaporation in a vacuum.

4. CONCLUSION

A CdO thin film was successfully deposited on a *p*-Si substrate to yield a solar cell via thermal evaporation in a vacuum. The XRD pattern showed that the thin film was polycrystalline in nature with a cubic structure and that the prepared film has a (111) preferred orientation. SEM results showed that the thin film exhibited a uniform surface morphology over the entire substrate and has a good quality structure. The direct band gap energy of the CdO thin film was 2.46 eV. The minimum effective reflectance was obtained from the deposition of the *n*-CdO on the *p*-Si substrate, evidently reducing light reflection and increasing light-trapping at 400 mm to 1000 nm wavelengths due to the high degree of roughness and large thickness of the CdO thin film. Moreover, the solar cell conversion efficiency (*n*-CdO/*p*-Si) was 5.92% under a 100 mW/cm^2 illumination condition using thermal evaporation in a vacuum.

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