Characterization of Closed Field Magnetron Sputtered ITO and CdTe Thin Films for use in Solar Cells

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Abstract

In this paper, a new magnetron sputtering strategy is introduced that utilises high plasma densities (~10 mA.cm^{-2}) to avoid or reduce high temperature processing. The technique uses magnetrons of opposing magnetic polarity to create a "closed field" in which the plasma density is enhanced without the need for high applied voltages. A batch system has been used which employs a rotating vertical drum as the substrate carrier and a symmetrical array of four linear magnetrons. The magnetrons are fitted with target materials for each of the thin films required in the photovoltaic (PV) stack viz. CdTe absorber layer, CdS buffer layer, metal contact and the back transparent conducting oxide (TCO) contact under superstrate configuration. The "closed field" sputtering technology allows scale up not only for larger batch system designs but it is also configurable for "in-line" or "roll to roll" formats for large scale production.

1. Introduction

Thin film CdTe solar cell technology is a highly promising technology for clean and low cost generation of solar electricity. The high efficiency, flexibility and lightweight advantages of CdTe solar cells, together with their stable performance and potentially low production costs further enhance their attractiveness. A distinct manufacturing advantage of CdTe solar cells is the potential use of fast vacuum deposition methods, providing the high throughput essential to reduce manufacturing costs. Industrial production of CdTe solar cells has already started in the USA, Europe and the Far East. For example, ANTEC Solar Energy GmbH, in Germany is producing CdTe modules from a 10 MW capacity plant while First Solar Inc. has announced its expansion of manufacturing CdTe based thin film solar cells with an annual production output that has already exceeded 1 GWp during 2009 [1]. However further fundamental device and materials research is needed to improve the commercial viability of the technology by improving the stability of higher efficiency devices and substantially reducing the CdTe layer thickness. A cost advantage would be obtained if a process is developed that is continuous in vacuum without the requirement for certain process steps to be carried out using wet chemistry at atmosphere.

The sputter-deposition technique is already well established in a number of coating applications. Magnetron sputtering has the advantage of producing uniform coatings up to +/-1% over large areas The process is also controllable and cost effective. It is also useful for various heat sensitive substrates such as polymers and plastics. Reactive sputtering using metal or ceramic material targets is generally applicable to deposit metal-oxides for instance transparent conducting oxides (TCOs), SiO_2 and Nb_2O_5. In this paper we will also discuss the application of closed field magnetron sputtering to deposit CdTe thin films for use in photovoltaic solar cells.

Closed Field Magnetron Sputtering

Reactive closed field magnetron sputtering was initially developed for wear resistant coatings by Teer [2]. In the closed field configuration (Figure 1), confinement of the reactive plasma is achieved using unbalanced magnetrons of opposite polarity. This arrangement links magnetic field lines between the magnetrons. The magnetic field created by such an arrangement of traps electrons in a magnetic bottle generating sustainable high density argon plasma. This plasma does not require a substrate bias voltage to sustain high plasma densities. The rotating substrate holder is in the form of a vertical drum which is normally faceted to accept flat substrates as also shown in Figure 1. This arrangement enables the creation of high ion current densities ~10 mA/cm^2 [3] and the revolving drum is allowed to electrically float to the plasma potential which is typically 25 V to 50 V. The use of the closed field results in no requirement for an auxiliary ion source, plasma source or micro-wave ion source with associated accelerating Voltages.

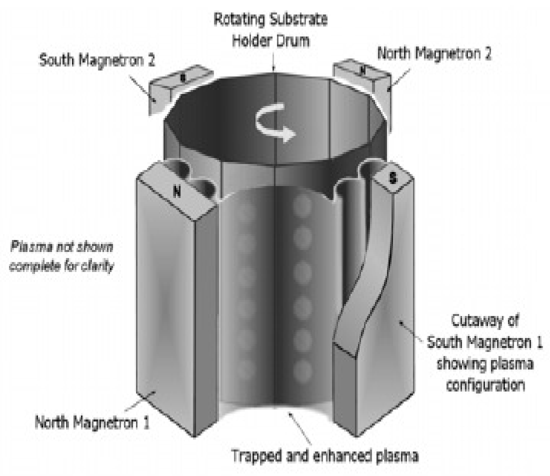

Figure 1 The arrangement of four magnetrons around a cylindrical substrate holder assembly to enhance the plasma density in a closed magnetic field [4].

The floating potential on the substrates determines the deposition energy which is close to optimum. Thin films deposited using closed field magnetron sputtering are dense, spectrally stable and exhibit low stress. They have also been shown to be very smooth.

2. Experimental

The closed field magnetron sputtering format has been incorporated into mid-sized batch system which consists of a 400 mm diameter vertical rotating drum (substrate holder), with four 600 mm linear magnetrons symmetrically arranged around the chamber. The sputtering targets are made up of materials for photovoltaic thin film solar cells. This includes cadmium telluride (CdTe) as the absorber layer, cadmium sulphide (CdS) as a buffer layer, and TCOs (or metals) for front and back contacts configured as shown schematically in Figure 2.

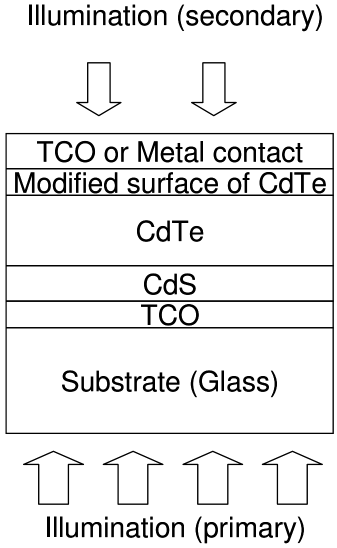

Figure 2 Schematic of a CdTe solar cell (superstrate configuration) showing the different layers.

The targets are powered using a pulsed dc supply in order to avoid arcing from the semi-insulating materials. In the closed field magnetron sputtering system used in this study four magnetrons are fitted around the segmented vertical drum as shown in Figure 3. The chamber is fitted with a turbo-molecular pump. The chamber is also fitted with radiant heaters in the door of the chamber.

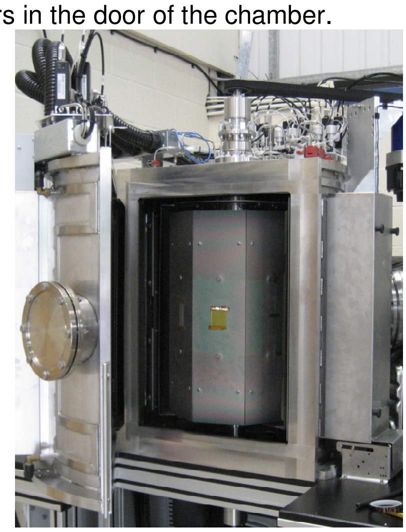

Figure 3 The closed field magnetron sputtering system with 4 linear magnetrons and a faceted drum-based substrate holder.

Although the results in this study were obtained in a mid-sized batch system, the closed field technology is also suitable for both "roll-to-roll" and "in-line" configurations for large scale production of CdTe based thin film solar cells.

3. Results and Discussion

3.1 Transparent conductive oxide

Figure 4 shows spectral transmittance data obtained from transparent conducting oxide (TCO) films of indium tin oxide (ITO) with thicknesses in the range 200-500 nm. These films show transmittance above 80%. The films deposited are very smooth with an rms roughness usually < 1 nm.

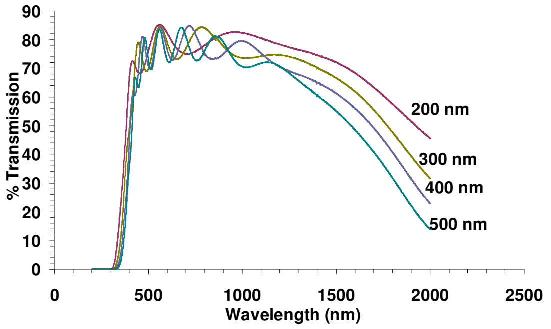

Figure 4 The spectral transmittance of ITO films deposited using closed field magnetron sputtering.

Sheet resistance and Hall mobility measurements were obtained from a range of ITO films of increasing thickness. The data is shown in Figure 5. The resistivity decreased with thickness. The Hall mobility increased with ITO thickness.

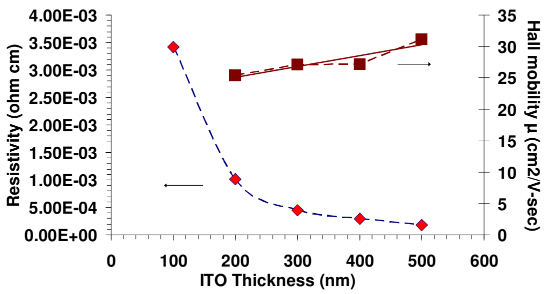

Figure 5 Sheet Resistance and Hall mobility measurements from ITO films with increasing thickness.

3.2 Cadmium Telluride Thin Films

CdTe thin film layers have been deposited on glass and TCO/CdS coated substrates. The layers have a compact surface morphology with columnar type grain growth structure. This is shown in the scanning electron microscopy (SEM) images of the CdTe surface (a) and cross-sectional view (b) shown in Figure 6. Energy dispersive X-ray spectroscopy (EDS) has shown that the composition of these films was stoichiometric Cd 50 at.% and Te 50 at.%.

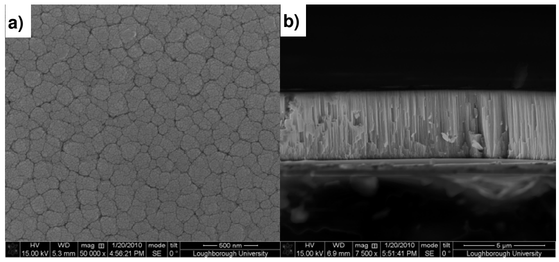

Figure 6 SEM a) surface and b) cross-sectional images of the CdTe layer on glass.

X-ray diffraction (XRD) data shown in Figure 7 shows a strong CdTe (111) revealing that the grains are strongly oriented in the (111) plane.

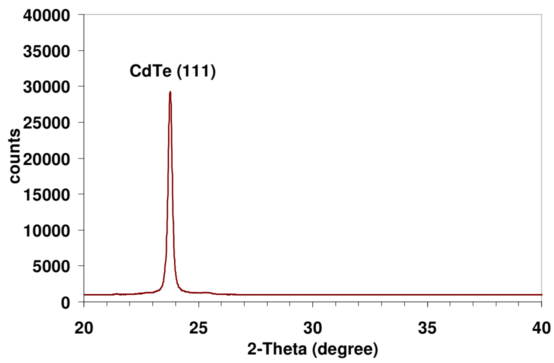

Figure 7 XRD data from sputtered CdTe films on a glass substrate.

Transmittance data from a CdTe layer (~ 5µm-thick) on a glass substrate shows a sharp absorption edge at 800nm and 65% maximum transmission (Fig. 8).

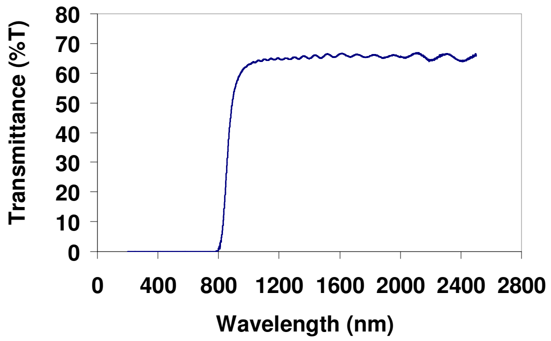

Figure 8 Transmittance (%) versus wavelength spectra of the CdTe layer on the glass substrate.

3.3 Glass/ITO/CdS/CdTe structure

Several sputtering depositions have been carried out to optimise the sputtering process conditions required for the CdTe layer. In one case an ITO layer of approximately 600 nm was sputtered on to a glass substrate. This was followed by chemical-bath deposited CdS layer (~ 80-90nm) and a surface conditioning step, and then an approximately 2.5 µm-thick CdTe layer was sputter-deposited on to the CdS layer. The SEM cross-sectional image of the glass/ITO/CdS/CdTe structure is shown in Figure 9. The image reveals that the sputter deposited ITO and CdTe show perfectly uniform growth of these layers. The CdTe layer shows columnar structure type grain growth.

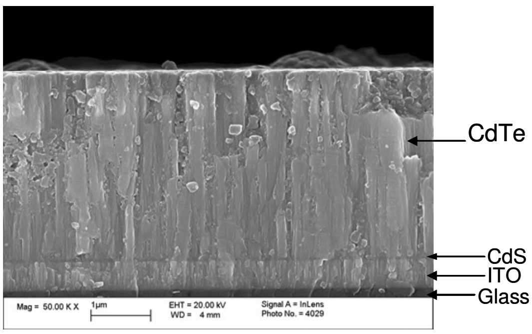

Figure 9. SEM cross-sectional image of the stack structure glass/ITO/CdS/CdTe showing highly uniform layer deposition.

4. Summary

The closed field magnetron sputtering configuration may be used to deposit all the layers in a CdTe/CdS PV stack. Sputtering allows nanometre thickness control of each layer. The morphology of each layer may be controlled by varying parameters such as gas pressure, substrate bias and deposition rate.
This study has shown that sputter-deposition of CdTe results in highly compact layers and the morphology reflects columnar grain growth. The CdTe films are stoichiometric and the CdTe grains are strongly oriented along the (111) plane. The study has also revealed that sputtering results in highly uniform thin film thicknesses both for individual layers and for multilayer stacked structures. This uniformity is important since it means that the CdTe absorber thickness can be controlled effectively, which is paramount to device properties and scaling up issues.

Acknowledgements

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