

# High efficiency, magnetron sputtered CdS/CdTe solar cells

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Received 20 January 2004; received in revised form 23 June 2004; accepted 25 June 2004

Available online 23 August 2004

Communicated by: Associate Editor T.M. Razykov

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## Abstract

Polycrystalline II–VI semiconductor materials show great promise for efficient, low-cost photovoltaics. Large-area deposition of the II–VI semiconductors such as CdTe is possible by a variety of methods but the use of a plasma-based method such as magnetron sputtering can have significant advantages. Here we present recent results in the fabrication of CdS/CdTe cells using rf magnetron sputtering and discuss some of the advantages that accrue from the use of sputtering methods in this class of materials. Some of these advantages are particularly relevant as the polycrystalline thin-film PV community addresses issues related to the fabrication of tandem cells with efficiencies over 25%. Our best results have been obtained with sputtered ZnO:Al to achieve a CdTe solar cell having 14.0% efficiency at one sun with an air mass 1.5 global spectrum. We have also studied reactive sputtering of ZnTe:N which shows promise for use as a transparent back contact or as a recombination junction with ZnO:Al for II–VI based alloy top cells in a tandem solar-cell configuration. Finally, some advances have been made in substrate-configuration CdTe cells on Mo using sputter deposition that hold promise for flexible CdTe-based PV.

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**Keywords:** CdTe solar cell; Tandem cell; Magnetron sputtering; Polycrystalline thin film

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## 1. Introduction

The deposition of polycrystalline thin-film semiconductors such as CdTe is possible by a variety of methods including close-spaced sublimation (CSS), vapor-transport deposition (VTD), physical-vapor deposition, metalorganic-chemical-vapor deposition, molecular beam epitaxy (MBE), pulsed laser deposition, and electrodepo-

sition (McCandless and Sites, 2003). However, the use of a plasma-based method such as magnetron sputtering can have significant advantages including the use of low energy particle bombardment to achieve lower growth temperatures and the use of excited state species to improve the doping control during growth.

We have reported sputtered cells with efficiency of 11.6% on soda-lime glass (SLG) with a commercial coating of SnO<sub>2</sub>:F (Shao et al., 1996). This substrate material (both the glass with its relatively high content of iron and the tin oxide) is known to have limitations in transparency and has less than optimum texture. Nevertheless, a good supply of inexpensive substrate material is

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readily available and convenient, and most of our effort has been focused on this starting material. Recently we have made slight adjustments in our process and have improved the cell performance on these 3 mm thick commercial substrates to 12.6% as measured at NREL (Gupta and Compaan, 2003).

Even more recently, we have used magnetron sputtered ZnO:Al as the transparent conducting oxide (TCO) layer and 1 mm thick aluminosilicate glass to obtain a 14.0% cell (Gupta and Compaan, 2003) with all the layers sputtered except for the evaporated Cu/Au back contact. Although this result is lower than the record efficiency of 16.5% (AM1.5) for polycrystalline thin-film CdTe cells (Wu et al., 2002), we believe that these results establish magnetron sputtering as a competitive deposition technique for these materials especially in view of the potential advantages of low growth temperature and good doping control.

In this paper we shall review these recent results on single junction cells and highlight additional work on related semiconductor alloys and transparent conductors that will be important for developing tandem II–VI semiconductor PV devices. We also describe a prototype, functional II–VI two-terminal tandem device.

## 2. Sputtered ZnO:Al films for the front contact layer

It is known that fluorine-doped SnO<sub>2</sub> has relatively low electron mobility so that high carrier concentrations are required to achieve the low sheet resistance needed for large-area PV devices. Thus, significant light loss occurs in the red and near infrared spectral region. Furthermore soda-lime glass, 2 or 3 mm thick, introduces significant loss due to absorption by Fe and other elements. By contrast, ZnO:Al is known to have higher electron mobility and better transparency in the region  $\lambda < 900$  nm important for CdTe cells (Gupta and Compaan, 2003). Thus it is an attractive candidate as a TCO. However, although ZnO:Al has been used very successfully as the final layer in substrate configuration cells such as copper–indium–gallium–diselenide (CIGS), attempts to utilise it as the TCO in superstrate configuration cells such as CdTe, during which it is subjected to subsequent high-temperature processing, have not been very successful. The best reported efficiency of a ZnO/CdS/CdTe device is ~9% (Tiwari et al., 2001) compared to 14% (Aramoto et al., 2003) for SnO<sub>2</sub>:F TCO on SLG, and 16.5% for a CdTe cell using Cd stannate and Zn stannate bilayer TCO on borosilicate glass. The limited efficiency previously experienced with ZnO:Al may be due to its thermal instability at high growth/processing temperature (e.g., CSS or VTD techniques) and its instability in high acidic or basic media (i.e., solution growth or electrodeposition techniques). The CSS and VTD processes for CdTe typically reach temperatures of

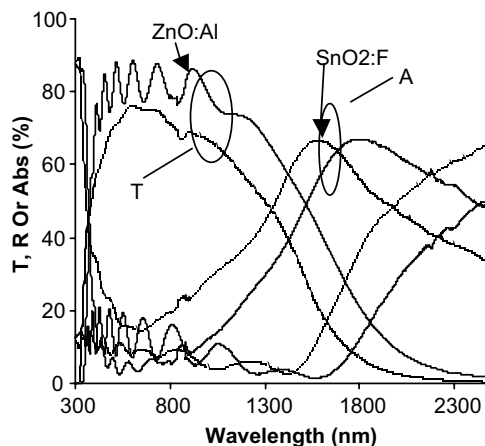


Fig. 1. Comparison of the optical properties of ZnO:Al & TEC-7 SnO<sub>2</sub>:F of similar thickness.

600–650 °C, where the ZnO:Al degrades. Thus, since our sputtered cells do not involve processing temperatures above the 385–390 °C needed for vapor cadmium chloride treatment, it is natural to examine the behavior of ZnO:Al for our sputtered cells.

The ZnO:Al films were deposited using RF magnetron sputtering from a ceramic ZnO:Al<sub>2</sub>O<sub>3</sub> (2%) target at 220 °C on 1 mm thick aluminosilicate glass (ASG) slides. The depositions were carried out in pure argon gas at 48 W of RF power and 1.3–1.6 Pa pressure. The deposition rate was ~2 Å/s. The films were characterized for optical and electrical properties. These magnetron sputtered films are not the highest conductivity ZnO:Al films reported (Igasaki and Saito, 1991) but the ASG/ZnO:Al substrates nevertheless show considerable improvement over the commercial SLG/SnO<sub>2</sub>:F (Pilkington TEC-7)<sup>1</sup> substrates used earlier. A comparison of the optical properties is given in Fig. 1. Although the sputtered ZnO film was thicker than the TEC-7 SnO<sub>2</sub>, and did not have a color suppression layer between the glass and the TCO such as used in the TEC-7 to reduce interference fringes, the optical transparency is noticeably improved.

## 3. All-sputtered solar cell with ZnO:Al as the TCO

We have used this sputtered ZnO:Al as the TCO layer to fabricate cells with sputtered CdS and CdTe layers. The structure of these cells was 1 mm aluminosilicate glass/1.5 μm ZnO:Al/0.13 μm CdS/2.3 μm CdTe/3 nm Cu/20 nm Au. This structure is similar to that used for previous devices on SLG/SnO<sub>2</sub>:F substrates. The CdS and

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CdTe deposition, the vapor  $\text{CdCl}_2$  treatment at  $387^\circ\text{C}$  for 30 min, the evaporated Cu/Au back contact and final Cu diffusion in air at  $150^\circ\text{C}$  for 45 min were the same as used for cells on TEC-7 substrates. No water rinse or chemical treatment such as etching was used after the initial glass cleaning in alkaline soap water followed by deionized water rinse. The metal back contacts were evaporated through a mask of  $0.15\text{cm}^2$  holes. The standard tests at NREL gave  $V_{\text{OC}} = 814 \pm 1\text{mV}$ ,  $J_{\text{SC}} = 23.6 \pm 0.1\text{mA/cm}^2$ , fill factor =  $73.25 \pm 0.2$  and efficiency ( $\eta$ ) =  $14.0 \pm 0.2\%$  (air mass 1.5). This compares with our best cell on TEC-7 which was tested at  $V_{\text{OC}} = 820\text{mV}$ ,  $J_{\text{SC}} = 20.7\text{mA/cm}^2$ , FF = 74%, and  $\eta = 12.6 \pm 0.2\%$ . The  $I$ – $V$  and QE tests are shown in Fig. 2.

One of the most interesting features of this cell structure is that the ZnO works so successfully with CdTe. Our results indicate that the use of sputtering for the deposition of the CdS and CdTe layers apparently can allow the use of this very attractive TCO. In our case, deposition of the CdS and CdTe was done  $250^\circ\text{C}$ . The highest temperatures were reached during the vapor  $\text{CdCl}_2$  treatment at  $387^\circ\text{C}$ . This result confirms that the moderate temperatures possible with magnetron sputtering can provide important advantages in cell fabrication and expand the range of materials available for thin-film polycrystalline solar cells (Lee et al., 2004).

The quantum efficiency curve in Fig. 2 shows relatively poor quantum efficiency, QE, in the region from 350 nm (the absorption edge of the ASG) to 520 nm which is caused by absorption in the CdS and interdiffused CdS layers. Other groups have shown that the use of a high resistivity transparent (HRT) layer between the TCO and the CdS, can facilitate the use of thinner layers for CdS and therefore higher response in the 350–520 nm range. We are currently working on an appropriate HRT layer for the ZnO:Al to increase this blue–green response. Additionally we have found that the performance of these ZnO-based cells is not as stable under one sun light soak conditions as those with TEC-7 substrates and attribute this to possible interdiffusion between the ZnO, CdS, and CdTe layers. Thus, we believe that the performance of these “all-sputtered” cells can be further improved.

#### 4. Substrate configuration CdTe cells

CdTe cells are unusual for the fact that they exhibit superior performance only in the superstrate configuration. Usually, it is advantageous to fabricate cells by forming the active junction as one of the *final* steps to provide maximum control of this critical interface. Thus the epitaxial III–V materials are grown from the bottom

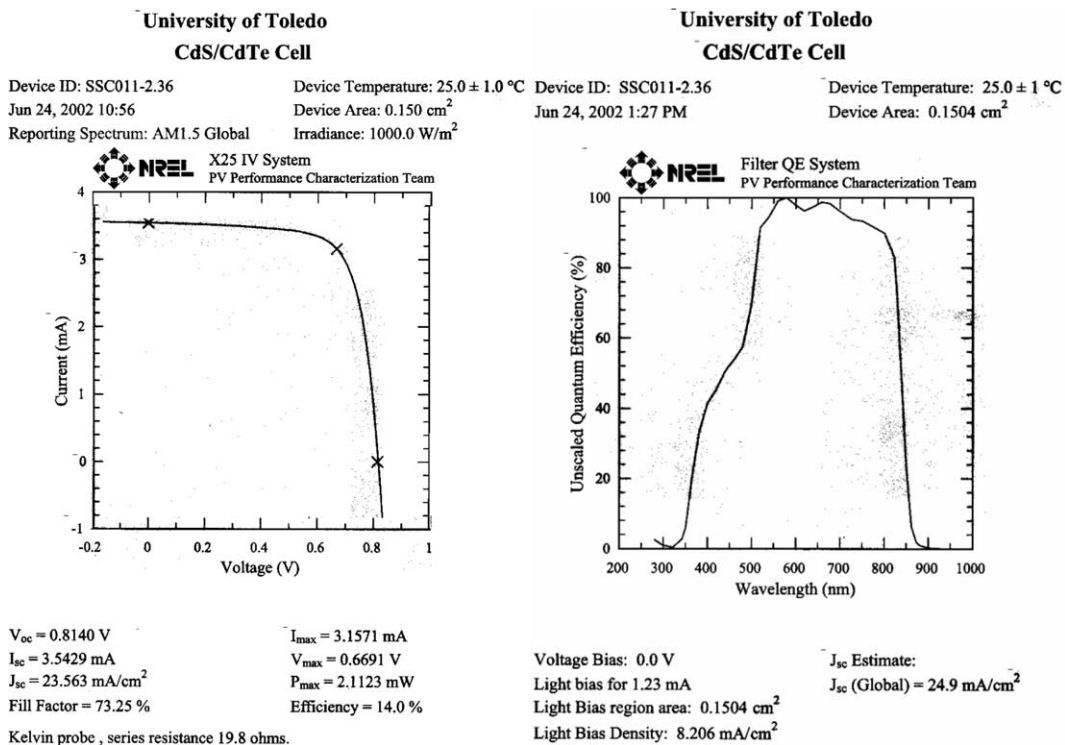


Fig. 2. Performance of cell as shown by the  $I$ – $V$  and QE traces obtained at NREL.

up, CI(G)S has the n-type CdS typically deposited by chemical bath deposition with the ZnO:Al TCO layers deposited at low temperature, and advances in Si cell performance have been achieved by texturing the surface, controlling surface recombination, and applying antireflection coatings in the final processes. a-Si:H is unusual in functioning well in both a substrate configuration on stainless steel and superstrate configuration on TCO-coated glass (Deng and Schiff, 2003), although the champion triple junction cells have the substrate configuration (Yang et al., 1997). The unusual “affinity” of CdTe films for the superstrate configuration is likely related in part to the very stable CdS/CdTe interface that can withstand CdTe deposition temperatures to 650 °C but especially to the difficulties in forming high quality back contacts to the CdTe (Li et al., 1999). With its high electron affinity of 4.28 eV (McCandless and Sites, 2003), few metals are available to form a low resistance contact to p-type CdTe. Thus, the superstrate configuration allows the formation of the back contact last and a variety of chemical etching processes or application of interfacial layers are typically used before applying the final metal contact. Usually some final diffusion steps are used to improve the back contact performance.

Superstrate configurations require a robust, transparent deposition “substrate” which has effectively limited the best CdS/CdTe devices to glass substrates. In fact the best laboratory devices have been produced on borosilicate or aluminosilicate glass partly because of the higher temperature capacity of these glasses. Their expense, however, precludes their use for large-area production devices. Furthermore, glass superstrates are too fragile and heavy to permit the serious consideration of CdTe cells for space applications. However, the lower deposition temperature of magnetron sputtered CdTe may provide some opportunity to develop efficient CdS/CdTe cells in the substrate configuration and facilitate the use of flexible substrates.

We have studied magnetron sputtering for fabrication of substrate-configuration CdTe cells on flexible, 100  $\mu\text{m}$  thick Mo foil. The structure of these cells was: Mo/ZnTe:N/CdTe/CdS/ITO. All layers were deposited by sputtering. We found some improvement with the use of the p-type, nitrogen-doped ZnTe as a buffer layer between the Mo and the CdTe. The indium tin oxide (ITO) was sputter-deposited to a  $\lambda/4$  antireflection thickness with the same process used for a-Si:H cells on stainless steel (Deng and Schiff, 2003). The best performance previously reported for a substrate cell on Mo was 5.3% (Singh et al., 1999) and for a CdTe substrate cell on CI(G)S was 5.5% (Birkmire et al., 1985). Fig. 3 shows the  $I$ - $V$  response of our sputtered device (Matulionis et al., 2001). Note that the  $J_{\text{SC}}$  is high but the  $V_{\text{OC}}$  is relatively poor and fill factor (FF) is particularly poor. The strong roll-over in forward current together with the poor FF point toward problems with the back contact.

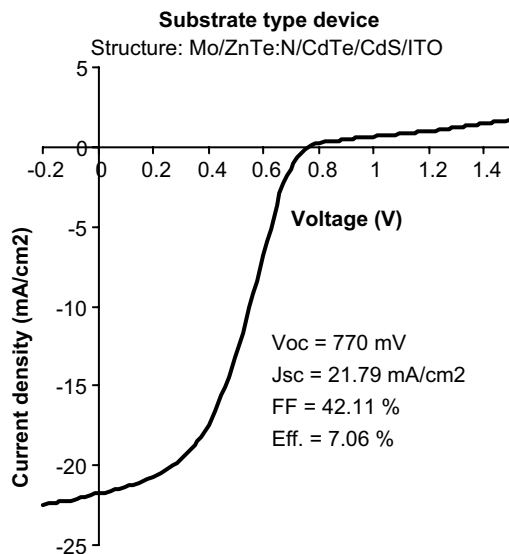


Fig. 3.  $I$ - $V$  response of cell with ZnTe:Ni back contact.

This is a focus of continuing effort. In addition, efforts are underway using sputtering to fabricate substrate configuration cells on polymer substrates.

## 5. Toward a polycrystalline, thin-film tandem solar cell

The highest efficiency PV devices have been realized from tandem (double junction) and triple-junction epitaxially grown InGaP/GaAs/Ge operated under high solar concentration (Olson et al., 2003). Similarly, the best amorphous silicon thin-film devices (14.7% AM1.5 initial and 13.0% stabilized efficiency) (Yang et al., 1997) have also been realized in the triple-junction structure: ITO/a-Si:H(n-i-p)/a-Si:Ge:H/a-Si:Ge:H/ZnO/Al/stainless steel. By contrast, high quality tandem solar cells have not been realized successfully in the polycrystalline thin-film materials such as CdTe or CuIn(Ga)Se<sub>2</sub>, partly because of less research effort but also because the best poly-thin-film devices have required the use of high deposition temperatures (550 °C) for the semiconducting absorbers and low temperatures for the final layers. Thus the final two layers for the (substrate-configuration) CI(G)S cells typically are chemical-bath-deposited CdS and the sputtered ZnO:Al layers, and the final copper-diffused back contact structures in the case of CdTe generally are not exposed to temperatures above 150–200 °C. Again, our successful use of the relatively low temperature sputtered CdS and CdTe may provide advantages for the fabrication of tandem devices in the II–VI materials.

A second challenge in the fabrication of tandem devices from the polycrystalline thin films is the develop-

ment of a transparent back contact to the top cell, in the case of a possible four-terminal, mechanically stacked cell, and of the development of a suitable interconnect (or recombination or tunnel) junction in the case of the two-terminal, monolithically fabricated device. The following provides some highlights of our recent work in this direction.

One of the major challenges for these materials is the development of transparent p-type films compatible with the semiconductor absorber layers of the poly-thin-film devices. Nitrogen-doped ZnTe has been successfully used in epitaxial thin films for light emitter devices prepared by MBE or MOCVD and it is an attractive possibility for contacts to CdTe because of its near alignment of valence band with CdTe (Wei and Zunger, 1998; Wei et al., 2000) and because of its potential for p-type doping (Baron et al., 1998). ZnTe doped with copper, ZnTe:Cu, has exhibited good p-type conductivity and has shown good performance as part of a back contact structure for VTD-deposited CdTe (Gessert et al., 2000). However, to our knowledge, polycrystalline ZnTe had not been shown to be amenable to p-type doping with nitrogen. One of the difficulties of N-doping is that molecular nitrogen,  $N_2$ , has a very high bond strength with a dissociation energy of 10 eV. This difficulty has been overcome in epitaxial growth through the use of remote plasma sources in MBE systems that provide a flux of atomic nitrogen or electronically excited  $N_2$ . We have extended this concept to use reactive magnetron sputtering to assist in doping of ZnTe films. The difference from MBE sources is that the  $N_2$  excitation in sputtering must be an integral part of the sputter process which controls the ZnTe deposition rate as well. In fact we have shown through optical emission spectroscopy that the introduction of 3%  $N_2$  in the Ar sputter gas can yield an abundance of metastable  $N_2$  in the sputtering plasma and, in particular, at the growing film surface (Drayton et al., 2002). This process readily produces films with hole concentrations of  $\sim 3$  to  $5 \times 10^{18} \text{ cm}^{-3}$  although the density of N incorporated in the film is typically 10 to 100 times greater.

The ZnTe:N films were produced by reactive sputtering at  $\sim 350^\circ\text{C}$ , a sputter power of  $\sim 2 \text{ W/cm}^2$  (40 W on a 50 mm diameter target) and gas pressure of  $\sim 2 \text{ Pa}$ . Films were characterized before and after annealing to determine changes in surface morphology and grain size, grain orientation, optical, and electrical properties. Studies of the temperature stability of these films indicate their conductivity increases by about a factor of two after a 30 min heat treatment in air (presumably due to some decrease in grain boundary barriers) but are stable thereafter while heated in air, nitrogen or argon to above  $350^\circ\text{C}$ . We have used such ZnTe:N films as part of a back contact structure for single junction CdS/CdTe cells in place of our standard

Cu/Au contacts. The cells were fabricated on TEC-15/CdS/CdTe plates from First Solar having the CdS and CdTe deposited by VTD. We sputter-deposited a back contact of ZnTe:N/Ni. The ZnTe:N was covered with a Ni layer to finish the back contact since the lateral resistivity of the ZnTe:N was  $\sim 10 \text{ cm}$  ( $1 \times 10^5 \Omega/\text{sq}$ . for a  $1 \mu\text{m}$  thick film) and therefore not suitable for use with a back contact grid. The cell performance was  $V_{\text{OC}} = 717 \text{ mV}$ ,  $J_{\text{SC}} = 19.3 \text{ mA/cm}^2$ ,  $\text{FF} = 68.8$ , and efficiency = 9.5%. The poor  $V_{\text{OC}}$  probably arises from insufficient p-type doping in the CdTe possibly related to the absence of any additional copper. However, we cannot rule out the existence of an oxide layer or other contamination since the ZnTe deposition was carried out in a separate chamber and after the separate vapor  $\text{CdCl}_2$  process carried out in dry air that is needed to “activate” the CdTe and provide high open-circuit voltage. Nevertheless, the demonstration of a  $\sim 10\%$  efficient device indicates promise for the use of ZnTe:N as part of a robust back contact to CdTe.

In addition to the use of ZnTe:N as part of a back contact structure, its use is attractive for potential interconnect junctions in monolithic tandem devices. In this case all carrier conduction is perpendicular to the film plane across a distance of  $\sim 50 \text{ nm}$  or less, rather than the  $\sim 5 \text{ mm}$  needed for conduction to a contact grid. True quantum-mechanical tunnelling typically requires doping densities of  $10^{20} \text{ cm}^{-3}$  or greater in order to achieve sufficiently narrow depletion or barrier widths, however, the highly defective structures of amorphous and polycrystalline material can produce defect-assisted tunnelling or recombination junctions that can yield acceptable performance for the needed interconnect in a tandem structure (Compaan et al., 2003). A typical tandem device is expected to produce current densities of  $\sim 15 \text{ mA/cm}^2$  and requires a contact resistance of about  $3 \Omega \text{ cm}^2$  or less.

In order to examine the suitability of the p-type ZnTe:N and n-type ZnO:Al to form a transparent back contact or a transparent recombination junction for polycrystalline II–VI solar cells, we fabricated several recombination junction structures on  $\text{SnO}_2\text{:F}$ -coated TEC-15 glass in the structure  $0.30 \mu\text{m}$  Ni on the  $\text{SnO}_2\text{:F}$  coated glass,  $0.16 \mu\text{m}$  ZnTe:N,  $0.25 \mu\text{m}$  ZnO:Al, and  $0.32 \mu\text{m}$  Al. Some of these gave essentially linear current–voltage curves with a contact resistance of  $2.5 \Omega \text{ cm}^2$ .

Optical transmission data of the ZnTe:N/ZnO:Al bilayer structure (without the  $\text{SnO}_2$  or metal layers) are shown in Fig. 4. The drop in transmission below about  $550 \text{ nm}$  is due to absorption in the ZnTe. The drop in transmission near  $2000 \text{ nm}$  is due to free-carrier absorption in the ZnO:Al. The bilayer structure is clearly smooth enough to show strong interference fringes.



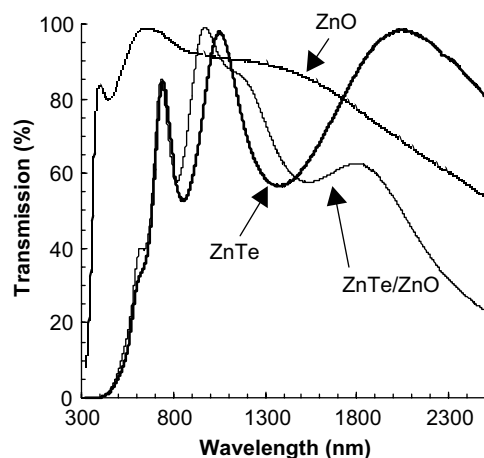


Fig. 4. Transmission of ZnO, ZnTe films and ZnTe/ZnO bilayer structure.

## 6. A prototype two-terminal, thin-film II–VI tandem cell

Following the acceptable performance of the ZnTe:N/ZnO:Al junction between metal contacts, we incorporated this couple into a prototype tandem device based on a top cell of CdTe and a bottom cell of HgCdTe and an interconnect junction of ZnTe:N/ZnO:Al. The  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  alloy film was deposited by magnetron sputtering with conditions very similar to those used for CdTe except that the substrate temperature was lowered to 90°C (Wang et al., 2004). Sputter targets were fabricated from cold pressed targets of two different compositions of binary compounds, CdTe and HgTe, in the at.% ratio of 70 and 30, and 85 and 15. An additional target was acquired from a commercial vendor with the sintered mixed binary composition of 77 and 23 at.% of CdTe and ZnTe. Table 1 provides details of the target preparation/source and the sputtered film compositions as-deposited and after chloride treatments. The films were examined by optical absorption, energy dispersive X-ray spectroscopy, and X-ray diffraction, before and after vapor  $\text{CdCl}_2$  treatments under conditions similar to those used for CdTe. The optical absorption edge studies and energy dispersive X-ray spectroscopy (EDS) studies indicated only small loss of Hg in the as-deposited films and little change with  $\text{CdCl}_2$

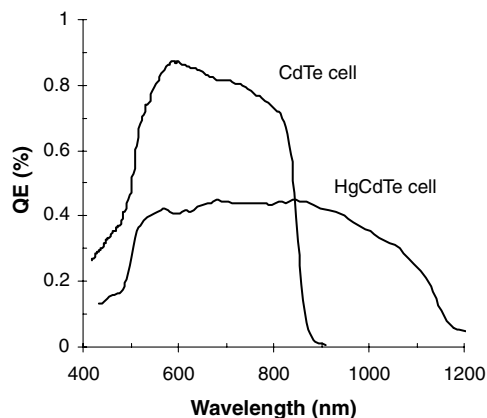


Fig. 5. Quantum efficiency of a sputtered HgCdTe superstrate cell compared with a standard sputtered CdTe cell.

treatments. The typical final loss of Hg was about 5–7% after deposition and chloride processing. Hot probe measurements confirmed that the films were p-type both before and after  $\text{CdCl}_2$  treatment.

Following these preliminary HgCdTe film optimization studies (Wang et al., 2004), we fabricated complete cell structures using TEC-7 substrates, 0.13  $\mu\text{m}$  CdS/1.5  $\mu\text{m}$  HgCdTe/4 nm Cu/20 nm Au. The vapor  $\text{CdCl}_2$  treatment was given to the structure after deposition of the HgCdTe layer. The back contact was diffused at 150°C in air. Fig. 5 shows a comparison between the quantum efficiencies of the pure CdTe and the alloy HgCdTe devices. The onset of optical absorption in the absorber alloy is indicated by the QE rise below 1150 nm and the typical absorption loss in the CdS window layer is indicated by the QE drop below 500 nm. Clearly the HgCdTe is p-type so that the junction lies at or very near the CdS/HgCdTe interface. The QE shows quite poor collection especially at the longer wavelengths which points to limited minority carrier lifetimes in the HgCdTe absorber.

We have prepared the tandem structure in the form shown in Fig. 6, using CdTe for the top cell (1.5 eV) and a bottom cell HgCdTe composition of  $x = 0.82$  to reach  $E_g \sim 1.1$  eV. Although the results are quite preliminary, we have demonstrated that an operational tandem device can be fabricated of these materials in a mono-

Table 1

Target composition/preparation and sputtered film composition (from optical absorption edge)

| Samples | Composition $x$ of target (source) | As-deposited  |                     | After $\text{CdCl}_2$ treatment (390°C, 2 min) |                     |
|---------|------------------------------------|---------------|---------------------|--|---------------------|
|         |                                    | Band gap (eV) | Composition ( $x$ ) | Band gap (eV)                                  | Composition ( $x$ ) |
| M17b1   | 0.70 (cold pressed)                | 1.02          | 0.77                | 1.03   | 0.77                |
| M52b2   | 0.85 (cold pressed)                | 1.23          | 0.88                | 1.28   | 0.91                |
| M67a3   | 0.77 (commercial)                  | 1.13          | 0.83                | 1.15   | 0.84                |

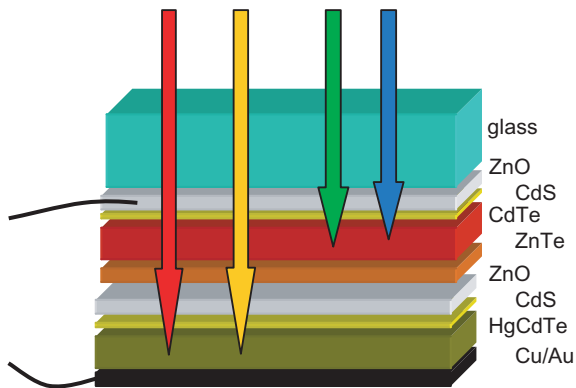


Fig. 6. Assembly sketch of the monolithically integrated two-terminal double junction tandem cell on glass.

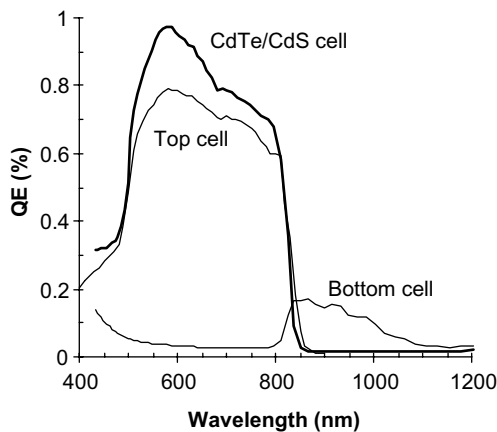


Fig. 7. Quantum efficiency of tandem device of Fig. 6 compared with the QE of a standard sputtered cell.

lithic structure by magnetron sputtering. We have found a quantum efficiency response, Fig. 7, covering the range from about 400 to 1000 nm, and an open circuit voltage of 0.99 V indicating voltage addition of the two junctions. Note that the CdTe cell with the ZnTe:N/Ni back contact produced a  $V_{OC} = 0.717$  V and we expect that the ZnTe:N/ZnO:Al back contact would have a  $V_{OC}$  no greater than this. Thus the bottom cell is likely responsible for about 0.27 V contribution to the  $V_{OC}$  of the tandem device. Fig. 7 also shows the QE of a sputtered CdS/CdTe cell with Au back contact. Note that the QE of the top cell of the tandem is not much different from this CdTe cell prepared without adding copper as part of the back contact, confirming that the top cell structure does not degrade substantially during the fabrication of the bottom HgCdTe cell.

Much effort is still required to reach the 25% efficiency goal for polycrystalline tandems. It will require optimizing the electronic properties of the materials,

the grain boundary passivation, and the film thicknesses to achieve current matching in the top and bottom junctions.

## 7. Conclusions

Our studies of planar magnetron sputtering have shown that under appropriate conditions sputtering can produce high quality semiconductor films at relatively low substrate temperatures. The fabrication of high efficiency (14% AM1.5) CdS/CdTe cells with sputtered ZnO:Al on aluminosilicate glass confirms that the films not only have high optical quality but excellent minority carrier lifetimes as well even though process temperatures do not exceed 300 °C during film deposition or 390 °C during the vapor chloride treatment. Such low-temperature processing of II–VI semiconductor films provides the opportunity for device fabrication on flexible polymer substrates and may provide the capability needed for high efficiency tandem device fabrication on temperature-sensitive polycrystalline thin film structures such as those based on chalcogenide materials.

## Acknowledgments

The discussions of X-ray diffraction and atomic force measurements were based on results provided by Brian McCandless and Puthur Paulson of the Institute of Energy Conversion at the University of Delaware. This work has been supported by NREL through the High Performance PV Program (Martha Symko-Davies) and also through the Thin Film Partnership Program (Ken Zweibel).

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