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High-efficiency flexible CdTe solar cells on polymer substrates

A. Romeo[a,1], G. Khrypunov[a], F. Kurdesau[a], M. Arnold[a], D.L. Bätzner[a], H. Zogg[a], A.N. Tiwari[a,b,*]

[a]Thin Film Physics Group, Laboratory for Solid State Physics, ETH (Swiss Federal Institute of Technology) Zürich, Technoparkstrasse 1, 8005 Zurich, Switzerland

[b]CREST (Centre for Renewable Energy Systems and Technology), Department of Electronic and Electrical Engineering, Loughborough University, Leicestershire, LE11 3TU, UK

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Abstract

Development of flexible and lightweight solar cells is interesting for terrestrial and space applications that require a very high specific power (kW/kg) and flexibility for curved shaping or rolling. Flexible CdTe/CdS solar cells of 11% efficiency in superstrate and 7.3% efficiency in substrate configurations have been developed with a "lift-off" approach. However, roll-to-roll manufacturing is desired in future.

Therefore, flexible superstrate solar cells were directly grown on commercially available ~10 μm thin polyimide (Upilex™) foils. A process for the deposition of ITO (front contact) has been developed to have a stable front contact on the Upilex™ foil. Post-deposition annealing treatments of the ITO/polyimide stacks bring a significant stability to the front contact, having almost the same sheet resistance at the beginning and at the end of the cell fabrication process. Solar cells with AM1.5 efficiency of 11.4% on Upilex™ foils (highest efficiency recorded for flexible CdTe cell) have been developed. A comparison of the cells prepared on different polyimides is presented.

Keywords: Solar cells; Thin films; CdTe; Flexible solar cells; Space solar cells; Solar energy

*Corresponding author. Also at: CREST (Centre for Renewable Energy Systems and Technology), Department of Electronic and Electrical Engineering, Loughborough University, Leicestershire, LE11 3TU, UK. Tel.: +41 1 4451474; fax: +41 1 4451499.

E-mail address: Tiwari@phys.ethz.ch (A.N. Tiwari).

[1]Present address: Scientific and Technological Department, University of Verona, Ca' Vignal 2, Strada Delle Grazie 15, 37134 Verona, Italy

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1. Introduction

Polycrystalline CdTe thin film solar cells have shown long-term stable performance [1] and high efficiency up to 16.5% under AM 1.5 illumination [2]. If produced in large volume, e.g. more than 60 MW/year, their cost could be lower than 1 Euro/Wp [3]. Conventional solar cells are grown on 1–4 mm thick glass substrates, while only a few micron thick layers are needed for the solar cell stack. Therefore, devices with a high specific power (kW/kg, ratio of output power to the weight) are expected if the glass is substituted with a lightweight substrate, since the glass substrate represents more than 98% of the total weight of the cells.

It has been shown that CdTe has the highest stability under proton and electron irradiation [4,5] compared to the other photovoltaic devices, which makes CdTe cells very interesting for space applications. High specific power is an important issue for space solar cells: if satellites are lighter they are easier and cheaper to launch in orbit. One approach to maximize the specific power is to substitute the glass substrate with a flexible and lightweight thin substrate, such as metal or polymer foils. Moreover, this gives flexibility to the solar panel that can be adapted to any kind of shape and is easy to deploy in space for power generation.

In the last few years, integration of photovoltaic modules in the facades and roofs of buildings has drawn a considerable interest. Flexible solar cells give much more possibilities for integration in buildings and can also be applied in a variety of other applications such as smart electronic cards, consumer electronics, solar cars and boats, portable source of power for emergency and recreation, etc. Therefore, flexible CdTe solar cells are immensely interesting for terrestrial and space applications. However, only a limited effort has gone in the development of flexible CdTe solar cells [6]. In this paper, we present two different processes for the fabrication of lightweight and flexible CdTe solar cells on polyimide films.

2. Fabrication of solar cells

We have developed a CdTe/CdS solar cell fabrication process in which all the layers are grown by vacuum evaporation [7]. Briefly, commercially available soda-lime glass coated with fluorine doped tin oxide (FTO) was used as substrates. CdS layers were grown in a high vacuum evaporation (HVE) chamber at a substrate temperature of 150 °C and subsequently annealed at 450 °C for recrystallization. Without breaking the vacuum CdTe was then deposited at a substrate temperature of 300 °C. In a standard deposition CdS thickness is 0.1–0.5 μm and CdTe thickness is between 3 and 4 μm. For the activation of the CdTe/CdS heterojunction a $CdCl_2$ annealing treatment was applied. Vacuum evaporation was used for the deposition of ~600 nm $CdCl_2$ layers on CdTe and the stacks were annealed at 430 °C for 30 min in air. For the electrical back contact the surface of the CdTe was etched with a Br-methanol solution followed by the deposition of Cu/Au stacks and a short annealing at 200 °C in air.

Solar cells in the efficiency range of 11–12% are routinely obtained on soda-lime glass substrates. Fig. 1 shows an *I–V* characteristic of a 12.5% solar cell (with open circuit voltage (V_{oc}) of 800 mV, short current density (J_{sc}) of 23.2 mA/cm^2 and fill factor (FF) of 67.5%) under AM1.5 illumination. The abovementioned process was adapted for the development of flexible CdTe solar cells on polyimide films. Highest recorded efficiencies

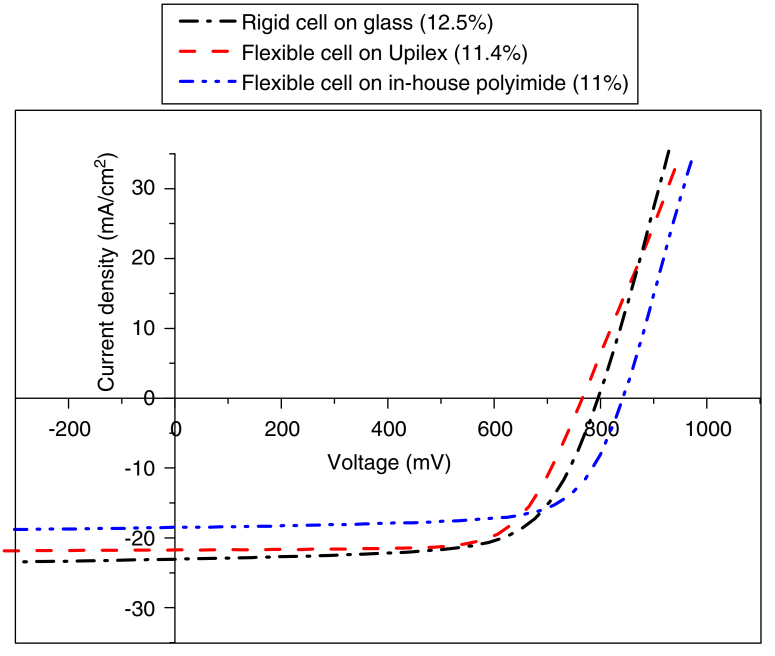


Fig. 1. *I–V* curves of a standard CdTe solar cell on glass with 12.5% efficiency, on Upilex^{TM} with 11.4% efficiency, and on in-house processed polyimide with 11% efficiency under AM1.5 illumination.

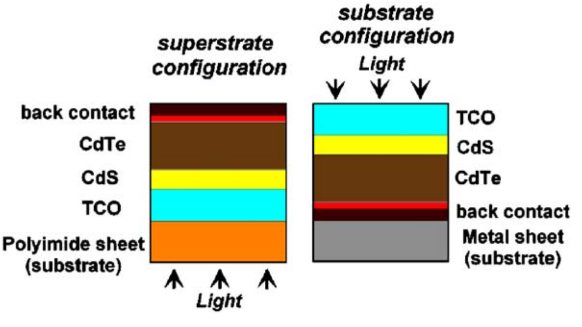


Fig. 2. Schematics of superstrate (left) and substrate configuration (right) solar cells, respectively, on polyimide and on metal sheets.

of 11.4% and 11% were achieved on commercial (Upilex^{TM}) and in-house processed polyimide films, respectively.

3. Flexible CdTe cells in superstrate configuration

The CdTe solar cell can be fabricated in a "superstrate" or a "substrate" configuration (see Fig. 2). High-efficiency CdTe solar cells are generally grown in a superstrate configuration where the CdTe/CdS stacks are deposited on transparent conducting oxide

(TCO) coated glass substrates. Efforts to develop flexible CdTe superstrate solar cells were, until recently, not successful, because of the incompatibility of the polymeric substrate with high-temperature processing steps. For superstrate configuration the choice of an appropriate substrate is crucial; the substrate should be optically transparent and should withstand high temperature during deposition and processing steps.

Most of the CdTe solar cell fabrication processes require temperatures of about 450–550 °C, while most of the transparent polymers are not stable at such high temperatures. However, some polyimides are "stable" at temperatures of up to 450 °C with an optical transparency sufficient for solar cell applications. As shown in Fig. 3, if the thickness of the polyimide film is reduced, the absorption loss in the substrate can be minimized further. The average transmission of the polyimide film is more than ~75% for wavelengths above 600 nm, while there is a strong thickness-dependent absorption of photons in the wavelength range of 400–600 nm.

CdTe solar cells on 50–100-μm-thick-polyimide films will yield a low current due to a large optical absorption loss in the substrate. We have developed a process in which, instead of using a commercially available foil, a "specific" type of polyimide film, thin and transparent in order to minimize the absorption loss, is prepared in-house [8]. A thin buffer layer of NaCl was evaporated on a glass substrate, and then a polyimide layer was spin-coated and cured at about 430 °C. The thickness of the polyimide film can be controlled by the spin-coating process, we have used about 10 μm-thin polyimide films. A layer of ITO was deposited by RF magnetron sputtering on top of the polyimide, followed by the standard HVE-CdS and CdTe deposition and the $CdCl_2$ annealing treatment, as described in Section 2. After processing the device is rinsed in water in order to dissolve the NaCl layer and the solar cell is detached from the glass carrier.

The morphology and microstructure of CdTe on polyimide are similar to those on glass substrates [7]. As shown in Fig. 4, the as-deposited CdTe layer is homogeneously compact with grains of up to ~1 μm size. The $CdCl_2$-annealed layers are crack-free and consist of

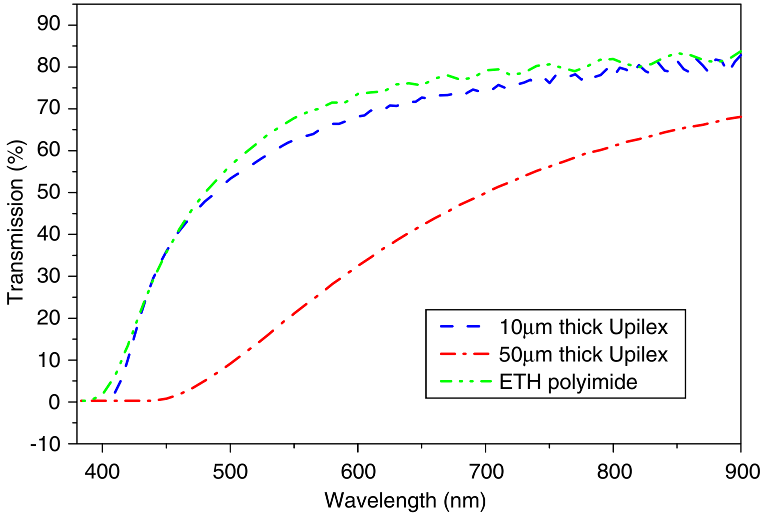
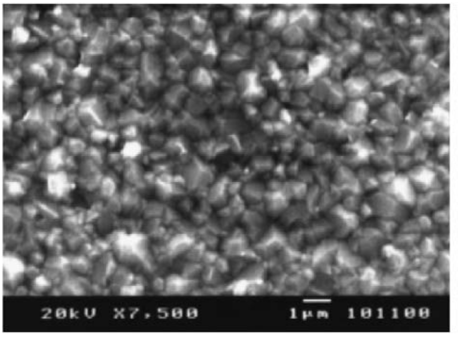


Fig. 3. Transmission spectra of different polyimide films, transparency is strongly dependent on the polyimide thickness.



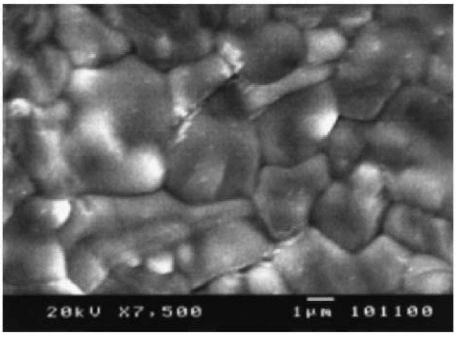


Fig. 4. As-deposited (left) and $CdCl_2$ treated (right) CdTe/CdS/TCO layers on polyimide, the layers are compact and crack-free.

large grains of up to ~5 μm. The solar cells grown on the spin-coated polyimide exhibit efficiencies of 11% with ITO as front contact under AM1.5 illumination (see Fig. 1). High values of open circuit voltage (842 mV) and fill factor (70.9%) are obtained, despite current density is lower (18.5 mA/cm^2) than the ones of CdTe/CdS solar cells on FTO-coated glass because of the absorption loss in the polyimide.

However, the application of a commercial polyimide film as a substrate would be more suitable for a roll-to-roll manufacturing process, and to reduce the production cost. For this reason, we have lately evaluated different polyimide films and found that a commercially available Upilex^{TM} film about 10 μm thin is sufficiently transparent and suitable for CdTe solar cells. As shown in Fig. 3, the average transmission of the polyimide films is more than 75% for wavelengths above 550 nm. There is a strong absorption of photons in the wavelength range of 350–600 nm.

The ITO layers were deposited with an RF-magnetron sputtering system on the Upilex polyimide foils. A particular study of the ITO properties on the polyimide has been made. The ITO deposition was performed at the Ar/O_2 (0–3 vol% O_2) pressure of 8×10^{-3} mbar and different power densities were tested, from 3000 to 1200 mW/cm^2. The successive steps of high-temperature CdS/CdTe layer deposition and $CdCl_2$ annealing may cause degradation in the optical and electrical characteristics of the ITO layer. Therefore, ITO film properties were investigated before and after annealing in air at high temperatures. An annealing of the ITO/Upilex stacks prior to the deposition of the subsequent layers improves the stability of the ITO to further high-temperature processes. Annealing of these stacks in air at 450 °C, improves transmission (in the range of 500–900 nm) from 69% to 72% but also increases the sheet resistance from 5 to 12 Ω/square. Repeated annealing cycles in the same conditions increased the ITO sheet resistance by only 0.8–0.9 Ω/square, with no degradation in transparency. The quantum efficiencies (Fig. 5) of cells made with annealed and non-annealed ITO/polyimide structures show that the difference in quantum efficiency is partly due to low transparency of non-annealed ITO/polyimide layers in the spectral region of 0.6–0.8 μm. The overall lower quantum efficiency for both solar cells is mainly caused by the lower transparency of the polyimide substrate.

Fig. 1 shows the light *I–V* characteristic of an 11.4% efficiency (AM1.5 measurement conditions) flexible solar cell on annealed ITO/Upilex-polyimide film ($V_{oc} = 765$ mV, $J_{sc} = 20.9$ mA/cm^2, FF = 71%). This efficiency is comparable to the 11% efficiency

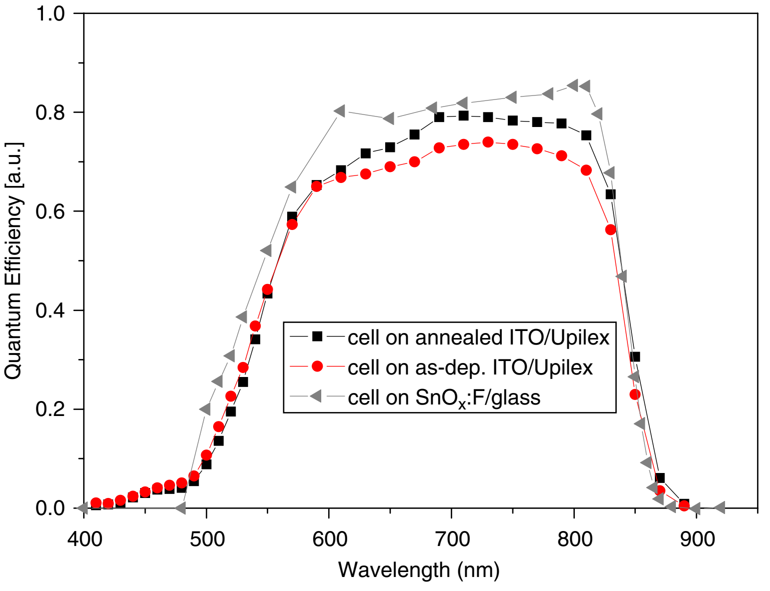


Fig. 5. A comparison of the quantum efficiencies of flexible solar cells with a cell on glass (12.5% efficiency). Efficiencies of the cells on as-deposited ITO and annealed-ITO are 8.5% and 11.4%, respectively, (AM 1.5).

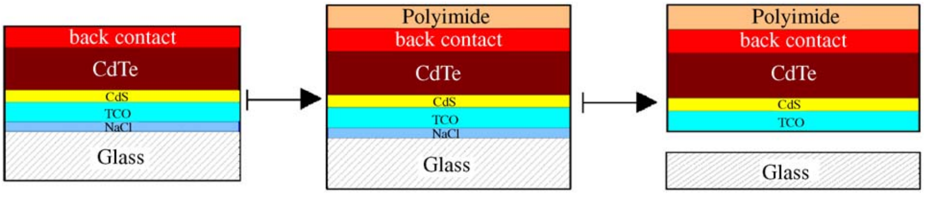


Fig. 6. Schematics of the flexible cell process in substrate configuration: after the polyimide is deposited on top, the cell is rinsed in water (in order to dissolve NaCl) and lifted-off from the glass.

obtained on the in-house polyimide solar cells ($V_{oc} = 842\,mV$, $J_{sc} = 18.5\,mA/cm^2$, $FF = 70.9\%$). It should be mentioned that the properties of the ITO on Upilex and in-house developed polyimide may slightly differ since the layers were grown in different sputtering systems under different conditions.

4. Flexible CdTe cells in substrate configuration

In the second process, schematically shown in Fig. 6, the CdTe/CdS/ITO stacks are not deposited on the polyimide substrate but directly on a thin layer of NaCl deposited by vacuum evaporation on soda-lime glass. After the complete processing of the solar cells, a polyimide or a metal foil can be laminated on the back of the device and the front glass is removed by dissolving the NaCl in water. This results in solar cells in the substrate configuration. The fabrication process is similar to the standard one, presented in Section 2. A layer of either FTO or ZnO:Al was deposited on NaCl/glass substrate (ITO was not investigated because of non-availability of the deposition equipment). The CdS and CdTe layers are grown by HVE and the back contacting is done using the standard procedure. In this way no polyimide layer is present during processing and there is no absorbing layer, except of TCO, between the incident light and the photovoltaic layers.

The structural properties of CdTe on CdS/TCO/NaCl stacks are similar to that on glass substrates. As shown in Fig. 7, the as-deposited CdTe layer is very compact with grains sizes similar to the ones shown in Fig. 4. The $CdCl_2$-annealed layers are crack-free and consist of large grains of up to ~6 μm. It is interesting to observe that the presence of NaCl on the substrate does not affect the morphology of the CdTe layers. TCO is a good barrier for NaCl, however more investigations have to be performed to ascertain the effects of NaCl on the structural and electronic properties of CdTe/CdS.

As shown in Fig. 8, cells in the substrate configuration exhibit efficiencies of 7.3% with FTO and 6% with ZnO:Al front contacts. The fill factor has very low values (49% and

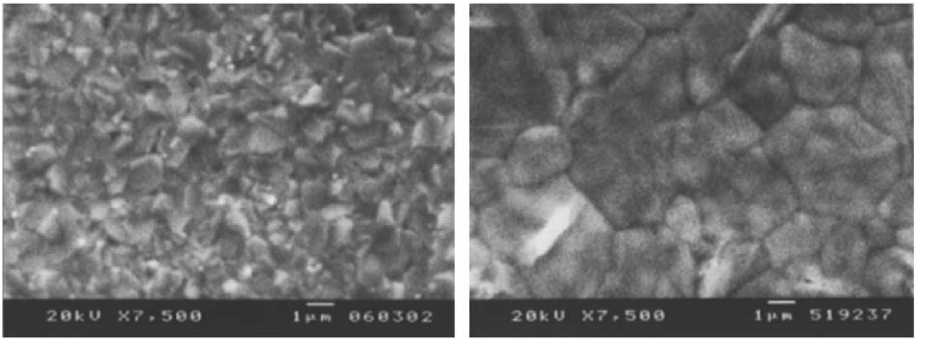


Fig. 7. As-deposited (left) and $CdCl_2$ treated (right) CdTe layers on CdS/TCO/NaCl stacks, the morphology is similar to the one shown in Fig. 4.

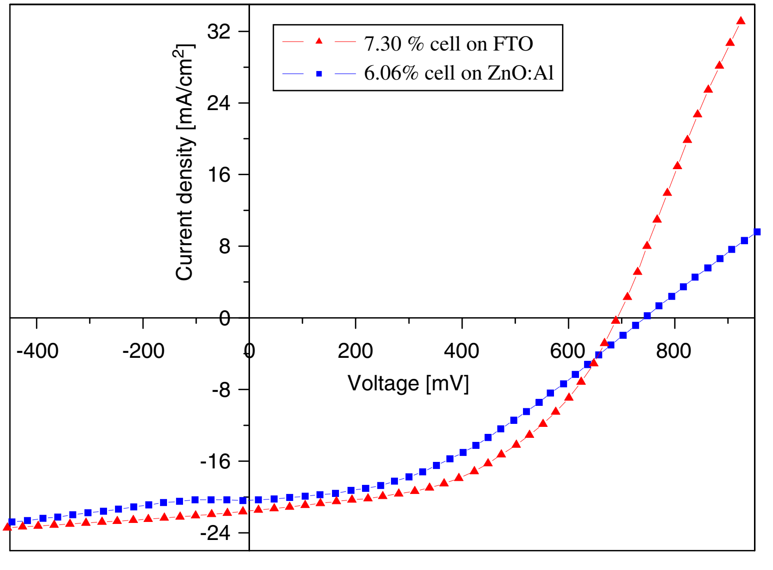


Fig. 8. *I–V* performance of flexible solar cells in substrate configuration with FTO and ZnO:Al as front contact under AM1.5 illumination.

40%), perhaps it is related to the low stability of the TCO on NaCl layer, which means that the electrical properties of the front contact tend to degrade after processing. Despite lower values of open circuit voltage (692 and 743 mV, respectively, for FTO and ZnO:Al as front contact) and fill factor the current density is higher than in the superstrate case (21.6 and 20.3 mA/cm^2, respectively, for FTO and ZnO:Al as front contact) because of the absence of the polyimide on the front of the cell. The lower efficiencies obtained are also to be attributed to the different $CdCl_2$ activation applied to avoid pinholes. We believe that with optimization of TCO/NaCl stacks and $CdCl_2$ treatment higher efficiencies can be obtained.

An advantage of this approach is that glass is the carrier (substrate) during all the fabrication steps, avoiding temperature issues as in the case of polyimide or diffusion issues like in the case of metal sheets. Another advantage is that in the substrate configuration the polyimide is at the back of the cell avoiding absorption losses and possible degradations on the transparency due to UV or electrons and protons irradiations, which are important for space applications.

5. Conclusions

Lightweight and flexible CdTe/CdS solar cells with 7.3% efficiency in "substrate" configuration and >11% efficiency in "superstrate" configuration have been developed with a low-temperature deposition process. Either a spin-coated polyimide layer or a commercial (Upilex^{TM}) polyimide film is used as a substrate. In order to reduce the absorption loss in the substrate, very thin (~10 μm) polyimide films are used for the cells in the superstrate configuration. A comparison of the quantum efficiency and optical transmission measurements suggests that thinner polyimide layers facilitate higher short circuit current. TCO layers with good thermal and chemical stability are needed for high-efficiency solar cells. Flexible CdTe solar cells with highest record efficiency of 11.4% have been achieved on a Upilex polyimide film. The fabrication processes are suitable for in-line production of solar cells and can be adapted for a roll-to-roll manufacturing. High-efficiency flexible cells on polyimides show a specific power potential of ~2 kW/kg on the cell level.

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