FLEXIBLE CdTe SOLAR CELLS BY A LOW TEMPERATURE PROCESS ON ITO/ZnO COATED POLYMERS

A. Salavei, I. Rimmaudo, F. Piccinelli[1], D. Menossi[2], N. Romeo[2], A. Bosio[2], R. Dharmadasa[2], A. Romeo*
Laboratory for Applied Physics, Department of Computer Science,
University of Verona, Strada Le Grazie 15, 37134 Verona, Italy,
*Email: alessandro.romeo@univr.it, ph: +390458027974, fax +390458027929
[1]Department of Biotechnology, University of Verona, Strada Le Grazie 15, 37134 Verona, Italy.
[2] Physics Department,University of Parma, Parco Area delle Scienze, 7A-43100 Parma, Italy

Second generation photovoltaics, thin film solar cells, have shown that it is possible to reduce dramatically the cost per Watt compared to crystalline silicon, because of the lower production energy, the in-line fabrication and the low amount of material needed. But another very important advantage of these technologies is that since they are extremely thin devices if deposited on flexible substrates they also become flexible. In this paper we present the study of a deposition process for flexible CdTe devices on ITO/ZnO coated polymers. Optimization of fabrication process and technological aspects of the device are taken into account. Moreover laser scribing tests on the different stacks deposited on the flexible substrates by fiber lasers are presented. The respective issues will be discussed.
Keywords: Flexible Substrate, CdTe, ITO, Laser Processing, Thin Film Solar Cell

1 INTRODUCTION

Thin film solar cells deposited on a flexible substrate are easier to integrate in buildings; they also have a very high specific power for consumer electronics and space applications [1]. Cells of equivalent performance can have specific power (kW/kg) 500 times bigger on 12.5 μm polyimide as compared to 3 mm glass substrates [2].

Flexible CdTe solar cells have shown efficiencies comparable, but still lower, than the ones of devices made on glass [3]. There are two reasons for efficiency loss: current density loss due to the lower polymer transparency and lack of rigidity which does not enable easy handling, giving place to possible pin-holes and cracks in the deposited films.

As far as polymer stability is crucially depending on temperature only low temperature processes are suitable for the production of solar cells on polymers. Vasko et al. and Drayton et al. from the University of Toledo have presented a sputtering process with vapor $CdCl_2$ treatment for fabrication of CdTe cells on polyimide with efficiencies of 10.5% [2, 4]. A record efficiency of 13.8% has been achieved by EMPA laboratories by the group of A. N. Tiwari with polyimide substrate by using vacuum evaporation and vacuum deposition of $CdCl_2$ [5]. In all mentioned cases ZnO doped with Al was used as a front contact.

In this work we show a CdTe solar cell fabrication process in superstrate configuration on flexible polyimides with an ITO/ZnO front contact and wet $CdCl_2$ treatment. Results are compared to our standard process on glass.

The choice for indium tin oxide (ITO) as a front contact is due to its high conductivity and better stability compared to ZnO doped with Al [6, 7, 8]. An intrinsic zinc oxide buffer layer is applied to avoid indium diffusion and to increase the open-circuit voltage (Voc). CdS and CdTe were deposited by vacuum evaporation at low temperature. Wet $CdCl_2$ treatment was used to activate the cells.

2 EXPERIMENTAL DETAILS

To develop a fabrication method for flexible CdTe devices, the solar cells were first optimized on glass by engineering a deposition process with a substrate temperature that should not exceed 450°C in order to prevent degradation of the polymer.

A specific study to find a suitable polymer that could withstand a high temperature and provide sufficient transparency was made. However a similar polyimide was already been used in the past and was shown to be the best choice [1].

The front contact was made by depositing 550 nm of ITO by direct current magnetron sputtering on the substrate, subsequently 120 nm of ZnO were deposited by reactive radio frequency magnetron sputtering on top of the ITO layer. Deposition was made in an Ar plus O_2 atmosphere. For ITO, 20 standard cubic centimeters per minute (sccm) of Ar and 0.5 sccm of O_2 were used, while for ZnO, the O_2 flux was changed to 3 sccm. Substrate temperature during deposition was 100 °C, lower than the typical value for the glass substrate (300°C).

The window layer and absorber were prepared by vacuum evaporation. 300nm of CdS and 6μm of CdTe were deposited in the same vacuum chamber with substrate temperatures of 100°C and 340°C, respectively. CdS was evaporated at a pressure of 10^{-6} mbar from a molybdenum crucible. CdTe was deposited by heating a special in-house made graphite crucible with deposition rates ranging from 1.5 nm/sec up to 2.nm/sec.

CdTe activation treatment was made by depositing μl of $CdCl_2$ saturated methanol solution on the surface and subsequently annealing the sample in an oven at 430°C, in order to recrystallize the polycrystals and enhance the electrical properties of the absorber. Finally the back contact was deposited by evaporation of 2nm of copper and 50 nm of gold. The cells were then annealed at 190°C in air for 20 min. Typically, before metallization, a bromine/methanol solution was applied in order to produce a p+ tellurium rich surface.

During the process, polyimide films were attached to glass in order to avoid bending. It is important to mention that the wet treatment step acts out the major difficulties. Deviation of the polymer flatness can result in

unhomogeneity and therefore in irreproducibility of the treatment. For this reason a more concentrated solution of $CdCl_2$ in methanol was applied; providing more reproducible results.

Finished cells were measured after having been separated from glass by current-voltage (J–V) characteristics with a Keithley SourceMeter 2420, using an halogen lamp calibrated with a silicon solar cell under an irradiation of 100mW/cm^2.

The morphological properties of the single layers were studied by atomic force microscopy (AFM) with a NT-MDT Solver Pro in semi-contact mode. X-ray diffraction analysis (XRD) of the CdTe layers has been performed by a Thermo ARL X´TRA powder diffractometer, operating in Bragg-Brentano geometry equipped with a Cu-anode X-ray source (Kα, λ =1.5418 Å) and using a Peltier Si(Li) cooled solid state detector.

3 RESULTS AND DISCUSSION

3.1 Layer and Device Characterization

Analysis of CdTe films with AFM showed that the morphology of the CdTe films of cells made on glass and polyimide films was very similar. Grain size of as-deposited (not shown here) and treated films on glass were slightly bigger then on polyimides (see Fig.1). One possible reason is the lower annealing temperature of CdS. CdS deposited on polyimide was annealed at 420°C while CdS deposited on glass was annealed at 450°C. The temperature was reduced in order to prevent degradation of polyimide.

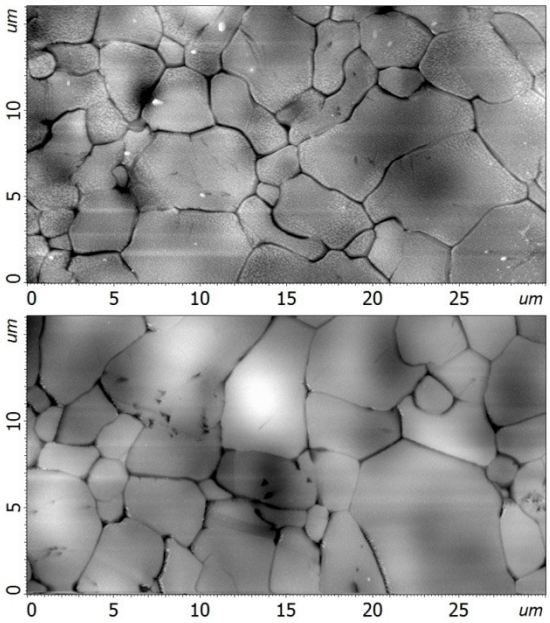

Figure 1: AFM pictures of treated CdTe on polyimide (top) and on glass (bottom)

Wet $CdCl_2$ treatment applied on CdTe films deposited on polyimide/ITO/ZnO/CdS results in the typical increase of grain size with a compact morphology [9]. We can conclude that changing the substrate from glass to polyimide does not affect the CdTe morphology.

CdTe layers deposited on glass/ITO/ZnO/CdS and polyimide/ITO/ZnO/CdS stacks have been analyzed by X-ray diffraction in both as-deposited and treated cases.

Typically, as-deposited CdTe layers on glass/ITO/ZnO/CdS stack show a (111) preferred orientation while after $CdCl_2$ treatment they have a randomized structure (not shown here) [9]. Very similar behavior was observed also for CdTe layers deposited on the polyimide/ITO/ZnO/CdS stack: as-deposited CdTe grains were (111) preferentially orientated, but after treatment, despite randomization, the (111) peak was still observed (see Fig.2), confirming a different crystallization of the grains with the polyimide substrate.

The different behavior could be partly explained by the lower temperature of CdS annealing, giving a different structure to CdS polycrystals and consequently also to the CdTe deposited on it. Another possible reason could come from the effect of the different substrate.

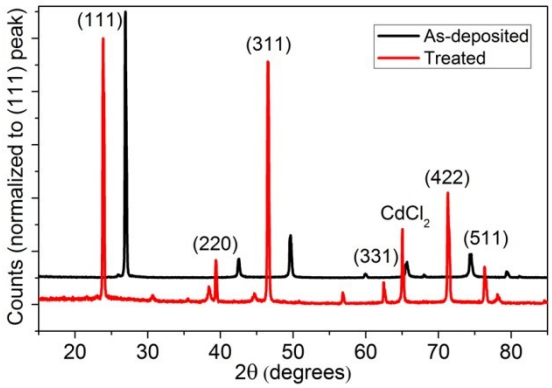

Figure 2: XRD patterns of the as-deposited and treated CdTe on polyimide/ITO/ZnO/CdS stack

Solar cells produced on glass in our lab have shown efficiencies near to 15%. However when glass is substituted with polyimide, efficiencies go down to 10%.

On Fig. 3 current-voltage characteristics of our best flexible and rigid cells are shown. Voc and fill factor have similar values for cells made on glass and on polyimide attesting that a good p/n junction is formed in both cases. The small losses for the flexible case (less than 10% from the values of the rigid cell) are explained by imperfection in the fabrication process, namely by micro-cracks of the films (due to the flexibility of the substrate) and by unhomogeneity of the wet treatment (because of flatness problem).

However the main loss in flexible cells performance is due to a much lower current. This can be explained by the lower transparency of polyimide compared with glass [10]. In our case losses in current are in the range of 20%, therefore in the future more transparent substrates will be applied.

3.2 Laser scribing

Single layers, namely TCO, CdS/CdTe and the back contact have been scribed with novel fiber lasers in order to test the feasibility of the industrial production of these devices. New fiber laser made in the scope of the ALPINE project (Advanced Lasers for Photovoltaic INdustrial processing Enhancement) was used.

Fiber lasers offer a number of attractive features over traditional solid-state lasers. The emitted beam quality is independent of power and resistant to thermo-mechanical disturbances, thanks to single-transverse mode wave guiding. These benefits, combined with high optical efficiency, compact and modular form factor, and support

for alignment-free and monolithic packaging make pulsed-fiber sources destined for widespread use in scientific, medical and industrial applications. In particular, solar cell processing needs very precise and high throughput processes that can only be achieved with short pulses and/or short wavelengths.

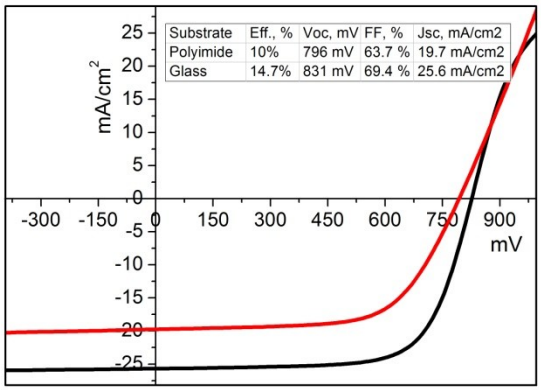

Figure 3: I-V curves of CdTe cells growth on glass (bottom) on polyimide (top)

The typical wavelengths for TCO of 1064 nm and for CdTe and back contact 532nm have been used and pulses in the order of the hundred nanosecond range were applied.

Laser scribing requires a flat surface in order to keep the scribes parallel to each other and to have the material under the laser focus, for this reason the flexibility of the solar cell is the main challenge. During the fabrication process polyimide was affected by high temperature, so that warping and some declension of flatness took place. Nevertheless P1 (removal of TCO) and P2 (removal of CdS/CdTe) scribing were applied to the stacks on flexible substrates showing very promising results.

For standard CdTe rigid solar cells, the ideal scribing process is with laser shining through the glass, so that vapors do not interfere with the beam. However attempts to scribe the TCO on polymer with this method tended to damage the polymide. Better results were obtained by removing ITO/ZnO using film-side scribing (see Fig. 4).

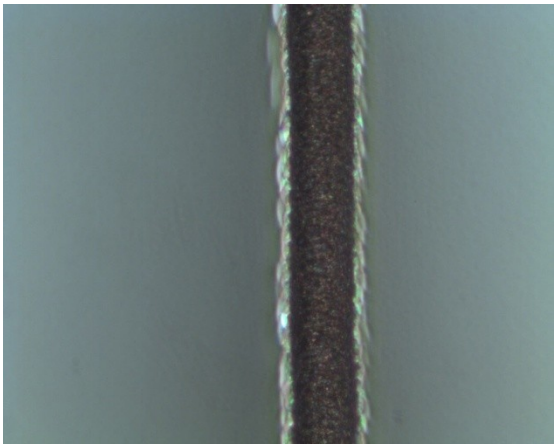

Figure 4: Laser scribe of polyimide/ITO/ZnO

P2 was provided by substrate-side scribing without damaging ITO and ZnO. To avoid any possible damage to the flexible substrate, tests were also made by scribing from the film side, however, CdTe ablation showed many imperfections, with recasting in the middle of the scribe.

4 CONCLUSIONS

Solar cells with efficiencies exceeding 10% were made; demonstrating the viability of flexible CdTe solar cells made with ITO front contact and wet $CdCl_2$ treatment.

AFM analysis shows no significant difference in morphology of CdTe layers deposited on polyimide/ITO/ZnO/CdS stacks compared with CdTe on glass/ITO/ZnO/CdS.

XRD measurements address the same re-crystallization processes of the CdTe layers deposited on glass/ITO/ZnO/CdS and polyimide/ITO/ZnO/CdS stacks while as-deposited CdTe on polyimide/ITO/ZnO/CdS showed more randomized structure.

Drop in efficiency for flexible cells is mainly due to the lower transparency of the polyimide substrate. Moreover wet treatment required further optimization in order to make this step more homogeneous.

Flexible cells on polymer substrates can be successfully scribed with a fiber laser, however a certain care has to be taken regarding the flatness to avoid damaging the polyimide. P1 and P2 steps were successfully applied to the stacks deposited on polyimide. Further experiments including P1, P2 and P3 steps will be made.

ACKNOWLEDGEMENTS

The Authors would like to acknowledge the EU funded FP7 ALPINE Project, n. 229231, for supporting this work.

REFERENCES

[1] A. Romeo, G. Khrypunov, F. Kurdesau M. Arnold, D.L.Bätzner, H. Zogg, A.N. Tiwari, Solar Energy Materials & Solar Cells 90 (2006) 3407–3415.

[2] A.C. Vasko, X. Liu, A.D. Compaan, Photovoltaic Specialists Conference (PVSC), 34th IEEE (2009) 001552–001555.

[3] J. Perrenoud, B. Schaffner, S. Buecheler, A.N. Tiwari, Solar Energy Materials & Solar Cells 95 (2011) S8–S12.

[4] J. Drayton, A. Vasko, A. Gupta, A.D. Compaan, Conference Record of the 31st IEEE Photovoltaic Specialists Conference, (2005) 406–409.

[5] Media release from EMPA, http://www.empa.ch/plugin/template/empa/*/108277/---/l=2, June 9, 2011.

[6] M. Chen, Z.L. Pei, C. Sun, J. Gong, R.F. Huang, L.S. Wen, Materials Science and Engineering B85 (2001) 212–217.

[7] M.Girtan, Solar Energy Materials & Solar Cells 100 (2012) 153–161.

[8] J. Pern, NREL/PR-520-44665, APP International PV Reliability Workshop, 2008.

[9] A. Salavei, I. Rimmaudo, F. Piccinelli, V. Allodi, A. Bosio, N. Romeo, S. Mazzamuto, D. Menossi and A. Romeo, Proceedings 26th European Photovoltaic Solar Energy Conference, (2011) 3030–3034.

[10] J. Perrenoud, S. Buecheler, A.N. Tiwari, Proceedings of Photovoltaic Specialists Conference (PVSC), 34th IEEE, (2009) 000695–000699.