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PACS: 68.60.-p; 71.23.Cq; 72.40.+w

THERMOMECHANICAL STABILITY OF THE P-I-N SOLAR CELLS STUDIED BY DEPTH SENSING INDENTATION TECHNIQUE

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Abstract

One of the most suitable methods for characterization of mechanical properties of thin films is the indentation technique. The objective of our study was to investigate the mechanical properties of p-i-n amorphous silicon based solar cells by means of depth sensing indentation technique. This method combined with the study of the morphology of the indentation prints enable to us to determinate besides the film hardness also other important material properties such as the film elastic modulus, the plastic and elastic part of the indentation work, the fracture toughness of the film and the film substrate interface etc.

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1. Introduction

The efficiency and in the same time the optoelectronic stability play the crucial role in the case of industrial production of the p-i-n amorphous silicon based solar cells. However, for the final applications, the good mechanical and thermomechanical stability of the solar cells is not of the second order of importance and may influence their lifetime. The large internal mechanical stress, weak adhesion can result the deterioration of the solar cell (cracking, delamination), especially when the flexible substrate are used. There are several basic problems associated with the determination of the mechanical properties of systems consisting of hard inorganic coatings and viscoelastic-plastic flexible substrates. The plastic substrate may exhibit significant creep (time dependent plastic)

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deformation at room temperatures. The determination of material parameters as elastic modulus and plastic hardness of both the film and the viscoelastic substrate is problematic in the case of thin film/substrate systems exhibiting, besides the elastic and plastic indentation response, also creep and anelastic (time dependent reversible) deformation. An elastic material on an easily deforming substrate exhibits so-called “plate-bending” effect. If we load such system to a maximum load and keep a constant penetration depth, the load will relax under some plastic or viscoelastic response. Indentation prints obtained at low loads may recover and heal over with time.

In our work we describe the determination of material properties such as the film hardness elastic modulus, the plastic and elastic part of the indentation work, the fracture toughness of the film and the film substrate interface for typical p-i-n amorphous silicon solar cells. The influence of the properties of the flexible polyethylene terephthalate (PET) substrate on the measured material parameters will be discussed.

2. Experiment

The studied p-i-n solar cells were deposited by RF glow discharge plasma enhanced chemical vapor deposition (PECVD). The solar cells consist of several layers: 10 nm thick p-doped a-SiC:H layer followed by 10 nm thick a-SiC:H layer and 12 nm thick standard buffer a-Si:H layer were deposited first on SnO₂ coated glass substrates under identical plasma conditions at 150 °C. The subsequent thick intrinsic i(a-Si:H) layer was deposited at 150°C (sample A, 0.9 μm) or 250 °C (sample B, 3.4 μm). Finally, the 12 nm thick buffer a-Si:H layer and the 20 nm thick n-doped n(a-Si:H) layer was deposited at 150°C. As it was shown in [1], the deposition temperature of the intrinsic layer strongly influences the properties of the p-doped and buffer layers.

To study the role of different substrate we provided measurements on two types of thin films: a-Si:H (#242) and μc-Si:H (#238) prepared in each case simultaneously on glass (Corning C7059, 0.9 mm thick) and polyethylene terephthalate foil (PET, 0.02 mm thick) by PE CVD in a capacitively coupled plasma reactor by glow discharge excited at 13.56 MHz in a mixture of hydrogen and silane at 70Pa

pressure. The amorphous layer #242 was deposited at 40 °C; the microcrystalline layer #238 deposited at 100 °C has the microcrystallinity fraction $X_c = 74\%$. The thickness was 850 nm in both cases.

The depth sensing indentation (DSI) test [2] was used to study the p-i-n structures and films on different substrates. Analysing the loading and unloading curves we determined the microhardness, the elastic W_{el} , irreversibly dissipated W_{ird} and interfacial deformation W_{int} part of the total indentation work W_{tot} , the effective elastic modulus $Y = E/(1-\nu^2)$, where E is the Young's modulus and ν is the Poisson's ratio of the layer. In case of the structured coatings the interfacial fracture toughness [3] of the particular interfaces is one of the most important parameters for the mechanical stability of the solar cells. Because of the complicated structure of the solar cells the measurements were made for several different indentation depths (i.e. several different applied loads) in order to map the mechanical properties from near surface up to film-substrate interface. In order to minimize the experimental errors, every measurement was repeated at least 9 times.

3. Results

In Figure 1 the load-penetration curves carried out at maximum load $L=30$ mN on p-i-n sample B are shown. The time of the loading and unloading was $t=20$ s. The measured universal hardness HU was (7.7 ± 0.7) GPa, the plastic hardness HU_{pl} was (25 ± 5) GPa, and the elastic modulus Y was (160 ± 10) GPa. The load-penetration curves with maximum applied load 1000mN for sample A and B are presented in Figure 2.

At low load the values of the HU and Y for the sample A were the same as for the sample B, only the plastic hardness HU_{pl} was (22.5 ± 0.5) GPa. The calculated interfacial fracture toughness of the cell A was $K_{ic} = (7.2 \pm 0.5)$ MPa $m^{1/2}$.

In Figure 3 the microhardness of the system layer+substrate for the layer #238 (microcrystalline) and for the layer #242 (amorphous), deposited on both Corning and PET substrates, as a function of the penetration depth is shown. The applied load varied from 2 to 100 mN in case of the C7059 substrate and from 2 to 20 mN in the case of PET substrate. The apparent elastic modulus as a function

of the indentation depth for the above mentioned series of the samples estimated from the DSI measurements is presented in Figure 4.

3. Discussion

We studied the influence of the deposition temperature in the case of p-i-n samples A deposited at 150 °C and p-i-n sample B deposited at 250 °C. In Figure 2 the load-penetration dependences for sample A and B are compared. Sample A and B exhibited almost the same hardness and elastic modulus at low loads. The p-i-n solar cell A was resistant against indentation-induced delamination even at maximum possible load $L=1000$ mN; no visible delamination or cracks around the indentation prints were observed. The higher statistical scatter and the decrease of these values with increasing load in the case of sample B was caused by fracture events such as interfacial microcracks. This can be seen like steps on the loading curve.

The effects of fracture could be observed also in Figure 1 as jumps on the curve. These microcracks were created at the first two interfaces between the n-doped a-Si:H and the buffer a-Si:H layer or between the buffer layer and the intrinsic layer.

The DSI technique enables quantitatively determine the indentation work, what was needed for the plastic, elastic and interfacial deformation. The indentation works made with applied load 100 mN evaluated from repeated prints for sample B were: $W_{total} = 26-30$ nJ, $W_{el} = 15-17$ nJ, $W_{ind} = 10-14$ nJ and $W_{int} = 0.7-4.9$ nJ. These values give us information about the resistance of the solar cell against deformation and fracture.

In case of the flexible polymer substrates, their structures and properties are very different from that of the deposited films. The hardness of common polymers is of about 0.1-0.2 GPa and the elastic modulus is the range from 1 to 5 GPa. Therefore the differences in hardness and elastic modulus between the film and the substrate may achieve two orders of magnitude in some cases. The significant influence of the flexible substrate on the measured hardness and elastic modulus is illustrated in Figures 3 and 4. In case of the flexible substrates was not possible to find interval of indentation depth, where the effect of the substrate were negligible. So, the systems of thin films on flexible substrates have to be treated as a complex. In this case the apparent mechanical parameters

are more convenient for the applications. In the case of the microcrystalline sample #238 the microhardness for very low applied load was very close for both kind of substrate (Figure 3), then the apparent hardness of sample deposited on PET substrate decreased more quickly than for glass substrate. This is explained by the very soft PET substrate. The decrease of the apparent hardness in both cases is caused by the fact that the microhardness of the film self is higher than those of substrates. The hardness of the amorphous film on C7059 substrate exhibited different behaviour. So, the microhardness of the layer #242 is lower than the glass substrate. Moreover, the microhardness of the amorphous layer (around 5 GPa) is lower than the microhardness of the microcrystalline layer (around 15 GPa).

Similar results give us the apparent elastic modulus (Figure 4), however its value is more influenced by the substrate properties.

4. Conclusion

The depth sensing indentation technique was used for characterization of the mechanical properties of the p-i-n solar cells. The solar cell prepared with intrinsic layer deposited at 150°C exhibited higher resistance against interfacial cracking as with the intrinsic layer deposited at 250°C. The possible deformation mechanism of structured thin films resulting loading curves by steps was described. The determination of important material parameters such as microhardness, apparent elastic modulus of an amorphous and a microcrystalline layer deposited on usual glass substrate and on flexible PET substrate was shown.

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Figure 1

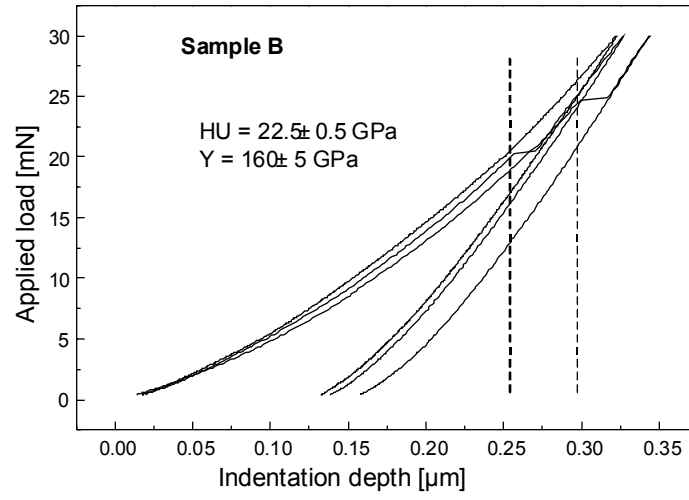


Figure 2

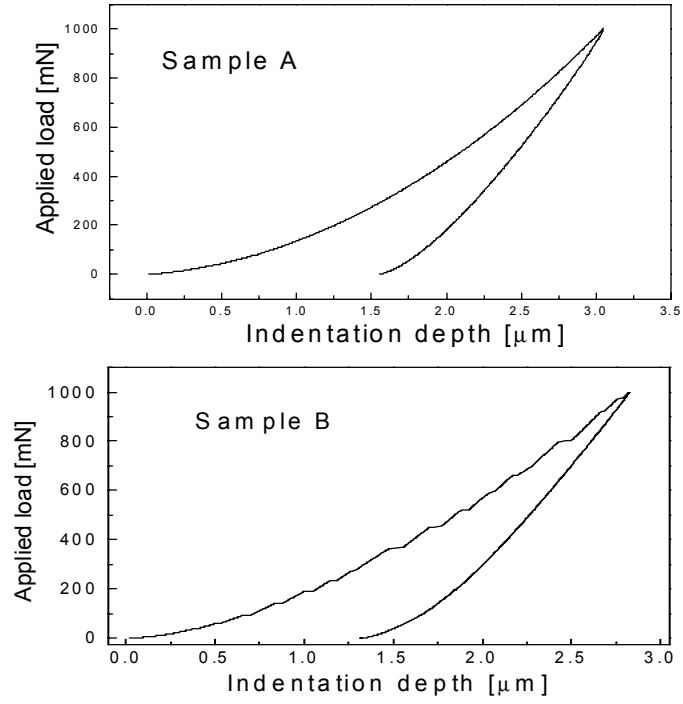


Figure 3

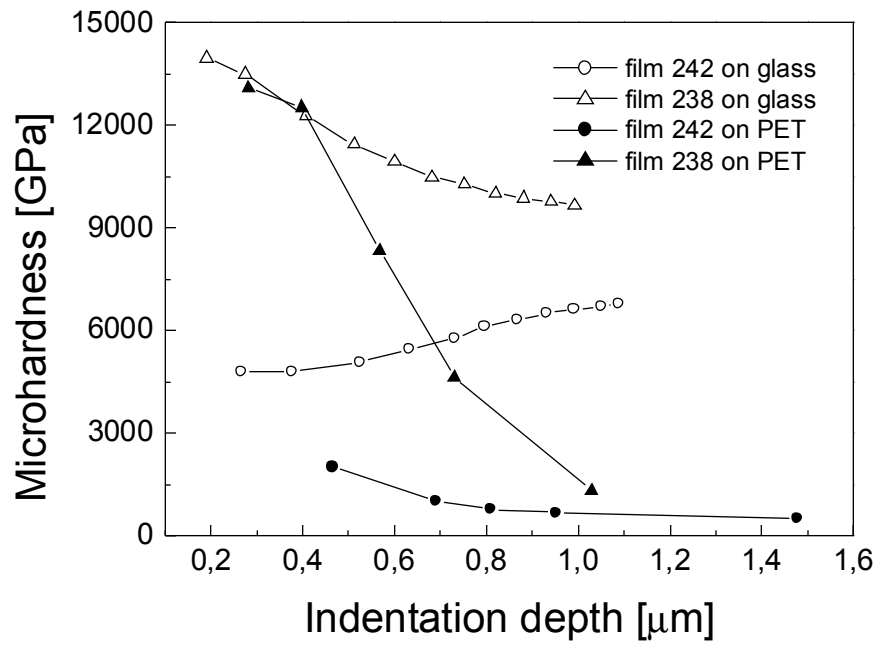
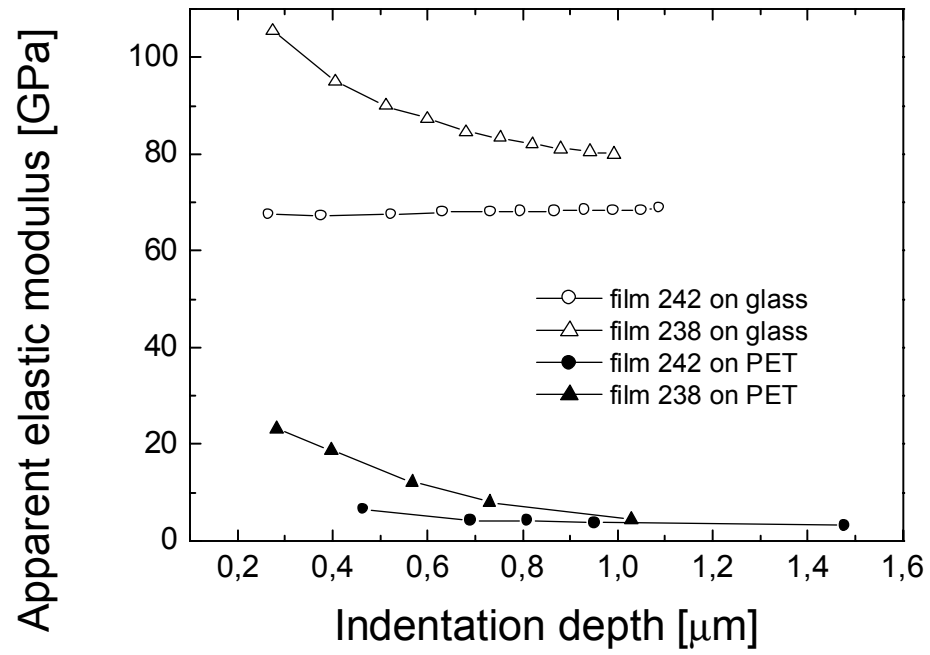


Figure 4



Captions for figures:

Figure 1:

Load-penetration curves measured for sample B. The maximum load was $L=30$ mN. The dashed lines show the position of the interfacial cracks.

Figure 2:

Load-penetration curves measured for sample A and sample B. The maximum load was $L=1000$ mN. The loading and unloading time was 60 s.

Figure 3:

Dependence of microhardness on indentation depth for thin films #238 (microcrystalline) and #242 (amorphous) deposited on glass and PET substrates.

Figure 4:

Dependence of apparent elastic modulus on indentation depth for thin films #238 (microcrystalline) and #242 (amorphous) deposited on glass and PET substrates.

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