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BALANCING ENCAPSULATION QUALITY AND ROBUSTNESS OF FILM SILICON PV TECHNOLOGY FOR OPTIMAL DURABILITY AND COST

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ABSTRACT: ECN develops thin-film silicon PV technology that can be produced roll to roll, with the objective to reduce costs per Wp. The production process as well as integration of the resulting PV-film in building products, requires flexible (front-side) encapsulation. This in turn relies on polymer materials with relatively high costs and water ingress. Defining the demands of an encapsulation system is not obvious and depends on the intrinsic properties of the PV materials. To obtain an optimum in durability and cost, a proper balance between encapsulation quality and PV materials robustness is essential. Our work concentrates on both understanding the chemical and thermo-mechanical deterioration mechanisms of the considered PV materials and development of fit-to-purpose encapsulation technology. We evaluated the influence of robustness parameters of our f-Si technology under exposure of humidity and condensed water at elevated temperatures. Condensation of water showed major effects on the stability of the (encapsulated) layered structures. It caused local delamination (buckling) which is attributed to the compressive stresses in the silicon layer and a decrease in adhesion at the various interfaces. Various adjustments in e.g. active layer microstructure, types of back contact layer material, and pretreatment of substrates, showed significant improvements in the stability of the f-Si technology under the test conditions.

1 INTRODUCTION

ECN develops roll to roll produced thin-film silicon PV technology, with the objective to reduce costs per Wp. The production process and the integration in building products require flexible (front-side) encapsulation. Such products need polymer materials with relatively high costs and water ingress.

Setting the demands of an encapsulation is not obvious and depends on the robustness of the PV technology. Encapsulation plays an essential role to ensure electrical safety for users and to guaranty stable power output over long life times of at least 20 years. The frontside of the encapsulation should be transparent, resistant to water, UV and temperature, and the active layers should be protected from water ingress. The essential parameter to characterize the protection against water is the water vapour transmission rate (WVTR) of the encapsulation materials.

The ingress of humidity in PV modules has been described in literature [1]. It is required that the encapsulation should prevent an oversaturation of water in the module at any time. This study indicated different demands for various PV-technologies and climates. High water barrier materials are an option but will come with certain costs. To obtain an optimum in durability and cost, a proper balance between encapsulation quality and intrinsic PV technology robustness is essential. Our work concentrates on both robustness and encapsulation properties.

As rigid glass plates can not be used low-cost though high-quality encapsulation is a key issue for flexible f-Si technology. The chance of finding a satisfactory solution will increase if the high demands can be mitigated through a more robust f-Si technology. Therefore our first aim was an evaluation of the degradation mechanisms occurring in flexible f-Si layers if exposed to dry, humid or condensed-water conditions at elevated temperatures. This has been done by using a newly developed test apparatus. This tool and the related procedures have the potential of being developed further to a well-defined method for accelerated durability testing.

2 EXPERIMENTAL

2.1 Sample materials

The samples used in our study had the build-up shown in Figure 1: a steel substrate, an insulating layer of sol-gel deposited by coating, a silver back contact layer, reflector layer (aluminum doped zinc oxide), microcrystalline silicon and an encapsulation of EVA (thickness 200µm) and ETFE (thickness 50µm). Each sample had a size of 20 by 20 mm^2 and the silicon was deposited over 10 by 10 mm^2 in the centre of the sample, using the PECVD equipment, jointly developed by Roth & Rau and ECN.

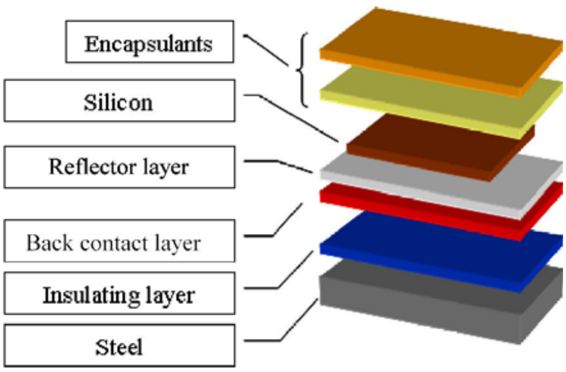

Figure 1: Overview of typical sample lay-out

2.2 Exposure conditions

An overview of the developed apparatus, the accelerated test facility (ATF), is shown in Figures 2 and 3. The apparatus consists of a box oven (Hereaus, T6120), an external water cooler (Colora WK5) and a closed glass box partially filled with a reservoir of demi-water. In the oven the temperature is typically held at 85°C and the humidity is low (RH < 10 %).

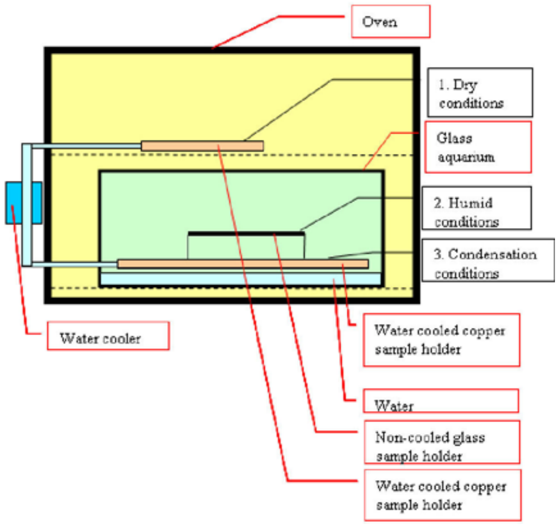

Figure 2: Schematic overview of the ATF

Figure 3: Photo of the ATF showing the glass box with the different sample holders

Three test conditions are created by the use of different sample holders. Within the glass box, a water cooled copper sample holder is placed. Water will condense on the surface of the samples during cooling, enabling water ingress. The water will slowly evaporate afterwards. This is the so called condensation condition.

A non-cooled glass sample holder is also placed in the glass box. Samples placed at this location are exposed to a humid environment but are not exposed to condensed water. This is the so called humid condition, generally a temperature of 80°C and relative humidity of ~80%.

A second water cooled substrate holder is placed in the box oven, but outside the glass box. This is the dry condition. The effect of condensed water and temperature can thereby be separated. To monitor the conditions, a thermometer and a humidity sensor are used in combination with a data logger.

2.3 Characterisation

The degradation was investigated by visual inspection using a stereomicroscope. The dimensional properties were measured using an optical image profiler with a resolution of 5 nm in the height direction.

3 RESULTS AND DISCUSSION

3.1 Comparison of dry, humid and condensation conditions

To investigate the degradation mechanisms of the flexible ECN f-Si technology, we started to analyze samples as described in section 2.1 in the ATF. The difference in sample behaviour of the humid and condensation conditions is of special interest. In general, condensation can be formed on the outer surfaces of an outdoor mounted module during the night as the ambient temperature drops. Condensation can also occur inside the encapsulant. If an oversaturation of water is present in the encapsulant, this can lead to the formation of condensation in pores and on the interfaces of the various layers, which promotes degradation mechanisms.

The samples were exposed to various conditions for various times, and subsequently analyzed. The results are shown in Figure 4 after 10 days of exposure in respectively dry, humid and condensed water conditions, and these show a clear trend. The dry conditions showed hardly any degradation, whereas the samples in the humid conditions showed quite severe degradation. The thin lines visible in the figure below are buckling of the silicon; this is shown in more detail in Figure 5 and Figure 6. The samples exposed to the condensation conditions showed very severe buckling over the total surface. This type of delamination took place between the insulating layer and the metallic back contact layer.

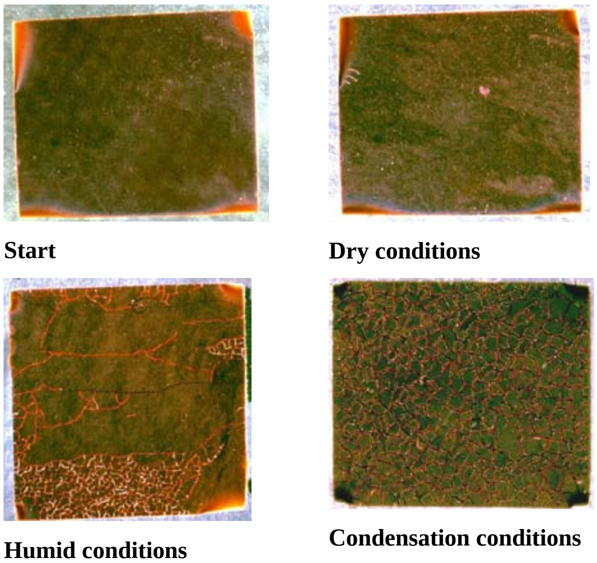

Figure 4: Test results on layered f-Si structure, initial and after 10 days of exposure

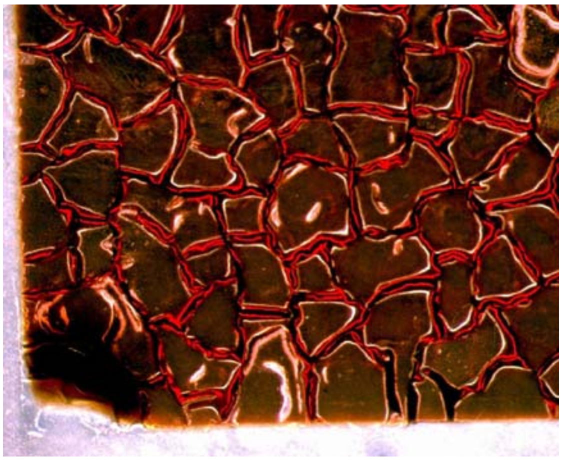

Figure 5: Close-up on the corner of the sample which was exposed to 10 days of condensation conditions.

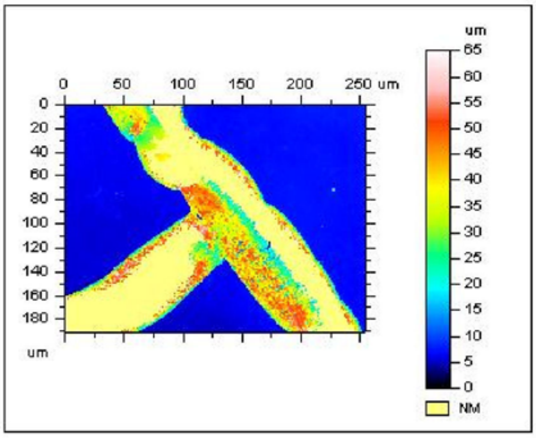

Figure 6: Height profile of the buckles measured with an optical image profiler, it shows the typical dimension of the buckling.

To understand how this buckling can be prevented, the background of the buckling and adhesion is discussed. Buckling with the geometry as shown in Figure 5 is known in literature as Euler buckling [2]. The straight shaped 'blisters' are typical for this type of failure. Other shapes of buckling that appear are undulated wrinkle patterns; so called telephone buckling. These buckling phenomena are observed with films, which have biaxial compressive stresses. The pattern of the buckling depends on the magnitude of the compressive stresses and the mechanical properties of the film (including elastic modulus and Poisson's ratio) [3]. The driving force of the buckling is the stored compressive energy in the film. If the energy release rate from the compressed material exceeds the energy needed to create new surfaces (work of adhesion), crack propagation will proceed.

We observed that under humid conditions and condensation conditions the samples delaminate due to buckling. This is explained by the influence of moisture which decreases the adhesion and enables the layer to delaminate by buckling [4]. The work of adhesion is described as [5]:

$$W_A = \gamma_s + \gamma_f - \gamma_{sf} \qquad (1)$$

Where W_A is the work of adhesion, γ_s is the surface free energy of the substrate, γ_f is the surface free energy of the film and γ_{sf} is the interfacial free energy between substrate and film. The surface free energies (γ_s and γ_f) can be reduced in presence of a liquid such as water. This can decrease the work of adhesion and enable delamination. It is difficult to get reliable values for the surface and interfacial energies; this limits the possibilities for quantitative analysis.

To prevent buckling formation several suggestions can be done. Firstly water penetrating to the interfaces can be prevented, secondly the work of adhesion can be increased by changing the interfacial free energies or surface free energies, for example by choosing different materials, and thirdly the driving force (compressive stresses) for the delamination can possibly be reduced by microstructural changes. The first mentioned approach relates to the quality of the encapsulation. The second and third relate to the robustness of the PV-technology. These last two approaches have been studied further in section 3.2 below.

3.2 Influence of f-Si technology robustness parameters

Reducing the driving force for buckling can be done by altering the microstructure of the silicon. Samples with μc-Si and a-Si have been compared, as μc-Si is supposed to contain more compressive stresses than a-Si [6]. The results in Figure 7 show major degradation for μc-Si and no degradation for the a-Si silicon. These samples were exposed for an extensive period of 62 days. Buckling did not take place for a-Si samples, obviously the driving force for delamination was reduced under the critical value. The results show that a more robust technology is possible when working with a-Si.

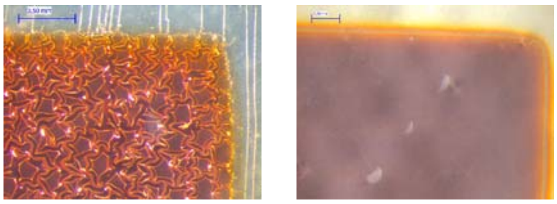

Figure 7: μc-Si (left) and a-Si (right) after 62 days of exposure under condensation conditions.

Delamination / buckling is initiated by the stresses in the Si layer, however it is observed that the layers buckle at the interface between the metallic back contact and the insulating layer. The adhesion between these layers is thus the weakest link. To investigate this further, three different types of back contact layers have been evaluated: silver, aluminium and copper. The results, given in Figure 8, clearly show that the sample with the silver reflector layer show strong buckling effects over the total sample, while no degradation took place for the aluminium and copper samples. The interfacial free energy in combination with the surface free energy of Al and Cu are expected to cause a higher work of adhesion even under condensation conditions then for silver. Although this particular material choice does improve the robustness of the f-Si technology, it reduces the efficiency by lower reflection of light. Therefore an optimization of the balance between efficiency and robustness may be necessary.

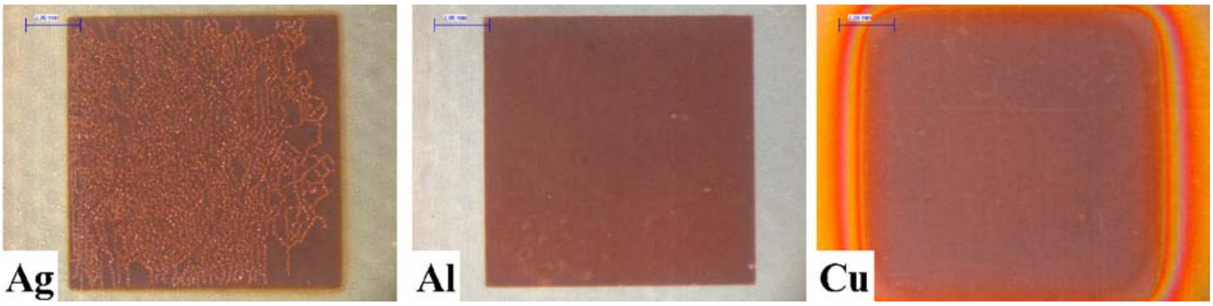

Figure 8: Influence of back reflector material on the occurrence of buckling degradation after 47 days of condensation exposure.

The third option to prevent buckling is to increase the adhesion between the insulating layer and the back contact layer by using a plasma pre-treatment of the substrate. The adhesion should be improved by the cleaning and activating effect of the plasma to the surface. The result of such approach is illustrated in Figure 9 with a sample that included a silver reflector layer, laser scribes and prints. It showed stable properties even after 52 days of exposure in the condensation conditions of the ATF.

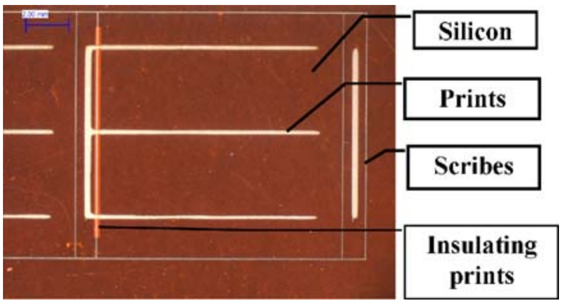

Figure 9: Technology improved by application of surface treatments shows no degradation effects after 52 days of exposure to the most severe test, i.e. exposure to condensed-water and elevated temperature.

4 CONCLUSIONS

For flexible film silicon (f-Si) photovoltaics (PV) costs can be reduced significantly by using a front side encapsulation that allows limited water permeation, rather than aiming for a nearly impermeable one. However, to meet durability targets this approach will require more robust PV materials. We evaluated the influence of robustness parameters of our f-Si technology under exposure of humidity and water at elevated temperatures. Condensation of water showed major effects on the stability of the layered structure. It caused local delamination (buckling) which is attributed to the compressive stresses in the silicon layer and a decrease in adhesion between the various interfaces. By adjustments in the microstructure of the active layer, types of back contact layer material, and pretreatment of substrate, significant improvements were achieved in the stability of the f-Si technology under the test conditions.

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