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The Use of Feature Parameters to Asses Barrier Properties of ALD coatings for Flexible PV Substrates

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Abstract. This paper reports on the recent work carried out as part of the EU funded NanoMend project. The project seeks to develop integrated process inspection, cleaning, repair and control systems for nano-scale thin films on large area substrates.

In the present study flexible photovoltaic films have been the substrate of interest. Flexible PV films are the subject of significant development at present and the latest films have efficiencies at or beyond the level of Si based rigid PV modules. These flexible devices are fabricated on polymer film by the repeated deposition, and patterning, of thin layer materials using roll-to-roll processes, where the whole film is approximately 3um thick prior to encapsulation. Whilst flexible films offer significant advantages in terms of mass and the possibility of building integration (BIPV) they are at present susceptible to long term environmental degradation as a result of water vapor transmission through the barrier layers to the CIGS (Copper Indium Gallium Selenide $CuIn_xGa_{(1-x)}Se_2$) PV cells thus causing electrical shorts and efficiency drops. Environmental protection of the GIGS cell is provided by a thin (40nm) barrier coating of Al_2O_3. The highly conformal aluminium oxide barrier layer is produced by atomic layer deposition (ALD) where, the ultra-thin Al_2O_3 layer is deposited onto polymer thin films before these films encapsulate the PV cell. The surface of the starting polymer film must be of very high quality in order to avoid creating defects in the device layers. Since these defects reduce manufacturing yield, in order to prevent them, a further thin polymer coating (planarization layer) is generally applied to the polymer film prior to deposition.

The presence of surface irregularities on the uncoated film can create defects within the nanometre-scale, aluminium oxide, barrier layer and these are measured and characterised. This paper begins by reporting the results of early stage measurements conducted to characterise the uncoated and coated polymer film surface topography using feature parameter analysis. The measurements are carried out using a Taylor Hobson Coherence Correlation Interferometer an optical microscope and SEM. Feature parameter analysis allows the efficient separation of small insignificant defects from large defects. The presence of both large and insignificant defects is then correlated with the water vapour transmission rate as measured on representative sets of films using at standard MOCON test. The paper finishes by drawing conclusions based on analysis of WVTR and defect size, where it is postulated that small numbers of large defects play a significant role in higher levels of WVTR.

1. Introduction

Flexible Photovoltaic cells are one of the newest developments in the renewable energy field. Currently the most efficient cells are those based on Copper Indium Gallium Selenide (CIGS) materials, up to 19%. These flexible cells are however highly susceptible to environmental degradation. The most critical problem with PV modules is the transmition of water vapour through the barrier films on the PV functional layers. This water vapour transmission is caused by the presence of tiny defects in the barrier coating and results in decreased cell efficiency and decreased cell lifespan. One of the most effective and reliable methods of protecting these cells is to apply a barrier coating of Al_2O_3 to the encapsulation material. The highly conformal Al_2O_3 barrier layer is produced by the atomic layer deposition (ALD) technique. The surface of the encapsulation substrate polymer (PET) film must be of very high quality; in order to achieve this high quality the substrate film is further planarised. However, even this ALD barrier is not at present effective enough; water vapour can still permeate through the barrier due to the presence of micro and nano-scale size defects on the barrier films, thus causing electrical shorts, efficiency drops and, ultimately, failure. This paper reports the results of measurements conducted to characterise the uncoated and barrier coated polymer film surface topography using segmentation feature parameter analysis. The presence of defects is then correlated with the water vapour transmission rate as measured on representative sets of films using a standard MOCON test. The overall process for manufacturing flexible PV's is by roll to roll technology. The results in this paper provide the basis for the development of roll to roll in process metrology devices for defect detection

1.2 Flexible PV Module

Flexible solar modules comprise of four functional layer groupings as shown in Fig [1]. The main focus of the investigation in this paper is the encapsulation/barrier layer. The barrier layer is typically formed from a planerised Polyethylene Naphthalate (PEN) sheet,with the Al_2O_3 barrier coating (40 nm thick) being produced by an ALD process. Despite the excellent barrier properties provided by this material, all of the published data indicates there is some remaining permeation, even when the barrier coating is reasonably thick ($\geq$ 50nm) [1]. This outstanding transmission of water vapor is considered to be due to the presence of small defects on the film.

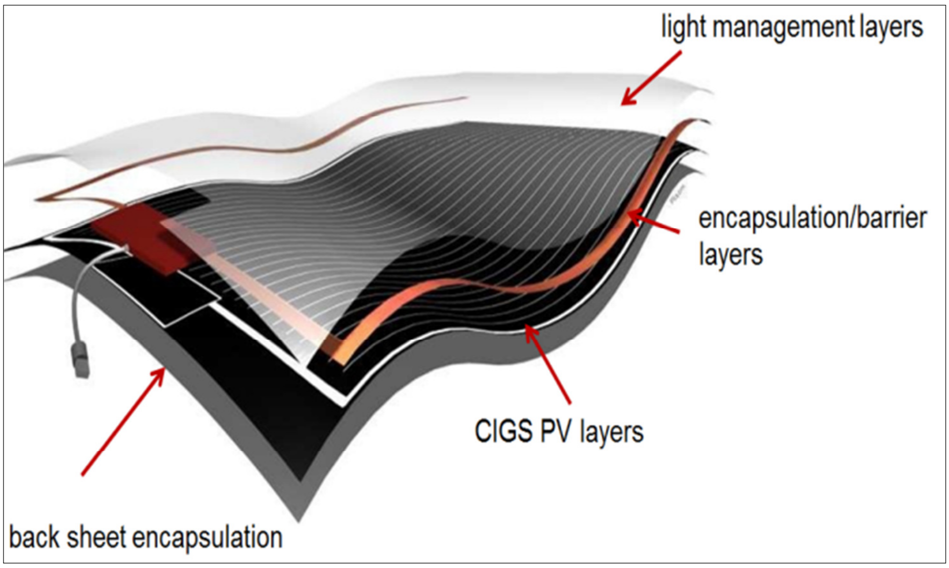

Figure 1: Schematic of the flexible PV Module (Courtesy of Flisom, Switzerland)

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2. Water Vapour Transmission Rate Assesment:

All coated samples were measured for water vapor transmission rate (WVTR) using standard MOCON test instrumentation prior to the surface measurement. With this method, the test specimen is held within the instrument such that it separates into two sides of a test chamber. One side, the “wet side”, is exposed to the gas or vapor to be measured. On the detector or the "dry side", the sample is subjected to zero relative humidity. The dry side is purged with a carrier gas which carries away any transmitted water vapour to a infrared sensor which records the transmission rate. The stady state rate was recorded along with the time to stable transmission. The area exposed to the water vapour was approximately 80mm^2

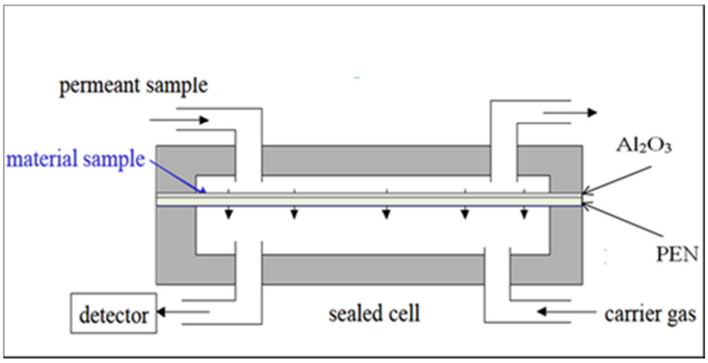


Figure 2: WVTR Measurement using MOCON method, exposed area 80mm^2[2]

2.1. *Measurement Methodology*

Four samples of ALD coated substrate with 40 nm Al_2O_3 as well as a non-coated substrate were assessed. The WVTR results were kept blind to determine the presence and the size of the features that had a potential influence on the WVTR value. Initially an optical microscope was used for visual inspection of the coated samples. Different types of defects were noticed for each sample and varied from one sample to another in terms of type, width, and height as shown in Fig [3] and Fig [4].

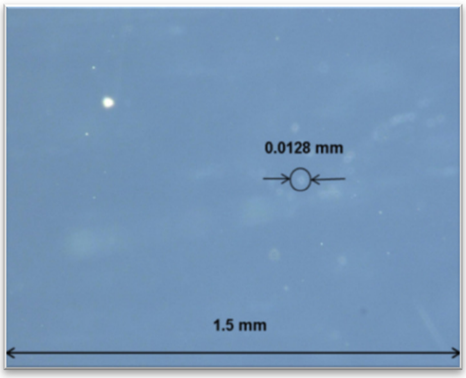


Figure 3: Scale of small defects x 200 Mag

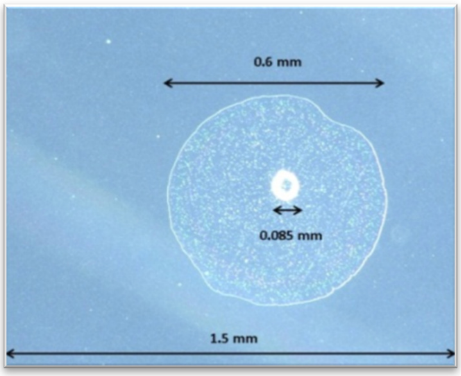


Figure 4: Scale of large defects x 200Mag

2.2. *White Light Scanning Optical Interferometry*

A Taylor Hobson Coherence Correlation Interferometry (CCI) was used to provide a rapid means of characterizing a number of important features; including surface roughness, defects density and other surface variations all of which were considered to have a major influence on the barrier properties of the Al_2O_3 layer and hence module efficiency. The instrument was calibrated according to the manufacture specifications prior to use. The issue of the measurement area is an important point to be considered, in the case 20× objective lens magnification was used this allows the instrument to measure a sample area of approximately $1mm^2$. This lens gave adequate spatial resolution to detect defects at both small and large sizes. However, it was not feasible for measurement of the entire surface, over which the WVTR is assessed ($80mm^2$). Consequently, 700 measurements, equating to 14% of the total surface area of all the specimens was measured.

3. Results

The WVTR (water vapor transmission rates) for each sample are shown in Table [1]. The MOCON test has shown that three samples have a relatively low WVTR and one sample has higher WVTR value (2705).

Table [1] Water vapour Transmission Rate values

Sample No	WVTR ($g/m^2/24$ hrs.)	Stabalisation Time
Sample 2701	Low	11 days
Sample 2702	Low	11 days
Sample 2705	***High***	***5 days***
Sample 2706	Low	5 days

The surface topography analysis of the Al_2O_3 barrier layer showed that many defects were observed on each sample; these defects varied from one sample to another, and were classified depending on the type and prominence. Fig [5] and Fig [6] show two of these typical defects which are peaks and holes.

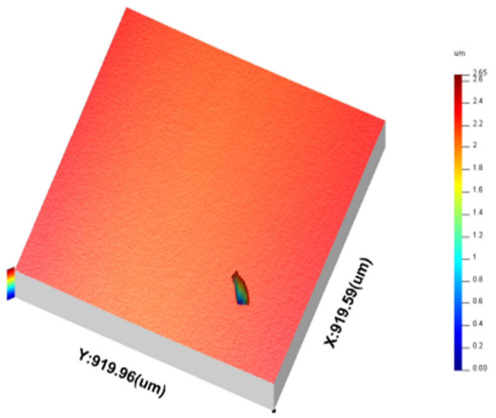


Figure 5: "Hole" type defect

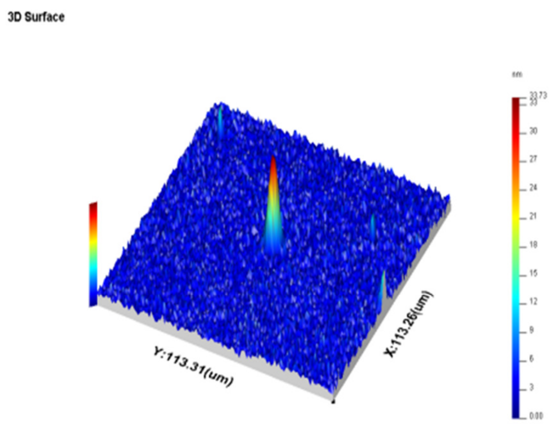
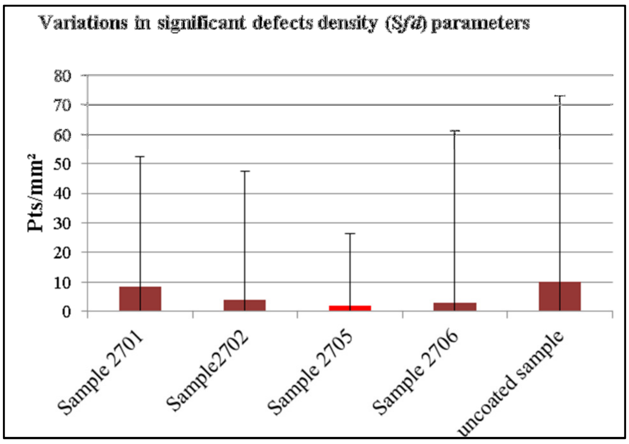


Figure 6: "Peak" type defect

3.1. Areal Surface topography assessment

Feature Parameters as defined in ISO 25178-pt2 [3,4] were used to adapt a scheme for setting appropriate boundaries in order to employ a suitable Wolf pruning method. The "toolbox" method was adapted to automatically detect significant hills and dales features. In this procedure in particular a parameter Sfd was used (where Sfd = the number of significant hills + significant dales) significance was defined as any peak/pit greater than 20% of the total peak to valley roughness (Sz). Using this default significance value for the defects the results showed no clear correlation with the WVTR results. Therefore, was conducted with additional prune conditions, those defects which satisfied the criteria of only large defects (6σ (Sq=0.8nm) height & 180μm^2) were measured and recorded for effective discrimination of significant and non-significant defects.



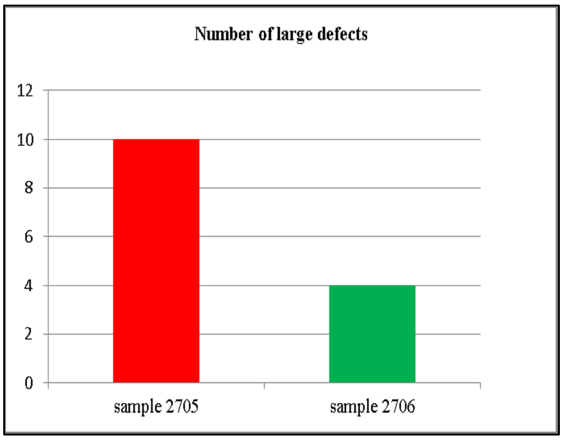


Figure 7: Variation in defects density initial 20% height Wolf prune

Figure 8: Significant defect count with additional prune criteria

The present findings would appear to suggest that small numbers of large defects (as detected by the optimal prune criteria) are the dominant factor in determining WVTR. Any detection system should focus on these scales of defects as a determinant of function.

4. Conclusions:

The use of feature parameter analysis allows separation of small insignificant defects from large significant defects automatically. The numerical approach has provided a clear evidence for the correlation of surface roughness, defect density, and the transmission of water vapour through the barrier coating layer. Hence, from the previous analysis, it can be concluded that the total permeation rate corresponding to small numbers of larger defects is much greater compared to the total permeation rate corresponding to large numbers of small pinhole-type defects over the same area of substrate. This result provides novel information to enable automatic detection and correction of potential restrictors to PV module performance in the line processes. Work is continuing to check repeatabiliy of these tests and produce “cleaner” substrates.

Acknowledgement

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