DEVELOPMENT OF THE BASIS FOR IN PROCESS METROLOGY FOR ROLL TO ROLL PRODUCTION OF FLEXIBLE PHOTO VOLTAICS

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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 thin films on flexible PV films. based on CIGS (Copper Indium Gallium Selenide $CuIn_xGa_{(1-x)}Se_2$). These films 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 final encapsulation. Current wide scale implementation however is hampered by long-term degradation of efficiency due to water ingress through the barrier layer defects to the CIGS modules causing electrical shorts and efficiency drops. A thin (~40nm) barrier coating of Al_2O_3 usually provides the environmental protection for the PV cells. The highly conformal aluminium oxide barrier layer is produced by atomic layer deposition (ALD). The paper reports initial measurement taken on prototype films and reports on the correlation of water vapour transmission with defect density, it also reports on a new in process, high speed, environmentally robust optical interferometer instrument developed to detect defects on the polymer film during manufacture. These results provide the basis for the development of R2R in process metrology devices.

Keywords: Photo-voltaics, roll to roll, in process metrology

1. INTRODUCTION

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 thin films on flexible PV films. The efforts of the Photovoltaic (PV) industry to reduce production costs has led to the introduction of highly efficient Roll-to-Roll (R2R) production processes for the manufacture of flexible photovoltaic cells. Such flexible and lightweight solar cells will potentially open up new market segments in sectors like portable electronics, automotive / transportation and architecture. Flexible Photovoltaic cells are one of the latest developments in the renewable energy field. Currently the most efficient cells are those based on Copper Indium Gallium Selenide (CIGS) thin films, with efficiencies up to 19%. Flexible solar modules comprise of several functional layer groupings as shown in Fig 1. The main focus of the investigation in this paper is the encapsulation/barrier layer. A significant drawback to the application of flexible PV cells is the fact that they are highly susceptible to environmental degradation. The most critical problem is the transmission of water vapour through the barrier films into 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 high quality barrier coating of transparent Al_2O_3 to the polymer 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 (PEN) film must be of very high quality; in order to achieve this high quality the substrate film is planarisedprior to the ALD process. Despite the excellent barrier properties provided by this material, all of the published data indicates there is still some remaining water permeation through micro/nanoscale defects, even when the barrier coating is reasonably thick (≥ 50nm) [1]. This water causes electrical shorts, efficiency drops and, ultimately, failure. The present paper reports the results of measurements conducted to characterise the barrier coated polymer film surface topography using segmentation feature parameter analysis and also outlines a new interferometric technique developed to facilitate non contact in-process metrology. The results in this paper provide the basis for the development of roll to roll in process metrology for defect detection

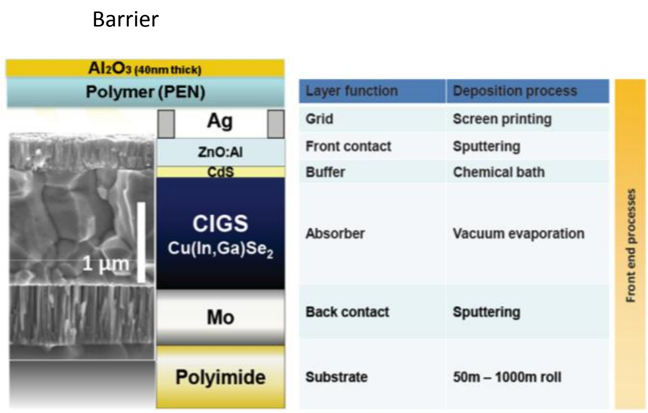

Fig. 1: Functional layers of a flexible PV cell

2.0 EXPERIMENTAL

Table: 1 Water vapor transmission rate at specified conditions 38^{o}C and 90%

Sample No	WVTR (g/m²/24 hrs.)	Time
1	$1.1x\ 10^{-3}$	11 days
2	$1.3\ x\ 10^{-3}$	11 days
3	**$4.1x\ 10^{-3}$**	***5 days***
4	$2.0x\ 10^{-3}$	5 days

2.1 Sample Preparation

A series of 4 coated PEN polymer substrates were produced having a 40nm ALD Al_2O_3 barrier coating. An area of 80mm^2 was used for testing of the barrier properties using a standard MOCON test [2]. The test measures the steady state WVTR for a barrier coating under defined conditions. The system places the substrate in a sealed unit where one side of the substrate is subject to high humidity and the other side is defined as the dry side. 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 steady state rate was recorded along with the time to stable transmission.

3. WVTR ANDSURFACE MMETROLOGY RESULTS

3.1 WVTR

The WVTR results Table 1, show that sample 2705 had a significantly higher WVTR than the other specimens. Following WVTR testing the surface topography of all samples was imaged using an SEM and measured using laboratory based coherence correlation interferometery.

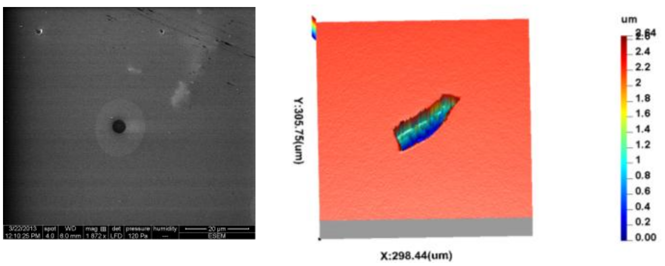

Fig. 2: Barrier Layer with defects in ALD layer, a) SEM b) interferometery

3.2 Surface Metrology

14% of the total surface area of all the specimens was measured. The results showed the presence of defects both particulate and pin hole type, in all specimens. Typical examples are shown in fig 2. The surface roughness of defect free samples was ~0.6nm. No correlation between the general surface roughness and the WVTR was noted. For enhanced visualisation prior to characterisation, the surface data was subject to a Sobel edge filtering to reduce the effect of measurement noise and general roughness [3] Areal topography characterisation was then carried out using the feature parameter set ISO 25178-pt2. In particular the parameter Sfd was used (where Sfd = the number of significant hills + significant dales); a significance critera applied was for hills (Peaks) and dales(pits) (over 2.5%Sz roughness and >15 data points where the sample spacing is 250nm in the lateral dimension). Applying this criteria the Sfd parameter could be used to count only the most severe defects over the total measured area. In this case the correlation was clear, Fig 3. This analysis has the effect of delineating defects automatically and allows for automatic defect density measurements, Fig4

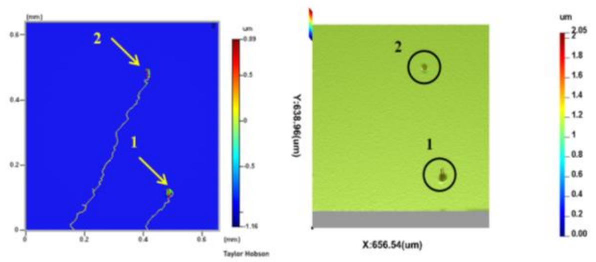

Fig. 3: Significant defect count

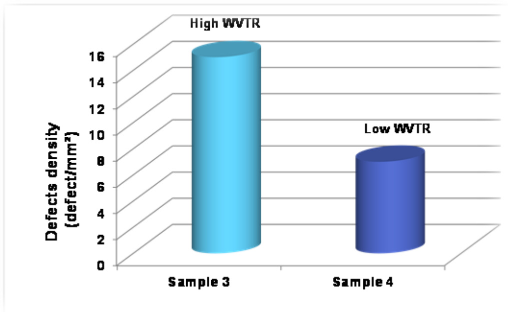

Fig. 4: a) segmented surface data showing two segmented defects b) typical measured data showing defects.

The results indicate the presence of small numbers of large defects dominate the WVTR of the barrier layer. ALD coating is highly conformal and is likely to coat particulate debris already existing on the polymer substrates and down deep pits. The mechanism for increased WVTR would appear to be that debris on the surface or within pits become detached exposing uncoated pen to water ingress.

4.0 IN-PROCESS METROLOGY

To facilitate in process measurement two significant issues need to be addressed; i) the measurement must be fast and non-contact ii) the measurement must be carried out in a "noisy" working environment. Given the general roughness level on the substrate is in the Nm range then only optical interferometry can assess the topography. Unfortunately this measurement technique normally requires environmental control of external vibrations. This level of control is not possible in a manufacturing environment, consequently in order to overcome this difficulty the authors have developed an environmentally compensated interferometric technique based around the principle of wavelength scanning interferometry (WSI) [4].

Wavelength scanning interferometry can be used to measure both smooth surfaces and those with large defects. Active servo control of a reference mirror provides phase compensation to eliminate environmental noise including vibrations perpendicular to the surface. A further advantage of the WSI over other measurement technologies is its ability to carry out quantitative measurements of micro/nanoscale surface topographical characteristics at much higher speeds than previously possible because the measurement method requires no mechanical movement.

4.1 Measurement principle

The measurement principle of the WSI is based on determining the phase shift of a reflected optical signal while the wavelength of the illuminating light is changed. The light wavelength is scanned through a range by filtering white light from a halogen source using an acousto-optic tunable filter (AOTF). The system comprises two interferometers that share a common optical path. The interferometer using a filtered white light source (the WSI) is used for measuring surface topography. Another interferometer using a super-luminescent diode (SLED) is used to monitor for surface movement due to vibration so the active servo control can by keep the optical path constant by moving the reference arm mirror with a piezo-electric translator (PZT), fig. 5.

Even though the wavelength scanning period required to make a measurement is less than one second, it is important that the position of the sample surface is kept constant. This can be achieved by ensuring a very stable setup or, in noisy environments, by using active servo control of the reference path of the interferometer. The distance to the sample surface is continuously monitored by the interferometer and the reference arm distance altered by moving the reference mirror with the PZT to maintain the difference between interferometer arm lengths (optical path difference). The wavelength scanning, 64-256 interferograms are captured by a CCD camera; each pixel in the obtained interferogram represents a specific point on the sample surface fig. 6. The number of interferograms taken depends on specific requirements for precision and range in the measurement. Isolating a single pixel (which corresponds to a specific point on the sample) from the interferogram set, a sinusoidal change of intensity with wavelength is apparent fig. 7. The overall phase shift across the wavelength scan range can obtained from the intensity signal using Fourier transforms. The height of the point represented by the pixel can then be calculated by:

$$h(x,y) = \frac{\Delta\varphi(x,y)}{4\pi\left[\frac{1}{\lambda_{max}} - \frac{1}{\lambda_{min}}\right]} \quad (1)$$

where $h(x,y)$ is the height of the specific pixel, and $\Delta\varphi(x,y)$ the calculated phase shift over the scan range. λ_{max} and λ_{min} are the upper and lower wavelengths of the scan range respectively.

The WSI system, being developed within the NanoMend project is a critical tool for the evaluation of surface topography where measurement speed is critical factor and the system must work within a vibrationally noisy environment. As part of the NanoMend project, the WSI system will be implemented at the Centre for Process Innovation (CPI) as a demonstrator sensor for the detection of defects in polymer film coated with an Al_2O_3 vapour barrier layers. The initial implementation of the system will acquire a series of static images and thus allow significant but not all of the substrate surface to be measured.

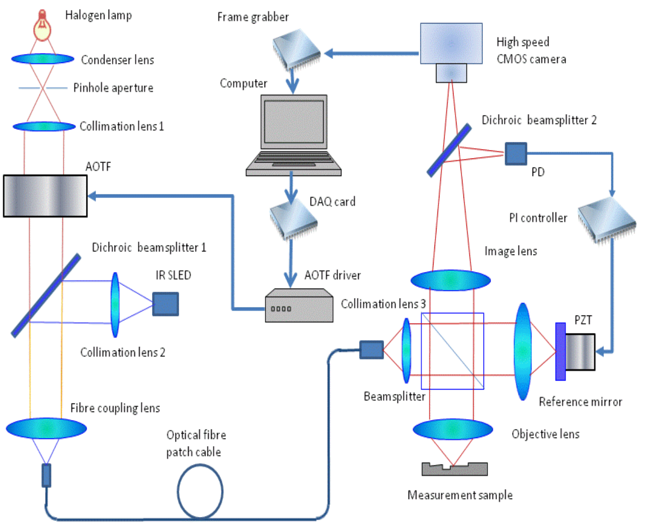

Fig. 5: schematic representation of WSI system

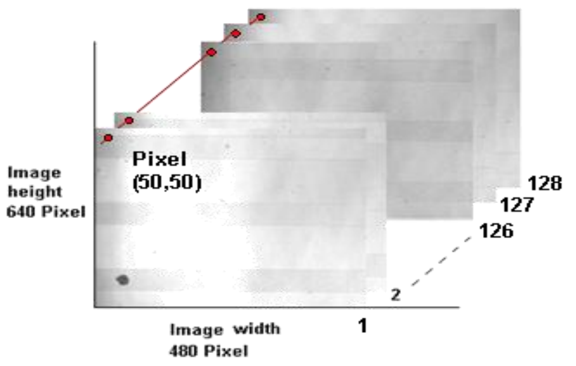

Fig. 6: Interferograms collected from a single pixel

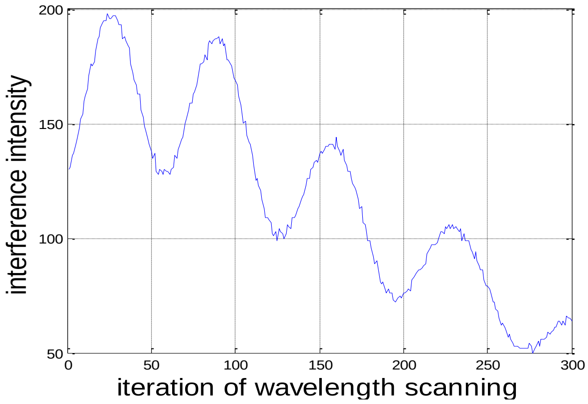

Fig. 7: Change of intensity across a single pixel

Fig 8 shows an optical micrograph of a defect on the barrier substrate surface. The defect was then measured using the WSI system and a 5x objective lens.

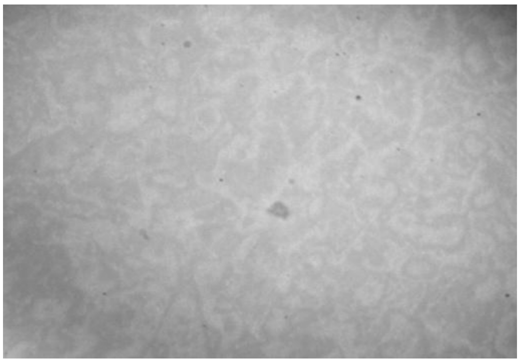

Fig. 8: Optical micrograph of defect on Al_2O_3 barrier substrate

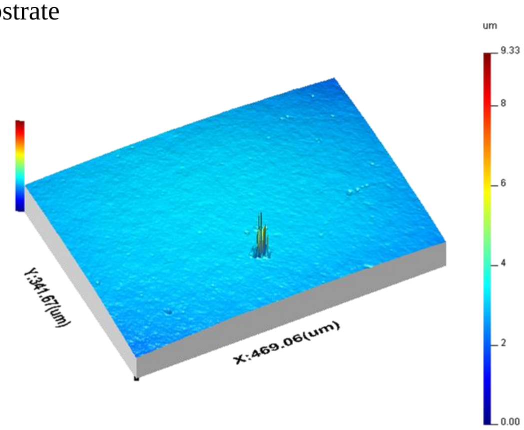

Fig. 9: defect measured using WSI system

5. CONCLUSIONS

High quality barrier films are critical if PV manufacturers are to exploit the possibilities offered by flexible large substrate area flexible photovoltaics The current work has shown that the presence of relatively large defects >5um in lateral dimension seems to have a dominant effect on the water vapour transmission rate through Al_2O_3 barrier films.

The use advanced segmentation techniques, ISO 25172-pt2, when applied to surface metrology data has the ability to extract salient information relating to the position size and density of defect present on the very low roughness barrier surfaces. The extraction ability is critical if defect information is to be correlated with WVTR of barrier films.

In order to implement in process metrology during the production of R2R barrier coating optical interferometery must be applied. In order to overcome the environmental noise a novel compensated wavelength scanning interferometry system have been developed this system has the ability to overcome environmental vibration and additionally to perform high speed measurement.

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