IN-SITU DEFECT DETECTION SYSTEMS FOR R2R FLEXIBLE PV BARRIER FILMS

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INTRUDCTION

The atomic layer deposition technique (ALD) is used to apply a thin (40-100 nm thick) barrier coating of Al_2O_3 on polymer substrates for flexible PV cells, to minimise and control the degradation caused by water vapour ingress. However, defects appearing on the film surfaces during the Al_2O_3 ALD growth have been seen to be highly significant in deterioration of the PV module efficiency and lifespan [1]. In order to improve the process yield and product efficiency, it is desirable to develop an inspection system that can detect transparent barrier film defects in the production line during film processing. Off-line detection of defects in transparent PV barrier films is difficult and time consuming. Consequently, implementing an accurate in-situ defects inspection system in the production environment is even more challenging, since the requirements on positioning, fast measurement, long term stability and robustness against environmental disturbance are demanding. For in-situ R2R defects inspection systems the following conditions need to be satisfied by the inspection tools. Firstly the measurement must be fast and have no physical contact with the inspected film surface. Secondly the measurement system must be robust against the environmental disturbance inspection. Finally the system should have sub-micrometre lateral resolution and nanometre vertical resolution in order to be able to distinguish defects on the film surface. Optical interferometry techniques have the potentially to be used as a solution for such application. However they are extremely sensitive to environmental noise such as mechanical vibration, air turbulence and temperature drift. George [2] reported that a single shot interferometry system “FlexCam” developed by 4D Technology being used currently to detect defects for PV barrier films manufactured by R2R technology. It is robust against environmental disturbances; but it has a limited vertical range, which is restricted by the phase ambiguity of the phase shift interferometry. This vertical measurement range (a few hundreds nanometres) is far less than the normal vertical range of defects (a few micrometres up to a few tens micrometres). It is not possible to detect the majority of defects in the R2R flexible PV barrier films.

In recent year two interferometric technologies, Wavelength Scanning Interferometry (WSI) and White Light Channelled Spectral Interferometry (WLCSI), have been studied for in-situ surface inspection at the EPSRC Centre for Innovative Manufacturing in Advanced Metrology, University of Huddersfield [3-5]. The WSI system developed at our Centre combines an active environmental disturbance compensation system and GPGPU fast data processing technologies which enable the WSI system to be used at the shop floor for precision surface inspection. The WLCSI system measures a surface profile in a single shot which makes it free from the requirements on the positioning and stability when the measurements are carried out on the shop floor and therefore has the potential to be used for in-situ surface inspection.

This paper reports on the development, deployment and integration of two in-situ PV barrier film defect detection systems; one of them based on WSI and the other based on WLCSI; into an R2R film processing line at the Centre for Process Innovation (CPI). Both systems are robust against environmental disturbances. They both have nanometre vertical resolution and micrometre lateral resolution, and up to 100 μm vertical measurement range. These systems have been tested and characterised, and initial results compared to results from using laboratory-based instrumentation are presented.

WSI PRINCIPLE

The measurement principle of WSI is based on measuring the phase shift of a reflected optical signal using wavelength scanning techniques by using an acousto-optic tuneable filter (AOTF). The measurement system is composed of two interferometers that share a common optical path. The measurement interferometer illuminated by a white light source is used to acquire the three dimensional surface profile of the sample in real time. The reference interferometer illuminated by a superluminescent light emitting diode (SLED) is used to monitor and compensate for the environmental noise. As the two interferometers suffer similar environmental noise, the measurement interferometer will be capable of measuring surface information once the reference interferometer is “locked” into compensation mode. Light reflected by the sample and the reference mirror are combined by the beamsplitter to generate an interferogram. A Dichroic beamsplitter is used to separate the measured interferogram signal and the reference signal. The interferograms are detected by a high speed CCD camera. The selected light wavelength of an AOTF is determined by:

$$\lambda = \Delta n \alpha \frac{v_a}{f_a} \qquad (1)$$

where Δn is the birefringence of the crystal used as the diffraction material, α is a complex parameter depending on the design of the AOTF, and va and fa are the velocity and frequency of the acoustic wave respectively. The wavelength of the light that is selected by this diffraction can therefore be varied simply by changing the driving frequency fa. As a result, different wavelengths of light will pass through the AOTF in sequence so that a series of interferograms of different wavelengths will be detected by the CCD.

Intensities detected by pixel (x, y) of the CCD camera that correspond to one point on the test surface, can be expressed by

$$I(x,y;k) = a(x,y;k) + b(x,y;k)\cos(2\pi k h(x,y)) \qquad (2)$$

The optical path different is given by

$$h(x,y) = \frac{\Delta\varphi(x,y,\Delta k)}{2\pi\Delta k} \qquad (3)$$

Since the change of   can be calibrated first by using an optical spectral analyser, the main issue here is how to calculate the phase change.

The schematic diagram of WSI is shown in Figure 1. It is employed to measure the surface topography of the barrier coating and is capable of generating surface maps with unambiguous height, without the 2π phase ambiguity limitation. The interferograms are produced with no mechanical movement but by scanning the wavelength of a halogen light in the visible region (683.4 nm-590.9 nm) using an acousto-optic tuneable filter (AOTF). Such a measurement methodology can provide significant enhancements in speed compared to comparable methods such as white light scanning interferometry (WLSI). In addition, the WSI can be stabilised against environmental disturbances by using an active control of the reference arm, thus enabling nanometre scale measurements with large amounts of environmental isolation [3, 4]. This active control consists of a reference interferometer, which provides positional feedback, and a piezo-electric transducer (PZT), which moves the reference mirror. The PZT is driven by a PI controller to track the altering in the optical path due to environmental disturbance such as mechanical vibration and refractive index drift.

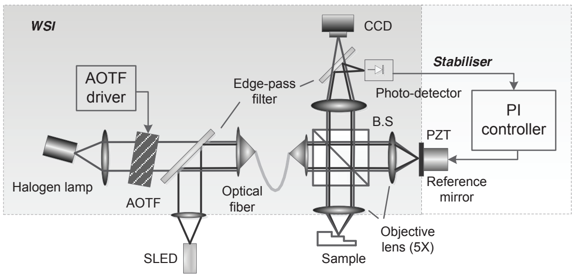


FIGURE 1. Configuration of the WSI

The reference interferometer is multiplexed with the WSI to share the same measurement optical path using an edge-pass filter (dichroic mirror) and a super luminescent diode (SLED) light source having a central wavelength of 820 nm. The intensity of the generated fringes is detected by a photo-detector which monitors the SLED light only, using a dichroic filter that reflects the IR light to the detector and allows the scanned visible light to pass through to the CCD. This control loop system can compensate for disturbances in the optical path length up to a few microns at 102 Hz and stabilise the WSI for wavelength scanning process.

During the measurement process, 256 interferograms are captured over a full field of view using 5X magnification objective lens and 640x480 CCD pixels. A periodic spectral interference pattern produced for each captured pixel is analysed individually using Fourier transform algorithm. This analysis is widely used to extract the phase from periodic fringe patterns by filtering out the DC interference term and the phase conjugate from the power spectral density obtained via the discrete Fourier transform. The extracted phase distribution suffers 2π ambiguity that can be removed using one-dimensional unwrapping method.

The evaluating process for areal topography requires long processing time when CPUs traditional sequential execution programs are used. The full analysis of all the pixels is, therefore, accelerated by parallelising the computation with a many-core graphic processing unit (GPU). The WSI can capture and generate a full areal topography in 3.7 seconds. The CUDA C program is used to achieve the data parallelism using a GPU device, hence increasing the measurement throughput, demonstrated. Typically, in a sequential programming model, the program generates a main thread that executes functions in a sequential manner. In contrast, the CUDA parallel programming model generates thousands to millions number of thread (typically equal to the captured frames size) to execute data-parallel functions, known as kernels, in a parallel manner. In this application, 307200 threads are generated to analyse each pixel individually in a parallel manner. The computing time is accelerated to approximately 1.1 second compared to 31.9 second using conventional sequential programming approach [6].The atomic layer deposition technique (ALD) is used to apply a thin (40-100 nm thick) barrier coating of Al_2O_3 on poly

WLCSI PRINCIPLE

Different from WSI using an AOTF for wavelength scanning, WLCSI employs a diffraction grating to separate a series of constituent monochromatic interferograms which encode the phase as a function of wavenumber along the horizontal axis of the CCD camera (chromaticity axis) [7]. For a diffraction grating with space d, if a plane wave is incident with an angle θ_i, the diffraction angle is θ_m at the order m, then for a beam with wavelength λ, the following equation should be satisfied

$$m\lambda = d(\sin\theta_i + \sin\theta_m) \qquad (4)$$

By selecting a proper grating spacing, the distance and the angle between the grating and CCD camera, it is expected that a desired spectral band of light can be captured with respect to the CCD pixels.

The basic configuration of the WLCSI in-situ surface inspection system is illustrated in Figure 2. A halogen bulb with broadband spectrum provides the white light illumination for the system, which is coupled into a multi-mode optical fibre patch cable with a numerical aperture of 0.39. The tested surface is observed through a cylindrical lens based Michelson interferometric objective. The measurement of long profiles can be achieved due to the imaging property of the cylindrical lens. The interference beam passes through a slit to block the light that is redundant for measurement. That is to say, for each measurement only a narrow line of light which represents an interference signal of a surface profile is selected, then diffracted by the grating and finally received on a CCD camera. After wavelength calibration wavenumber σ spreads along the chromaticity axis in a range of 1.50 μm^{-1} 1.71 μm^{-1}. The direction of the slit is set to be parallel to the columns of CCD pixels, so that the dispersion axis is along the rows. The CCD camera (ICL-B0620 from Imperx) has a resolution of 648 x 488 pixels and a frame rate of 208 fps in normal working condition.

When the measurement is performed, the sample should be placed within the depth of field (DOF) of the objective to resolve the details of the tested surface. Fringes still can be observed as the optical path difference (OPD) between the tested surface and reference surface exceeds the DOF, the visibility of the fringes and the signal-to-noise of the interference output, however, greatly decreased and eventually no interference exist when the OPD is greater than the coherence length. Therefore, the measurement range is related directly to the DOF and coherence length, and determined by the smaller of these two numbers. The depth of field is defined by:

$$DOF = \lambda\left(1 - NA^2\right)^{1/2} NA^{-2} \qquad (5)$$

The coherence length is expressed as

$$l_c = \frac{k\lambda^2}{\Delta\lambda} \qquad (6)$$

where k is the correction factor depending on spectral profile. For the Gaussian distribution and Lorentzian distribution, k is equal to 0.32 and 0.66, respectively. As for the WLCSI, the coherence length is much greater than the DOF due to the function of the spectrometer. Therefore, the measurable heights range is limited by the DOF, which is theoretically approximately 144 µm.

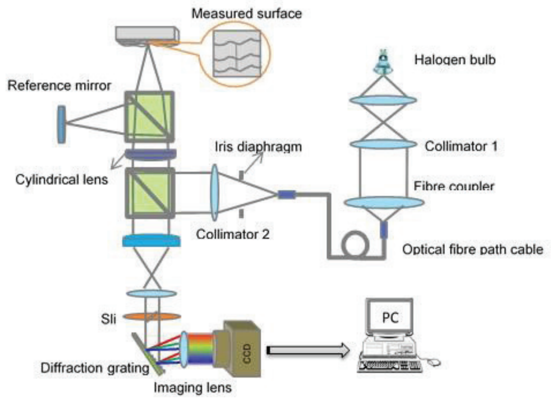
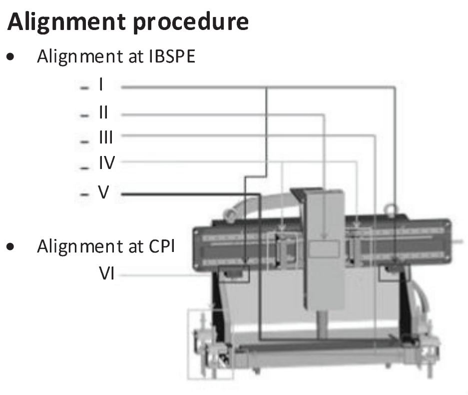


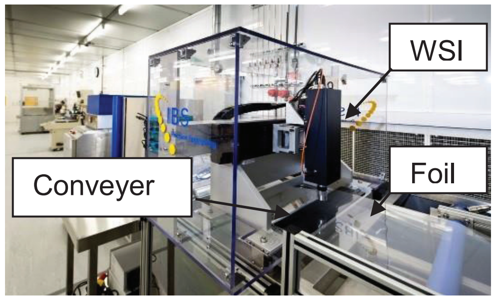
FIGURE 2. Schematic diagram of WLCSI

SYSTEMS IMPLEMENTATION

The WSI system has been mounted into a metrology frame using kinematic adjuster as described in Figure 3.a, resulting minimum tilt fringes across WSI field of view (i.e. less than 5 fringes per FOV). A porous air-bearing conveyor is placed underneath the polymer film to stabilise the web at fixed height. A standard artefact supplied by NPL has been mounted beside the edge of the foil web and aligned with respect to the conveyor in order to justify the WSI performance. The final setup of the system is shown in Figure 3.b.



(a)



(b)

*FIGURE 3. (a) Opto-mechanical inspection system, where **I** is align Y-stage w.r.t. conveyor in Z and R_x, **II** is align WSI w.r.t. Y-stage in Z, **III** align conveyor w.r.t. WSI in Ry, **IV** align WSI w.r.t. conveyor in Rx, **V** align artefact w.r.t. WSI in Z, R_x and R_y, **VI** align setup w.r.t. foil (b) Integration the inspection system onto rewinder stand.*

The porous air-bearing conveyor is used for handling the film web which supports the film at fixed height and maximize the flatness of the web relative to the measurement plane. The handling solution should also be approved for use in clean room environment. The porous air-bearing conveyor can satisfy such conditions if uniform dry air pressure is supplied across the entire air bearing area with a vacuum pre-tension force to hold the foil. In this application, a conveyor type H-Series from New Way Ltd was used to supply uniform clean dry air (CDA) pressure, through a porous medium with a thin air gap, resulting in a more consistent fly height and better flatness across the full width of the flexible foil web. This technology can also act as a stop-gap filter, trapping any particles which may have escaped the filter system.

The conveyor performance was investigated by IBS Precision Engineering [8] using an optical sensor which scanned across the foil web after supplying 2 bar air pressure and vacuum pressure ranges 0-0.3 bar with 0.05 incremental step, see Figure 4. It has been found that the conveyor can hold the web with local height variation of <5 µm under 0.05 bar vacuum. The worst case peak to peak variation is found to be < 25 µm over the 60 mm foil width without vacuum pressure. This height variation is within the focal depth limit of the objective lens used in WSI (e.g. the focal depth for 5X objective is equal to ±14 µm).

An effective auto-focusing methodology is crucial to the successful implementation of the WSI for large flexible substrate measurement. Although the flexible substrate is held by a porous air-bearing conveyor, the surface undulation is still substantial across the 500 mm web width. Fast, automated positioning of the WSI head so its focal point is at the top layer of Al2O3 barrier is needed which must also be robust against the possibility of mis-focusing due to the multilayer structure of the web.

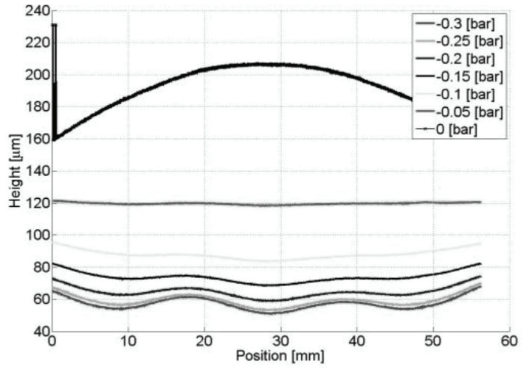


FIGURE 4. Air bearing performance at 2 bar air pressure when altering the vacuum pressure [8]

The auto-focus method is based on tracking the peak of the coherence envelope of the reference interferometer sourced by the SLED when the head is moved normal to the web to scan the focal plane of the WSI objective lens using a stepper motor. Simultaneously the intensity response is monitored by the reference interferometer, with the maximum intensity (coherence envelope peak) being found to be the point of focus. Throughout the translation, the position of the film is acquired continuously from the encoder of the stepper motor in order to map the physical position of the translation stage to peak position of the coherence envelope. This information allows the stage to move to the precise point of focus after the scan. The speed of the auto-focusing method is dependent on the speed of motorised translation stage. For the current setup, the auto-focus routine, using a 1 mm translation distance, took approximately 0.6 second.

The limiting factor for the auto focus method is the number of tilt fringes which results in the degradation of signal-to-noise ratio of the feedback signal. Experimentally, it has been determined that a sufficient interference signal can be obtained for effective autofocusing operation when there is more than 5 fringes (equivalent to 2.4 mrad surface gradient) appear across the WSI field of view, see Figure 5. Increasing the number of fringes across the active photo-detector area, which is equal to 0.5 mm^2, will average out the coherence intensity and hence degrade the feedback signal.

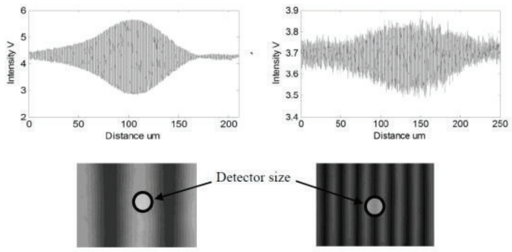


FIGURE 5. The coherence intensity response with its corresponding FOV.

The start position is located at the artefact such that the operation of the system is initiated by measuring the 1.2 μm step height sample. It has been found that the measurement precision is better than 20 nm. The WSI is translated incrementally over the web width while the foil is stationary. Instead of inspecting a foil coated by Al_2O_3 barrier, gold coated PET film has been measured to obtain preliminary such that three defects were detected as shown in Figure 6. The measurement throughput to cover 500 mm width is approximately 2 hours using 5X objective lens. The overall data size for full width (i.e. 500 mm x 0.7 mm) is larger than 300 megabyte.

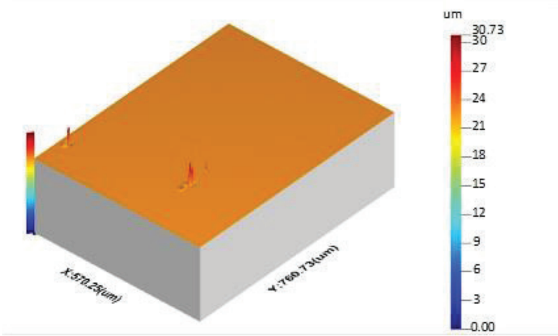


FIGURE 6. PET film areal measurement using WSI

The WLCSI system can be integrated into the metrology frame the same as the WSI system. Compare to the WSI system it does not have an auto-focus system which results the demanding for the metrology frame is high. With the specifications of the metrology frame and the air bearing system and the relative large vertical measurement range the prototype can be fitted into the R2R system for the inspection. A measurement on a scratched glass surface is shown in Figure 7.

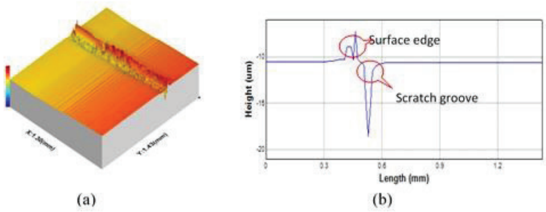


FIGURE 7. Measurement results of a scratch by WLCS: (a) 3D surface map, (b) cross-sectional profile.

CONCLUSION

It is well established that the efficiency of flexible PV is correlated to the WVTR which is dominated by the presence of large defects in the barrier layers. Implementation on-line defect detection systems can enhance the he roll-to-roll (R2R) manufacturing process. The WSI and WLCSI systems can be considered as a solution for R2R process as combined to traverse and autofocus stages and air bearing conveyor. These two inspection systems can measure wide foil area in spite of environmental disturbances and without interaction by the operator for alignment or focusing the instrument.

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