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PHOTO-THERMAL DEGRADATION ANALYSIS OF SINGLE-JUNCTION AMORPHOUS SILICON SOLAR MODULE'S EVA ENCAPSULATION

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Ethylene vinyl acetate (EVA) encapsulation degradation affects the performance of photovoltaic (PV) module. Hot spot formation causes the EVA encapsulation to undergo photo-thermal deterioration, this process encourages the molecular breakdown by ultra-violet (UV) radiation. This leads to diffusion of chemical particles from one layer to another. During outdoor deployment, the EVA encapsulation in the affected region losses its adhesive strength, when this happens the layer in the affected region undergoes rapid delamination. The presence of photo-thermal degradation is detrimental to the reliability of PV modules because it causes both optical and thermal degradation. This mode of degradation makes the encapsulant in the affected region to be more susceptible to chemical substances and moisture. Scanning Probe Microscope (SPM), Energy Dispersive X-ray *(*EDX*)* and Thermogravimetric analysis were used to investigate the observed photo-thermal degradation. Why Fourier Transform Infrared Spectroscopy (FTIR) was used for the optical degradation characterization. Our findings show high concentration of Sodium, Phosphorus and Aluminium, which originate from the glass substrate, cell emitter and back contact respectively.

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1. Introduction

Most EVA polymer possesses similar direct optical band gap but differs in their structural and thermal properties. This explains the difference in their thermal stability during operation. The higher the thermal stability, the more the EVA can provide protection and stability to the photovoltaic (PV) active layer. A good encapsulating polymer for use in PV solar cells encapsulation process need to have a high stability against UV radiation and high adhesive force to the top layer substrate [1]. This is because the primary goal of EVA encapsulant in PV module is to provide structural support, electrical isolation, and physical isolation [2]. Normally the materials used as PV encapsulant are made from polymer of high insulation to maintain good circuit isolation. In addition, EVA need to provide high optical transmission of sunlight as well as thermal conduction for the solar cell inbuilt circuit [1-2]. From the manufacturer point of view all EVA encapsulant are designed to have good circuit isolation, but after photothermal degradation the circuit isolation capability decreases. This is because for a photo-thermally degraded a-Si:H PV module, the encapsulating layer losses its adhesive strength, this process induces the delamination of the layer interface thereby affecting the long term stability of the PV modules. Photo-thermally degraded EVA encapsulant, have weak bonding force to glass, cell layer, and such encapsulant can react with the active layer or cell surface [3-5].

The knowledge of thermal and optical properties of PV modules can be used to study its electrical performance. Knowing the thermal and optical degradation of such PV materials is an interesting method of investigating the degradation observed in such materials and hence predict the stability. Consequently the absorption of light and the subsequent transmission of photon energy into the affected region absorbant layer depends to a certain degree on the EVA

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encapsulation degradation. Research has shown that photo-thermal effect induces a change in the quantity of light transmitted to the absorption layer of the active cell (a-Si) [6].

The purpose of this study is to demonstrate the diffusion of chemical particles from one layer to another due to photo-thermal degradation effect. Finally to show how the presence of photo-thermal degradation affects the optical property of a-Si:H and the thermal stability of the EVA encapsulant.

1.1. Theory (Chemical inter-Diffusion)

Fig. 1, shows the inter-chemical diffusion which occurs during photothermal degradation. In field aging degraded amorphous silicon solar module, at the active layer/encapsulant interface, the module is subjected to both solar irradiation and moisture condensation [7-11]. After layer delamination due to photothermal effect, the back contact releases alumimium (Al) via corrosion and this migrates to the active layer thereby upsetting the elemenatal composition in the encapsulant since the EVA is reactive at this state.

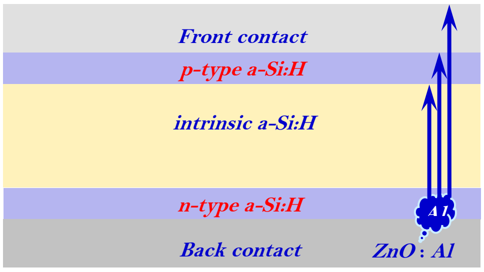

Fig. 1. Schematic representation of diffusion of elemental particles across layers

For outdoor PV module, EVA delamination increases as the degradation time increases. At the same time the migration of impurities, such as alumimium (Al), sodium (Na) and phosphorous (P) begins, this further aids the delamination process. Delamination usually occurs along the scribe line, due to stress associating with solar cell surface and the interconnecting scribe line that has been monochromatically scribed on it with laser beam during production stage. Another factor responsible for this is the strain that exists between the solar cell surface, and the corner of the scribe or solder ribbon because of the differences in their thermal expansion coefficient [9-11].

2. Methodology

2.1. Experimental procedures

A degraded single junction amorphous silicon solar module which has been deployed outdoor since 2011 for performance monitoring and found to have shown degradation above the acceptable value was delaminated and carefully cut into sample sizes. Samples were prepared from two areas of interest, the perfect regions which show no sign of discoloration and region with high discoloration effect as shown from visual and optical inspection [15]. The sample was carefully cut into the required size using saw edge. The samples were later washed with water and cleaned with methylated spirit to remove any carbon print. Then dry with a compressed air at high pressure to remove any water moisture for optical characterization. There after these sample were delaminated by removing the top layer (glass), before used for elemental distribution, elemental composition and thermal degradation analysis. These prepared delaminated samples were analysis with SPM, EDX and TGA respectively.

To investigate the effect of photothermal degradation on the absorbance of the sample, Fourier Transform Infrared (FTIR) spectrometer was used to characterized the optical degradation. FTIR utilises electromagnetic radiation to examine the crystal lattice vibrations, free electrons-holes, electronic band, microstructures and the impuirities and defects. But in this study it was used for absorption characterisation, one advantage of this technique is that it is a non destructive characterisation technique.

The general analysis of varying signal into its frequency constituent is known as Fourier spectroscopy [12], when the spectroscopy involves infrared rays, then it is known as Fourier transform infrared (FT-IR). This technique is a powerful tool, which gives information about substance, absorption, reflection, transmission etc. [13, 14]. The operational principle of FTIR is defined by the ability of the interferometer to generate an interferogram (signal) which is recorded in the infrared detector.

Immediately after FTIR analysis, the samples were delaminated to remove the front contact for further analysis. Scanning probe microscopy (SPM) was used to characterise the morphology, elemental distribution and defective spots in the a-Si:H samples. SPM provides high resolute surface image of up to some degrees of their atomic scale. This device uses sharp tips of several nm to contact with the analysed sample, this interaction between the sample and the device tip is controlled and monitored for better output. Though this technique shows both the surface morphology and the distribution of elemental particles alone the samples, but to unveil the identify of the elements present, EDX was used.

EDX was used to identifiy the element present as well as show the chemical susceptibility of the affected region. The samples were analysed with the aid of computer controlled field emission scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) system. The samples were introduced into the device after been mounted on the sample hold stub. The SEM-EDX system was pre-set at an accelerating voltage of 20kV, while the current beam was 40 – 50 μA, with an X-ray detection limit of ~0.1%. At each analysis point the quantitative and qualitative analysis of the chemical elements present were measured by EDX. The weight percentage of each chemical substance present was identified. On normalizing to 100%, the weight percentage of C, O and other elements were identified. Next was the thermal degradation investigation of the EVA encapsulant.

Thermo-gravimetric Analysis (TGA) was used to analyze the thermal stability of the EVA encapsulation of both regions during outdoor operation. This method gives qualitative information about the thermal stability of encapsulating material. This decomposition of the encapsulating material in affected region necessitated the use of thermo-gravimetric analysis. For this study, an Afrox thermo-gravimetric analyzer 7 was used, with nitrogen acting as the baseline gas at 20 °C while the pressure was one atmosphere [18, 21]. The operating condition of the analyzer ranges from a temperature of 20°C to 900 °C with a heating rate of 10 °C/min while the gas flowing rate was 10 ml/min. The samples were carefully prepared to an accuracy of 1μg, one from the affected region and the other from the non-affected region, and the weight of each sample was 21.337 mg.

3. Results and discussion

3.1. Optical degradation Analysis (Fourier Transform Infrared (FTIR)

Fig. 3, presents the optical characterisation of analysed samples, and it also shows the photo-degradation of the affected region of the module. The red curve represents the sample obtained from the affected region, while black curve is for the sample from the non-affect region.

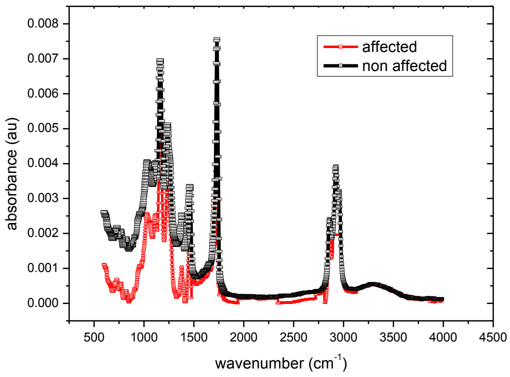

Fig. 3. Absorption characterisation of the analyzed samples

FTIR analysis shows the optical degradation at the various bonds, primarily due to bond decomposition in the bond site where absorption takes place. The FTIR spectra of the samples overlap without change in the wavelength except intensities because the molecular bond vibrations occur at exactly the same position when illuminated by light ray. This result shows a reduction in the absorption property of the affected region at the various absorption positions. This is because, in the affected region, photothermal effect limits the response of the absorbant layer to the incoming photons. First by selective absorption principle of light due to colour (yellowish effect) and by reducing the absorption bond length. Also, since migration of chemical particles occur in these region, this creates an upset in the relationship between the various energy band levels hence most incident photon energies become lower than the band energy of the region. Finally, the movement of particles from the EVA encapsulant to other layers, prevents the layer below to fully utilize the incident energy from the higher and low energies of the incoming light.

3.2. Scanning Probe Microscopy (SPM)

Fig. 4, shows the SPM anlysis of the samples after carefully removing the top substrate, hence the active layer became the top surface. For this investigation the areas of interest was free from the transparent glass layer which is not conductive, this active layer is suitable for EDX analysis unlike the top contact which was not.

The SPM results, for the affected region and the non-affected region of the module shows, inhomogeneity in the chemical composition of both samples. In figure 4a the analysis for the affected region is presented why figure 4b is for the non-affected region. The Subscripts 2-D and 3-D denote 2-dimensional and 3-dimensional views, respectively. The 2-D image of the affaceted region shows high intensity of elemental precipitation, this is very clear from its 3-D image. But for the non-affected region slight impurities are observed, the 3-D image shows niddle like fingers of foreign elements of low intensities. Changes in the morphology are function of the impurities present, and the morphological change increases as the impurities concentration increases. In order to identify the chemical impurities present, chemical composition analysis was done with EDX. The presence of carbon, oxygen and aluminium in the EDX spectra confirms the diffusion of chemical particles from the affected region into the active layer (a-Si).

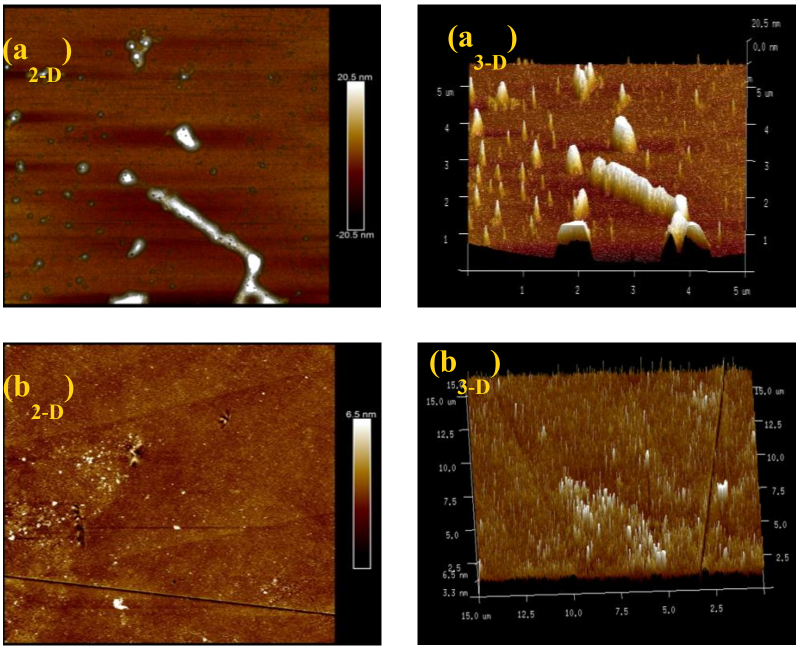

Fig. 4. SPM analysis of the affected and non-affected region of the samples.

3.3. Energy Dispersive X-Ray Analysis (EDX)

The elemental analysis od the samples are presented in figure 5, figure 5a is for the affected region why figure 5b present the non affected region.

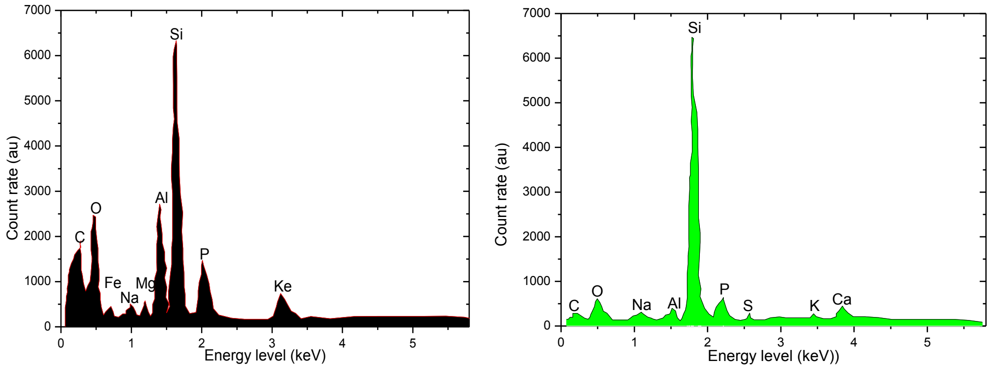

Fig. 5. EDX analysis of (a) affected region (b) non affected region

The EDX analysis shows the presence of other elements in both the affected and non-affected region.

This indicates that lower concentration of some elements does not constitute impurities. But higher concentration of these foreign element constitute impurities, these is indicted by the intensity of the EDX spectra. The results show high concentration of C, O, Al and Fe in the affected region, hence they are considered as an impurity. The presence of Fe in the affected region is generally considered as an impurity and believed to be detrimental [19], to a-Si:H solar cells.

3.4. Thermogravimentric Analysis (TGA)

Thermogravimetric analysis (TGA) measures the change in weight of a sample as the temperature increases. We have investigated the thermal stability of the EVA encapsulation of the a-Si:H in the temperature range of 20 ^{o}C to 900 ^{o}C. While the measured percentage weight loss from a temperature of 40 ^{o}C to 800 ^{o}C is represented in figure 6. The red line shows a perfect curve of what is expected of an EVA polymer, but the black line representing the affected region, shows a poor EVA polymer curve. An onset temperature of 40 ^{o}C was used to eliminate the presence of water ingress in the calculation. It is important to note that the thermal stability of the analysed sample is directly proportional to the change in the percentage weight loss. From the analysis, the sample with a higher change in its percentage weight loss means less or no chemical weight loss was experienced during the outdoor deployment, because the EVA encapsulation was thermally stable [6, 21-22]. While the curve with a lower change in its percentage weight loss means a higher part of the encapsulating material substance has been lossed during outdoor deployment. This is because the encapsulation of the affected region was thermally unstable due to EVA encapsulation degradation which resulted to molecular break down of the region. To get the actual percentage weight loss of the VA equation1 was used:

$$\mathrm{VA} = \mathrm{wt\ loss\ of\ acetic\ acid}\,\frac{(\mathrm{Mwt\ of\ VA})}{\mathrm{Mm\ of\ acetic\ acid}} \tag{1}$$

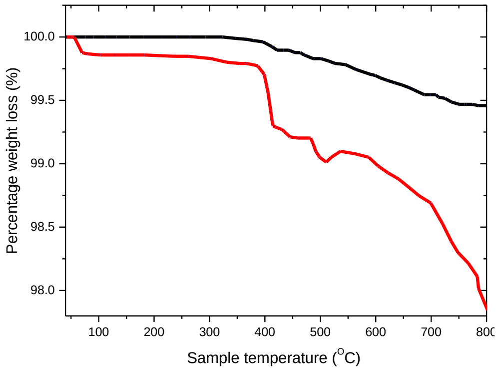

Fig. 6. TGA curves of both the affected and the non affect region of the module

In Fig. 6, The thermogravimetric analysis (TGA) is use to examine the changes in weight of both the affected and non-affected samples as the temperature increases. From the analysis the weight percentage loss was calculated using equation 1. Since percentage weight loss is proportional to the EVA polymer content of the sample [16-17], therefore the percentage weight loss for the non-affected region is greater than the affected, this is expected since it contains more EVA polymer. Considering an onset temperature of 40 ^{o}C as stated before, the weight percentage (%wt) loss for the affected and non-affected region are 0.701%. and 2.717% respectively, at 800^{o}C. In a TGA weight loss curve the degradation onset of most copolymer encapsulatant is taken as 85 ^{o}C [18, 21-22], and the weight loss below this temperature represents the initial water content in the encapsulant.

4. Conclusions

In this study, SPM micrographs show that the morphology and shape of the active layer change as the impurities concentration increases, due to particles migration. The study shows high concentration of Carbon, Oxygen, Sodium, Phosphorus and Aluminium in the affected sample, these particles originated from the EVA, cell emitter , glass and back contact. This study established that photo-thermal degradation makes the encapsulant in the affected region to be more susceptible to chemical inter-diffusion and moisture ingress. The TGA analysis shows that during operation, the red line was very stable and no significant weight loss occurred under the operational cell temperature.

The result demonstrates that the thermal stability of the affected region is lower than that of the non-affected. During outdoor exposure the thermal resistivity of both the affected region and the non-affected is expected to be the sample for any encapsulatant used for PV encapsulation process except for a photothermally degraded EVA.

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