



An outdoor investigation of the absorption degradation of single-junction amorphous silicon photovoltaic module due to localized heat/hot spot formation

GILBERT O OSAYEMWENRE*, EDSON L MEYER and
SAMPSON MAMPHWELI

Fort Hare Institute of Technology (FHIT), Chemistry Building, 3rd Floor, University of Fort Hare,
Private Bag x1314, Alice 5700, South Africa

*Corresponding author. E-mail: GOsayemwenre@ufh.ac.za

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Abstract. This paper investigates the absorbance degradation of single-junction amorphous silicon (a-Si:H) photovoltaic (PV) module, due to the presence of localized heat. The decrease in optical density is a huge challenge due to the long-term degradation of PV modules. The reduction in solar cell optical density causes a decline in its conversion efficiency. This decreases the photogenerating current, hence reduces the effective efficiency of the PV device. An infrared thermography was used for mapping the module temperature profile. Fourier transform infrared spectroscopy (FTIR) was used for the absorption characterization. The rationale behind the outdoor deployment was to deduce a practical effect of hot spot formation on the module's absorption ability. The results show a direct correlation between localized heat and the absorption degradation.

Keywords. Thermography; hot spots; localized heating; single-junction amorphous silicon module; Fourier transform infrared spectroscopy.

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1. Introduction

The importance of PV modules' outdoor monitoring over indoor evaluation cannot be overemphasized [1]. It gives us a practical method of performance assessment, because the PV module's output depends on irradiance. A better understanding of the PV degradation mode is required to address the problem of reliability [2,3].

Amorphous silicon (a-Si:H) provides an excellent platform for low-cost, large-area photovoltaic devices. However, amorphous silicon (a-Si:H) is not very attractive as a photovoltaic material. Its lack of long-range order in the a-Si structure is the main drawback [4]. The presence of short-range disorder structure in a-Si network is known as unsatisfied

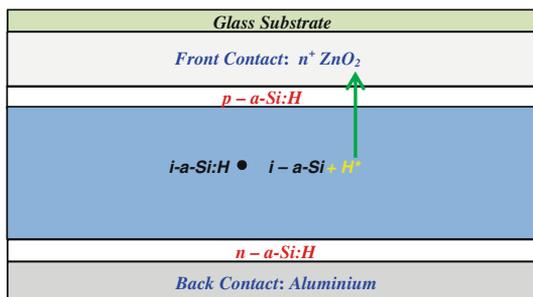


Figure 1. a-Si:H structure (after ref. [4]).

or dangling bonds. These dangling bonds can be detrimental to the electrical efficiency of the final solar cell, because they provide recombination centres within the energy band gap. Some of its atoms may only be two-fold- or three-fold-coordinated. The two-fold or three-fold-coordinated atoms release the strain in the a-Si structure, but they possess unsaturated dangling bonds, which are electrically inactive [5]. Continued research on the cell structure [6–8] revealed that atomic hydrogen passivates these dangling bonds; hence make the material a better candidate for solar cell applications. The nature of a-Si:H material is influenced by the presence of the incorporated hydrogen and the bonding nature. These factors affect the internal mechanical stress of the device [9,10]. In regions where there are localized heating, the passivated hydrogen may dissociate and migrate across the p-layer and to the ZnO layer, leaving the intrinsic layer deficient of hydrogen. The formation of more dangling bonds during operational condition as a result of the thermal decomposition of the intrinsic layer has a negative effect on the electrical and optical properties of the device. As such the absorption coefficient decreases causing a lesser amount of photon to reach the absorber layer, thus decreasing the photogenerated current. Figure 1 illustrates a-Si:H structure and the hydrogen migration during the breakdown of intrinsic (i-a-S:H) layer.

The localized heating can cause structural damage which increases surface recombination and reduces the mobility and lifetime of photogenerated electrons. This study looks into the effect of hot-spot formation on the absorption ability of a-Si:H. Moreover, the study looks at the chemical bonds (functional groups) present in both the affected and the non-affected regions. FTIR was used as an analytical tool to investigate the optical behaviour and functional groups in each region.

2. Method and experimental details

2.1 Infrared surface mapping/infrared camera (IR)

The IR camera was used to evaluate the temperature distribution across each module [11,12]. The hot-spot evaluations were carried out on a daily basis. At the end of each outdoor investigation, an indoor analysis was undertaken using ThermoCAM Professional Researcher 2.8 software SR-3 developed by FLIR system. Figure 2 illustrates how the hot-spot regions are identified using IR in-built analytical tool (2.8 SR-3 spot meter). In module 1, the hot-spot region corresponds to point AR01 (SP01), while that of module 2

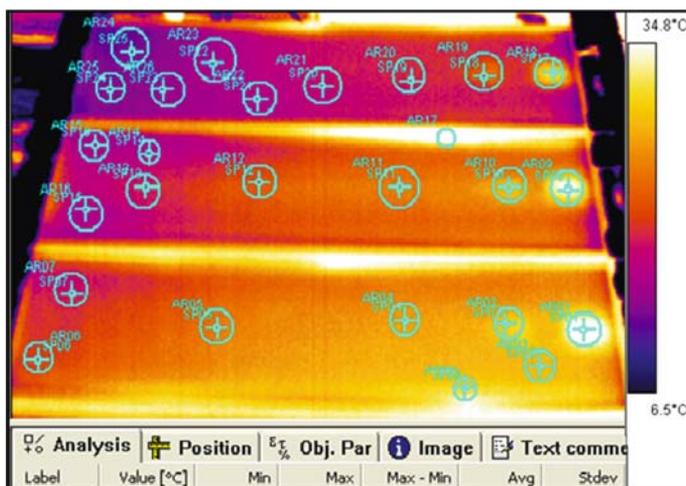


Figure 2. Illustration of how IR analysis was carried out during indoor analysis.

corresponds to AR09 (SP09) point. The highest temperature observed was 34.8°C, while the ambient temperature was 6.5°C.

The infrared (IR) camera used in this study is manufactured by FLIR. Scientifically, it is referred to as ThermaCam E300 and possesses 25 lenses. The object parameters include (camera): emissivity of 0.98 (right emissivity for a-Si:H PV module) [12,13], reflective temperature of 20°C, atmospheric temperature of 20°C and atmospheric transmissivity of 0.99. The distance of the camera from the object was 2 m, while the relative humidity was 55%.

The IR camera was used for the hot-spot detection in each module. Infrared ThermaCAM Pro 2.8 SR-3 spot meter software was used to locate and mark the hot-spot area/region (for further details refer to [14,15]). The IR investigation shows the hot spot in each region. The centre position was considered as the point of hot-spot origin. The two regions were marked from each cell; one from the affected region and other from the non-affected region.

2.2 FTIR investigation

2.2.1 Sample preparation. After locating the hot-spot regions, the next stage was the sample preparation. In this stage, a corrugated cardboard (larger than the size of the sample), straight edge (metal rule), cutting glass tools (tungsten carbide scraper blade) and a jig were used. The jig was used for holding the module during cutting. The module was placed on the corrugated cardboard and a masking clip holder was used to hold the sample while the metal ruler was placed on the module to assist the process particularly for instituting a uniform force distribution across the device. A sharp tungsten blade was used to cut out the required regions meticulously, while a jig was used to hold the sample during cutting [15]. The area of the sample's cuts were larger than the region earlier marked during the IR analysis to ensure that the properties of the regions were not affected by the cuts [16].

After cutting the samples into the required sizes, two samples were carefully prepared and cleaned. Non-flammable moisture-free and quad-filtered (easy duster) compressed air was used to clean the sample surface which was placed under a closed sample holder. These samples were analysed using Fourier transform infrared spectroscopy (FTIR) in the frequency range $660\text{--}4000\text{ cm}^{-1}$. The aim was to study the effect of hot-spot formation on the absorbance of PV cells. The optical absorption and transmission spectra of the two different PV technologies were examined. All the samples were analysed, and the FTIR spectra patterns were obtained [10,16,17].

3. Results and discussion

3.1 IR results

Figure 3 shows the infrared thermography photographs used for the degradation analysis. These IR images were photographed at 4 μm on the day of the analysis. This was done to prevent artifact in the analysis. This procedure, of taking IR photographs at 12 noon, when the irradiance is maximum, poses challenges related to the correct identification of the hot-spot region due to the high temperature sensitivity of silicon solar cell when using this camera. From these figures, areas of higher temperatures are seen. These indicate the development of hot-spot formation.

When modules have different thermal properties, it indicates that the temperature gradient varies from one part of the module to another. In our experiment, all the modules showed temperature variations that were above $\pm 6^\circ\text{C}$. This statistic is at variance with the expected measurements [17]. The temperature profile presented in figure 4 is of a section in module 1 as represented by the red line in figure 3d. This represents the hot-spot region temperature profile at the back side of the modules. The temperature on the back of the module was found to be different from the surface temperature of the module. This could probably be due to poor heat exchange rate resulting from the back cover.

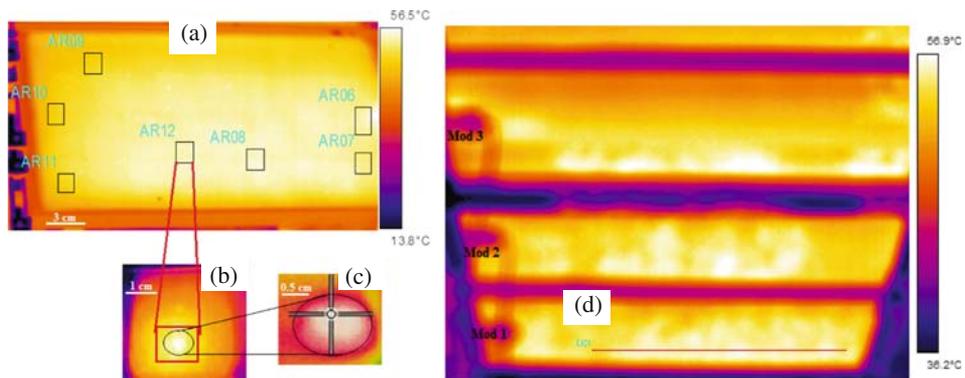


Figure 3. IR image of (a) module 1 in the reverse order (back view), (b) showing hot-spot region at point AR (0.5 cm), (c) the front side of figure b (1 cm) and (d) shows the 3 modules and line (red).

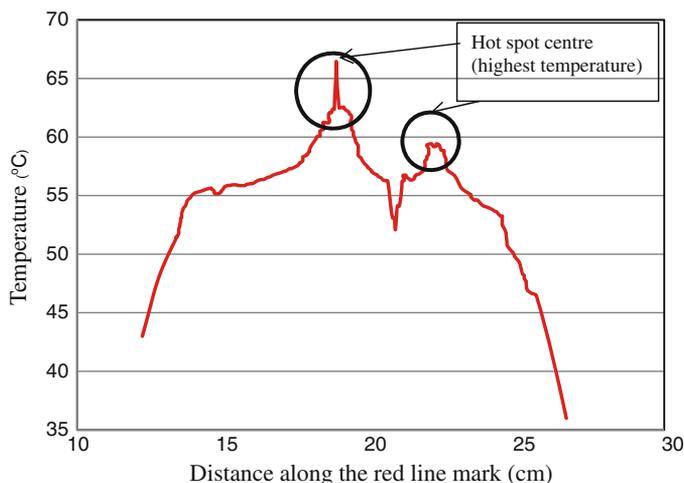


Figure 4. The IR temperature profile of the analysed thermograph in figure 3d red line.

Thermalization loss (loss due to excess photon energy) is a common degradation mechanism in solar cell. However, in the presence of hot spot it assumes a geometric progression [17,18]. Electron excitation from the valence band to conduction band takes place when the incident photon energy is equal to the band-gap energy of the illuminating device. In most cases, the photon energy (E) is greater than the band-gap energy (E_g) of the device, the difference between $E - E_g$ is dissipated as heat into the lattice vibration, and this loss is approximately about 34% [18]. But when this dissipated heat is localized due to defect, it leads to hot spot.

3.2 FTIR investigation and functional group analysis

Several regions were analysed for optical degradation and their outcomes were similar depending on the classification of the regions. The objective was to differentiate the optical capacity of the non-affected region from the affected region. At the end of the experiment, all the samples from non-affected region exhibited similar behaviours. In the affected region, there was a general decrease in the optical absorption capacity; some areas exhibited more optical degradation than others. From FTIR, the effect of hot spot on the module absorption was analysed and investigated, to determine the transmittance and the absorbance [19].

3.2.1 Transmittance. The transmissivity of the module is presented in figure 5. For samples from the same solar device, the transmissions are expected to be uniform. But when defect occurs it leads to structural damage and for a module this microdefect can be observed anywhere in the structure. Therefore, the degree of transmission in the affected region is governed by an equation called the generalized Planck's photon distribution

equation [20–22]. This helps to evaluate the magnitude of the photon absorbed in a particular region in the PV module.

$$GP(E, \Omega, T, \mu) = \frac{2\Omega}{C^2h^3} \times \frac{E^2}{\left(\frac{E - \mu}{KT}\right) - 1}, \quad (1)$$

where C is the speed of light, E is the photon energy, T is the solar cell temperature, h stands for Planck’s constant, k is the Boltzmann’s constant, μ is the chemical potential, Ω is the angle of absorption or emission. The absorption angle is affected by changes in the surface morphology and crystal defects. More the defect, less the value of Ω ; and μ is zero for PV modules.

Defect resulting from structural damage also increases morphological reflection and hence affect the available photon for useful absorption [23]. For amorphous silicon solar cell the IV characteristic for p–i–n can be represented as

$$J = J_L - J_{Rec} - J_O \left[\exp\left(\frac{qV}{nkT}\right) - 1 \right], \quad (2)$$

where J_L and J_O are the photogenerated current and reverse saturated current while J_{Rec} is the recombination current which is proportional to the dangling bonds and defect density [24,25].

The present work shows the influence of hot-spot formation on the transmission spectra of the module, which reduces the amount of photons reaching the absorber layer. Figure 5 presents the spectra from the affected and the non-affected regions; the discrepancy in their spectral peaks is due to optical degradation.

In figure 5, both spectra have distinct peaks in the following ranges: 3736–3854, 3602–3619, 2921–2989, 2854–2877, 2358.38–2358.36, 1643–1651, 1524–1525.25 and 675.47–676.9 cm^{-1} . In addition to the above peaks, the red spectrum has two transmittance peaks at 2930 cm^{-1} and another strong stretch peak at 1114 cm^{-1} . The broad band located in the 3736–3854 cm^{-1} range can be attributed to the unsaturated nature of amorphous cell [23,26]. The band at 3602–3619 cm^{-1} is attributed to C–H stretching vibrations [26] as the two bands are in the 2921–2853 cm^{-1} range and this helps to eliminate the presence of N–H and O–H groups. The strong peak at 2358.38–2358.36 cm^{-1} is probably due to Si–H stretch band (hydrogen passivation) in the silane group. The peak at 1643–1651 cm^{-1} is attributed to C=N bending bond. While the peak at 1689 cm^{-1} can be attributed to C=C, the bond is absent in the non-affected region. The strong peak in figure 5 at 1114 cm^{-1} is due to the C–O weak bond, which may be formed during the thermal decomposition process in the affected region.

3.2.2 Absorption spectra. The quantity of useful photon that gets to the intrinsic absorber layer depends on the absorption power of the device. There is a need for establishing the module absorbance characteristics because it is affected by hot-spot formation [16,22–27]. Figure 6 shows the absorbance spectra of both the affected and the non-affected regions. The thermal stress created by the hot spot can lead to the infiltration of metallic impurities (contaminant) of some spot in such a way that the internal resistance (series resistance) of the affected region will increase [25,28]. Metallic infiltration

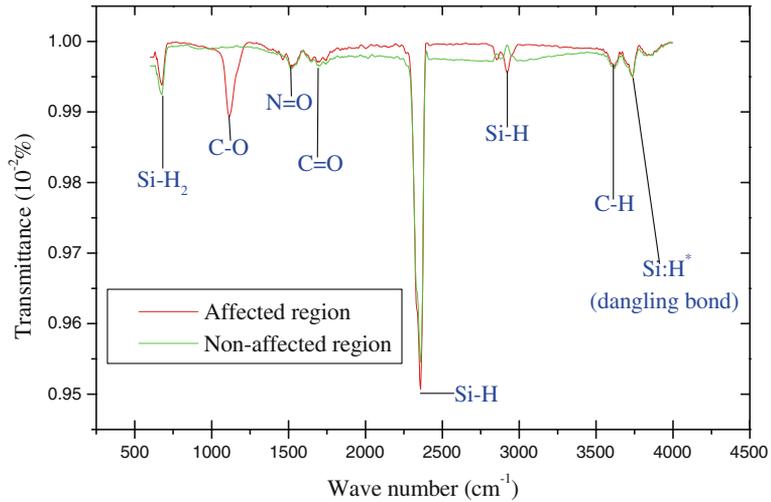


Figure 5. FTIR spectrum showing the transmittance analysis.

aids metallic diffusion, diffusion of hydrogen or any other metallic ion (as illustrated in figure 1) from the intrinsic layer reduces the shunt resistance. It is generally known that increase in shunt resistance decreases the photon absorption capability of a device [28,29]. This theory explains the rise in absorbance of the affected region around 720 cm^{-1} wavenumber, because only an insignificant spot in the affected region is affected by metallic infiltration [30–32]. The induced defect due to particle diffusion has the ability to upset the geometrical orientation of molecular bond [32], leading to an increase of the light trapping mechanism around 720 cm^{-1} location (for detail, see [33,34]).

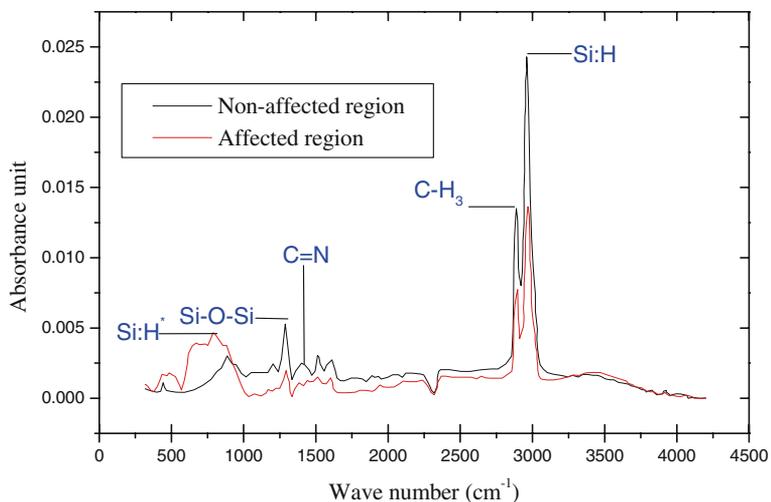


Figure 6. Absorbance of the affected and non-affected regions of the module.

In figure 6, there are two important absorption peaks. These peaks are in the ranges 2929–2852 and 1450–1021 cm^{-1} . For the non-affected region, the corresponding absorbance values are 0.022 and 0.0052 units. But for the affected region, the corresponding absorbance values are 0.012 and 0.0035 units. These bands absorbed lesser photons in the affected regions when compared to the non-affected regions, due to the decrease in the absorption coefficient. This decrease in the absorbent power is attributed to the absorbance degradation.

4. Conclusion

This report dealt with optical degradation analysis of a-Si:H. This demonstrates the effect of hot spot and optical degradation on the absorption capability of the PV module. The study examined the transmittance of both the affected and non-affected regions and showed a higher percentage of transmission from the affected region. The experiment also established the effect of hot-spot formation on the absorbance of the module. The absorbance of the module decreases from 0.023 to 0.013 a.u. (2929–2852 cm^{-1}), which translates to a 43.5% reduction in the absorption capability. This study, therefore demonstrated the effect of hot-spot formation on the absorption coefficient of the PV module. This is an interesting and profound finding because it demonstrates how optical density degradation affects the photogenerated current of the PV module.

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