IMAGING OF TCO LATERAL RESISTANCE EFFECTS IN THIN-FILM PV MODULES BY LOCK-IN THERMOGRAPHY AND ELECTROLUMINESCENCE TECHNIQUES

Archana Sinha[A], Martin Bliss[B], Xiaofeng Wu[B], Subinoy Roy[A], Ralph Gottschalg[B], Rajesh Gupta[A]*
[A]Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Mumbai – 400076, India
[B]Centre for Renewable Energy Systems Technology (CREST), Wolfon School Mechanical, Electronic and Manufacturing Engineering, Loughborough University, Loughborough LE113TU, UK
*Email: rajeshgupta@iitb.ac.in, Phone: (+91-22) 2576 7837

ABSTRACT: The lateral sheet resistance of transparent conductive oxide (TCO) electrode in thin-film photovoltaic (PV) modules is a major component of series resistance losses that causes significant reduction in the fill-factor and output power. This paper presents the investigation of TCO lateral resistance effects in the encapsulated thin-film modules by lock-in thermography (LIT) technique, which is predominantly used for shunt investigation in the solar cells. The LIT technique has been employed under both dark and illuminated conditions to compare their spatial sensitivity for imaging TCO resistance effects in a module. The LIT images have also been compared with electroluminescence (EL) images to find a correlation between localized heating and voltage drop across distributed TCO layer resistances, and to determine their advantages and limitations. Experimental results show that both, DLIT and ILIT, exhibit a gradient in thermal signal along the cell width due to variation in power dissipation across the lateral resistance of TCO electrode. However, ILIT appears to be more sensitive for imaging TCO resistance losses due to less junction masking effect. The spatial sensitivity also depends on the width of cell in a module. For narrower cells, DLIT and EL techniques are observed to be more sensitive near the higher potential edge of a cell as compared to ILIT. The study concludes that the LIT technique is also a potential candidate for providing the spatially-resolved characterization of TCO resistive losses in thin-film modules.
Keywords: transparent conductive oxide; lateral sheet resistance; thin-film; photovoltaic module; lock-in thermography; electroluminescence imaging

1 INTRODUCTION

Transparent conductive oxides (TCO) are widely used as a transparent front electrode in most of the thin-film technology photovoltaic (PV) modules due to high optical transmittance (~90%) and low electrical resistivity (~10^{-4} Ωcm). The sheet resistance of TCO material is a key parameter in determining the electrical performance of PV module since the current flows laterally in this layer, as illustrated in Fig. 1. The outdoor degradation of thin-film modules under the moisture and thermal stresses cause a gradual increase in TCO resistivity [1], that increases the overall series resistance of the module and thus a decrease in fill-factor and maximum power [2], [3]. In order to achieve the goal of higher energy yield and improved service lifetime, the TCO lateral resistance losses need to be investigated.

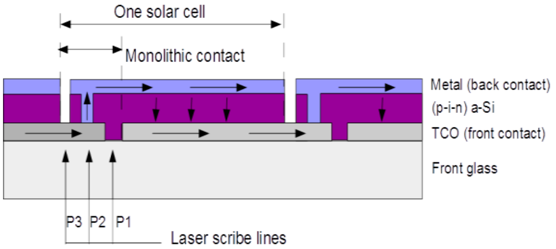

Figure 1: Structure and direction of current flow through the TCO layer of a-Si thin-film solar module

Initial measurements of TCO resistivity were performed by Four probe or Hall effect measurement [4], [5]. However, these methods are only applicable on standalone TCO thin-films. In case of a complete PV device, the camera based electroluminescence (EL) imaging technique has been used as a non-destructive characterization tool for the qualitative and quantitative analysis of TCO lateral resistance effect in coupled with the distributed electrical modelling and simulation approach [6]–[8]. However, EL measurements need a dark environment and higher integration time in thin-film devices for increasing the EL counts (particularly a-Si) [9]. Lock-in thermography (LIT) technique is another popular imaging technique, which characterizes any resistive losses that cause extra power dissipation in the cell. The built-in lock-in feature of this technique allows the detection of weak heat sources with improved spatial resolution by overcoming fast thermal diffusion of heat in the active layer (silicon) and packaging materials. LIT is predominately used for the detection, localization and classification of localized shunts in the c-Si solar cells [10], [11]. Some of the recent studies reported the application of LIT for the detection of processing induced defects or shunts in different thin-film technology modules [12]–[14]. However, it is less utilized to investigate TCO resistance losses. Further, the LIT at the module level is seldom done.

2 METHODOLOGY

In the present study, LIT technique has been employed under both dark and illuminated conditions for the investigation of TCO lateral resistance effects in thin-film PV modules. Dark lock-in thermography (DLIT) is the most common mode of LIT that detects the flow of externally applied current through the cell and enables to identify all the resistive paths contributing to the power losses. In illuminated lock-in thermography (ILIT), the power losses due to series resistance preferentially appear at short-circuit condition, while the dark saturation currents and recombination losses are best observed under open-circuit condition. In view to this, the ILIT investigation has been performed under short-circuit condition. In addition, the EL imaging technique has been utilized as a reference tool for comparison of results obtained from LIT technique, along with their advantages and limitations.

3 EXPERIMENTAL

The experiments were carried out on some single junction amorphous-Si mini-modules, having glass in the front side and a polymer material at the rear side. These modules contain different number of monolithically-connected cells. The electrical parameters of the samples were extracted from their illuminated I-V characteristic curves, which is given in Table 1. It shows that M-3 and M-4 samples have higher FF and efficiency than M-1.

Table 1: Electrical parameters of a-Si mini-modules

Sample	No. of cells	P_{max} (W)	J_{sc} (mA/cm^2)	Cell V_{oc} (V)	FF (%)	η (%)
M-1	1	0.14	10.4	0.90	33.4	3.4
M-3	3	0.12	13.5	0.88	49.9	6.8
M-9	9	0.14	10.7	0.87	53.9	6.0

The LIT investigation was performed by a Stirling-cooled IR camera, consisting of 320 × 256 pixels InSb detector with spectral sensitivity in the range of 3–5 µm. In DLIT, the module was excited by injecting a periodic forward electrical current equivalent to Isc, while in ILIT, the front surface of module under short-circuit condition was periodically irradiated with 850 W/m^2 ± 5%, using 625 nm wavelength (red light) LED source. The temperature modulation was measured at the module rear surface by IR camera. A controller was used to synchronize the power supply excitation with the frames of IR camera to implement lock-in algorithm over the captured images. The lock-in frequency was fixed at 0.5 Hz to assist deeper probing as lock-in frequency is inversely proportional to thermal diffusion length. The thermal images of module were captured at 150 Hz for 200 s. A larger integration time improves the signal-to-noise ratio of the captured images due to reduction in thermal noise level, which is facilitated by averaging over more number of cycles.

The EL imaging was carried out by 1024 x 1024 pixels Si-CCD cooled camera in a dark enclosure. A constant forward current (Isc) was applied into the module and the luminescence radiation was captured through the front glass by EL camera. The integration time was kept 5 mins to increase the EL emission counts from the sample. The image quality was further improved by employing the image subtraction on the EL images of module with and without excitation that reduces the bad pixels of camera and background noise.

4 RESULTS AND DISCUSSION

The DLIT and Jsc-ILIT techniques have been exploited for investigation of TCO sheet resistance effect by correlating it with the extent of power dissipation in the cell. Fig. 2(a) presents the DLIT image and line profile of M-3 mini-module, which shows a characteristic gradient of thermal signal along the cell width (x-direction) with almost no change in signal along the cell length (y-direction). This lateral gradient appears due to the variation in power dissipation along the cell width. The magnitude of lateral external current flow is higher at the injection edge of cell, which decreases as approaching the collection edge of cell due to lateral sheet resistance of TCO layer and back contact, as illustrated in Fig. 3(a). As a result, the power dissipation is higher near positive terminal compared to negative terminal of cell and creates a thermal signal gradient along the cell width. The thermal gradient shows good correspondence to the gradient pattern visible in EL image of same mini-module, as shown in Fig. 2(c) [15]. In this case, the injected current from positive terminal introduces more minority carrier density that causes high radiative recombination at this end and hence high EL intensity. As the position moves towards the other end, the current distribution in the junction changes because of voltage drop across TCO sheet resistance that decreases EL signal.

Fig. 2(b) presents the Jsc-ILIT image and line profile of same mini-module. It also exhibits similar pattern across the cell width, besides little higher thermal signal at the upper edge which is attributed due to small non-uniformity in illumination along the cell length. In this case, almost uniform current generation takes place in the entire module that flows towards the higher potential side of cell and causes increase in the power dissipation at that end, as represented in Fig. 3(b). An interesting observation is found that the decline of thermal signal in Jsc-ILIT is slower than in DLIT. It is because DLIT injects power into the device that is also lost through the junction as heat, while in ILIT, the energy produced can exit the device that is dissipated at short-circuit point and not in the junction, which infers that the lateral gradient is mainly due to TCO losses in ILIT than in DLIT. This suggests that ILIT technique is more appropriate for investigating TCO lateral resistance effects in a PV module as compared to DLIT.

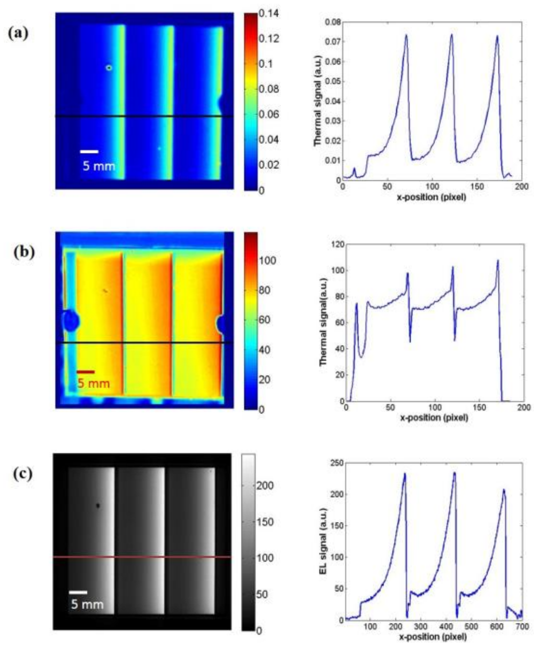

Figure 2: Spatial images and line scan from: (a) DLIT; (b) Jsc-ILIT; (c) EL of M-3 mini-module

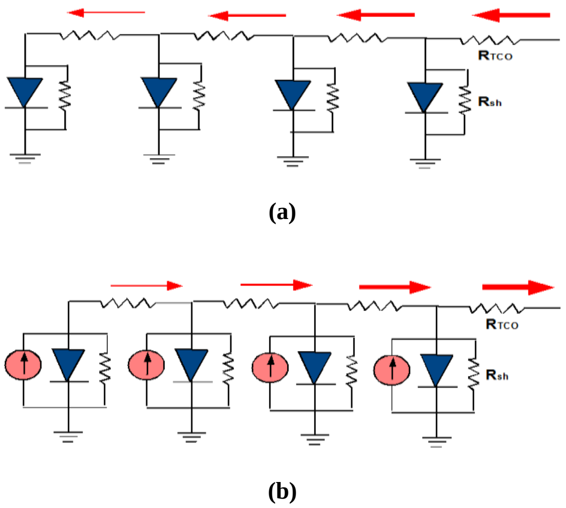

Figure 3: Schematic of distributed circuit of a solar cell indicating the current flow in TCO layer of thin-film module under (a) dark and (b) illumination

The lateral dimension of cell controls the current transport in the module and hence the resistance losses. In order to investigate the effects of cell width on the TCO lateral resistance, both LIT and EL experiments were performed on two other mini-modules of varying cell width. Fig. 4(a)-(c) and Fig. 5(a)-(c) show DLIT, ILIT and EL images of M-1 and M-9 mini-modules respectively. The gradient due to lateral sheet resistance of TCO layer in a wider cell (M-1 sample) is following trend similar to an exponential decay due to logarithmic behavior of junction current to the voltage. In narrower cells (M-9 sample), the gradient appears to be more linear. It is because the resistive path is shorter in a narrower cell, which reduces the voltage shift and makes the current distribution more even. The intensity of EL signal depends on the voltage at that point and the current through the junction. In DLIT, similar effect occurs but the power dissipation is seen from the non-radiative recombination which ends up as heat and I^2R losses through TCO layer; whereas in ILIT, the heating contribution comes from non-radiative recombination at the junction, I^2R losses through TCO layer and the absorbed light energy that can't be converted to current generation. This observation is again in agreement with EL images. By comparing all the images and line profiles, ILIT appears to be more sensitive to the variation of TCO sheet resistance compared to EL and DLIT because of less junction masking. Further, in the case of wider cells, DLIT and EL loses the characterization capability of TCO losses as the output signals get almost saturated.

Also, M-9 mini-module contains some point defects, which are identified as shunts due to increased local heating in the DLIT image. These strong shunts decrease the lateral gradient pattern in both DLIT and EL images since they sink current from surrounding reduce the current flow in lateral direction, resulting in reduced power dissipation and EL emission respectively. The shunting effect is not visible in Jsc-ILIT image because the generated photocurrent flows through the external circuit and bypasses the local leakage paths.

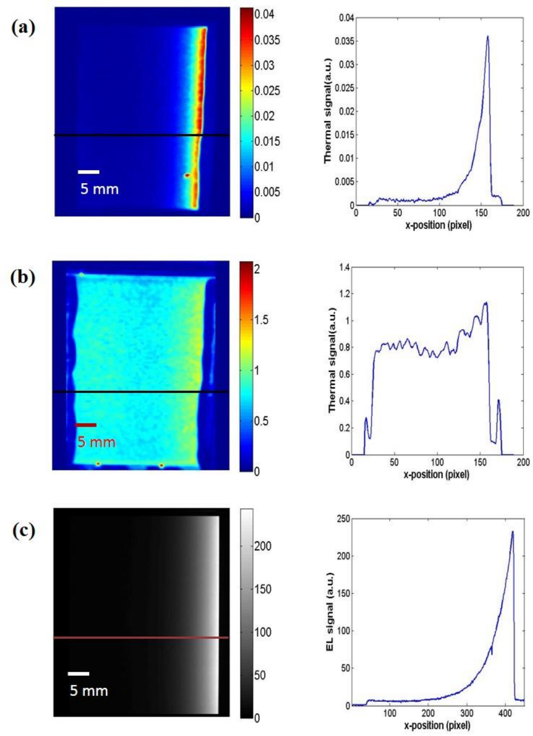

Figure 4: Spatial images along with line scan of M-1 module from (a) DLIT, (b) Jsc-ILIT, and (c) EL.

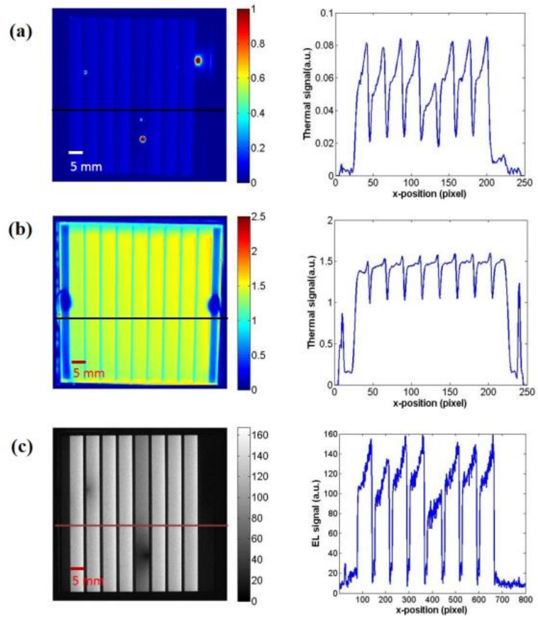

Figure 5: Spatial images along with line scan of M-9 mini-module from (a) DLIT, (b) Jsc-ILIT, and (c) EL.

The results exemplified that LIT method can also be used for investigating the sheet resistance problems of TCO electrode that is detrimental to the health and lifetime of thin-film modules. Although the magnitude and spatial resolution of thermal signal get affected by the encapsulant materials and surrounding conditions, LIT can serve as a diagnostic tool for qualitative investigation of distributed resistive losses in thin-film modules. The quantitative analysis of TCO losses by this technique will be done in future research and is outside the scope of present work.

5 CONCLUSIONS

This paper presents the application of LIT technique under dark and illuminated modes for the electrical investigation of sheet resistance losses in TCO contact layer of thin-film modules. A lateral gradient of thermal signal along the cell width was observed, which can be used to determine the variation in TCO sheet resistance. The gradient pattern observed in DLIT and ILIT images was found to be in close resemblance with that in EL image; however, each technique exhibited different spatial sensitivity for investigation of TCO lateral resistance effect in the module. It is inferred from the study that ILIT was more sensitive near the higher potential edge of cell to the variation of TCO sheet resistance as compared to EL and DLIT methods, particularly for wider cells. Also, this lateral gradient pattern was influenced by presence of strong shunts in a cell that causes significant voltage drop. The study shows that LIT has potential for extending its capability for spatially-resolved characterization of TCO resistance variation in the thin-film modules.

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