UV FLUORESCENCE IMAGING OF DEFECTS AND BILL OF MATERIALS VARIATIONS IN BIFACIAL SOLAR PANELS

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ABSTRACT: UV Fluorescence (UVF) is a high-throughput, non-contact method of imaging defects and bill of material variations in solar panels. Cracks in silicon solar cells are easily seen by this technique since oxygen can diffuse through polymer backsheets, through the cracks in the cells, and then quench the fluorescence in the front encapsulant above the crack lines. Most of the reported data on UVF imaging in the literature shows images of panels with polymeric backsheets, but bifacial panels with rear glass layers are steadily taking market share, and oxygen cannot penetrate the rear glass in such panels except through the junction box penetrations and the perimeter edges. We therefore ask the question, “Does UVF have a useful role in imaging glass/glass panels?” Here we present data from several different glass/glass bifacial panels installed in desert climate (Qatar), showing effective UVF imaging of varying levels of oxygen ingress from the frame edges, varying oxygen ingress from the junction box penetrations, encapsulant bill of materials variations, hot spots, and cell cracks. We therefore conclude that a use case does exist for UVF in at least certain glass/glass solar panel models.

Keywords: UV Fluorescence, Characterization, Defects

1 INTRODUCTION

UV Fluorescence (UVF) is a powerful imaging technology for revealing defects and bill of materials variations in solar panels [1-5]. In this technique, the panels are illuminated with UV light in the dark, and the encapsulant and/or polymer backsheet fluoresce in the visible spectrum. The longer the field exposure or environmental chamber exposure, the stronger the encapsulant will fluoresce. The benefits of the technique include its non-contact and high throughput nature, adaptability to drone imaging, and ability to see a wide range of defects. Such defects include 1) solar cell cracks, 2) edge and junction box sealing failures, 3) hot spots (regions that had run hot during the panel lifetime), 4) cracked glass, and 5) gridline corrosion. Bill of materials (BOM) variations in the panel construction that can be seen directly or indirectly include: 1) encapsulant, 2) polymer backsheet, and 3) metallization paste. An important mechanism for seeing some of these defects involves the diffusion of oxygen into the panel to quench the fluorescence of the encapsulant. In panels with polymer backsheets, the oxygen can diffuse into the panel continuously over the entire back surface. In the case of detecting cracked solar cells, the oxygen can diffuse through the cracks and then spread laterally a few mm’s to either side of the crack lines to create a vivid image of the crack locations as dark lines against a brighter background.

Over the last several years, the market share of bifacial panels has steadily grown due to the importance of gains in energy delivery. A majority of these bifacial panels use rear glass layers rather than transparent polymer backsheets. Oxygen cannot penetrate the rear glass in such panels except through the junction box penetrations and the perimeter edges, and thus any defect imaging that relies on oxygen quenching may be less effective with such panels as compared to polymer backsheet panels. We therefore ask the question, “Does UVF have a useful role in imaging glass/glass panels?”

The literature mentions only a few examples of glass/glass UVF imaging. Koentges showed an example of ring pattern fluorescence in a panel that incorporated a metal foil oxygen barrier on the rear side, and showed an example of a cell crack which fluoresced brightly due to fluorophores diffusing through the crack from the back encapsulant [2]. Although this panel did not use rear glass, the use of a similar oxygen barrier suggests that bright crack lines might be visible in glass/glass panels for certain bill of material combinations. Sinha showed ring pattern fluorescence in glass/glass modules indicating that fluorophores could migrate though the gaps between cells from a rear encapsulant rich in fluorophores to the front encapsulant with a low fluorophore concentration, but no defects were found in this case [3]. Gilleland showed the quenching of fluorescence near the short edges of a glass/glass panel as is shown below in Figure 1, which may indicate greater diffusion of oxygen through the edge seals on the short edges of that panel type than the long edges [4]. Although not explicitly mentioned in their paper, there is observable darkening near several interconnect wires which could be due to quenching from oxygen diffusing through cell cracks commonly found by the interconnect wires. Most recently, Buerhop showed small bright spots in UVF images over interconnect wire locations where intense resistive heating was taking place in panels with cracked glass [5].

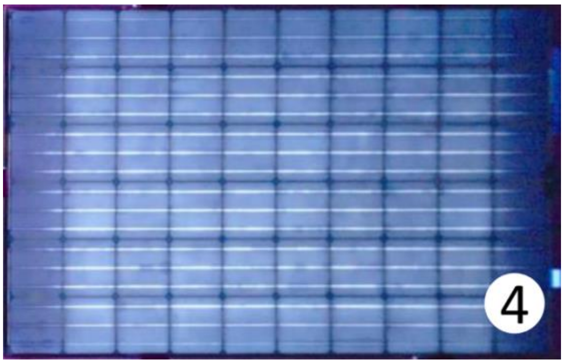

Fig. 1: Taken from [4]. UVF image of a glass/glass panel with oxygen quenching near the short ends and apparently by some interconnect wires.

In order to add to the body of literature on UVF imaging of glass/glass panels, we imaged several different glass/glass panel models installed at the QEERI outdoor test facility in Qatar.

2 UVF IMAGING METHOD

The panels imaged were installed outside for varying amounts of time at the Qatar Environment and Energy Research Institute (QEERI) OTF Outdoor Testing Facility at GPS coordinates 25.326661, 51.432340. Most panels were installed on single axis trackers.

The hardware used for imaging was a **UVF-Spot**™ system from BrightSpot Automation [6]. The system components included a broadband flash head with filters to allow only the UV light to be transmitted, a full-frame sensor consumer camera with a UV cut filter and a 28mm lens, a tall monopod to elevate the camera and flash above the panels for frontside imaging, a remote eyelevel display to see the captured UVF images or the field of view of the camera prior to imaging, and a remote trigger to focus and capture images.

For panels that were imaged outdoors, the images were all taken at least 45 minutes after sundown to reduce noise light effects. An initial image was captured for each panel type, and then the camera gain was adjusted to give good brightness for that panel type. The f-stop of the camera was kept constant at 2.0. The field of view of the camera varied but was generally at least as wide as the panel under test. The monopod pole was employed for imaging the front side of some panels, but in a few cases, the camera was removed from the pole for rear-side imaging underneath the racking.

No post processing was performed for any of the images presented here, but in general, post processing can be valuable to allow certain defects to appear more clearly or to remove perspective distortion. Images shown below are cropped to show the regions of interest.

In addition to the UVF data, in some cases the Performance Ratio (PR) of the panels was measured where PR is defined as the Pmax measured indoors with an IV flash tester divided by the nameplate Pmax value.

3 UVF IMAGES AND COMPLEMENTARY DATA

Panels displaying different types of UVF signatures are grouped into the following subsections.

3.1 Bill of Materials Variations

Figure 2 shows UVF images of two Heterojunction (HJT) panels with identical model numbers but which show the incorporation of a different front encapsulant layer. The panel on the left has a front encapsulant which fluoresces strongly and where oxygen is apparently diffusing inward both from the panel edges as well as from the gaps between the cells to produce a darker ring around each cell where the fluorophores are partially quenched. It is unclear why oxygen diffuses so uniformly through these gap regions when the source of the oxygen is presumably only from the perimeter of the panels. In contrast, the panel on the right displays ring pattern fluorescence, where the front encapsulant did not incorporate UV absorbing additives, but where fluorophores from the rear encapsulant are diffusing through the gaps and across the surface of the cells. In both cases, oxygen has diffused in from each long edge up to the first interconnect wire to produce a dark band along each long edge. It is unclear whether the abrupt ending of oxygen quenching at the first interconnect wire is a coincidence, or whether perhaps the thinner region of encapsulant between the glass and wire reduces the inward diffusion of the oxygen. If the kinetics of oxygen diffusion can indeed be affected in this manner, perhaps this effect could be intentionally designed into oxygen and moisture sensitive panels.

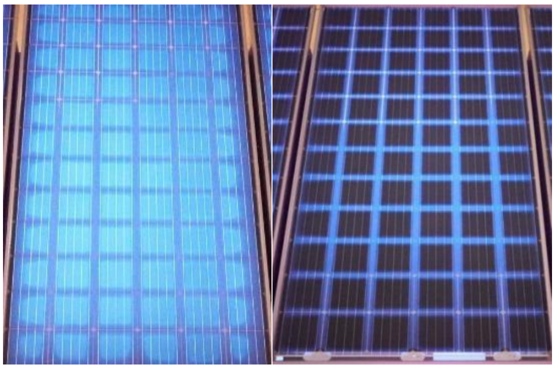

Fig. 2: UVF images showing BOM variations in the front encapsulant layer for the same model number of HJT panels installed in 2020. PR = 92.7%.

3.2 Sealing Failures

Figure 3a shows a UVF image taken from the back side a different HJT panel type where oxygen is diffusing inward from both the edge perimeter regions as well as through the 3 junction box penetrations. It is interesting to note that the diffusion front from each long edge shows that oxygen appears to have diffused inward faster over the middle regions of the cells. In contrast, the UVF image taken from the front side in Figure 3b shows the oxygen diffusing inward more strongly from the gaps between cells, but overall that the quenched regions reach less far inward than on the backside, perhaps due to the differences in UV additives within the encapsulant layers or the different UV aging doses experienced on the front and back sides. Also, there are some scattered dark spots seen on the rear side that are unexplained. It is possible that these correspond to cell crack locations, but it is not clear why enhanced oxygen diffusion would take place from the front side.

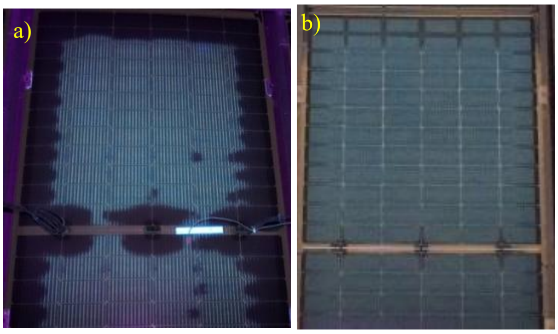

Fig. 3: a) UVF image from the rear side of a HJT panel showing oxygen diffusing through holes in the glass for junction box penetrations, varying degrees of oxygen diffusion from the perimeter, and a few unexplained dark spots; b) UVF image from the front side of a panel of the same model. Panels installed in 2020. PR = 94.7%

Fig. 4 shows another example of strong rear side fluorescence where oxygen is seen diffusing inward from the perimeter in a PERC panel. In contrast with the panel shown in Figure 3, there the diffusion appears to be occurring more rapidly in the gaps between cells. Also, here the sealing around the junction box penetrations appears to be more effective.

Fig. 4: UVF image from the rear side of a PERC panel showing oxygen diffusing inward from the perimeter. Panels installed in 2018.

We also collected UVF images from thin-film CIGS panels. Although these panels were not of a bifacial design, these data points have high importance in evaluating the potential for UVF in imaging thin-film panel defects. Figure 5 shows the UVF image of panels where the CIGS is deposited on the rear glass in a substrate type configuration and the encapsulant between the CIGS and the top glass is fluorescing brightly. Each panel displays some degree of sealing problems on the edges, but in 3 of the panels, there are large dark regions emanating from an edge which incur deeply into the panel central regions. In some cases narrow dark lines extend down the length of the scribed cells. It is not clear why oxygen can diffuse down the length of a cell, but perhaps the scribing process in some cases leaves channels that are not fully filled with encapsulant or where delamination is occurring. These correspond to white regions by eye. Each panel also displays some large brighter regions that can be seen by eye as light brown spots where perhaps hot spot heating has occurred.

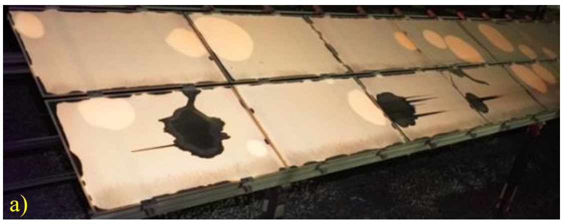

Fig. 5: UVF image of CIGS panels showing likely sealing failures and possible delamination (dark spots) and bright regions where possible hot spot heating has occured. Panels installed in 2015.

3.3 Cracked Cells

Figure 6 shows a UVF image of a TOPCon panel with ring pattern fluorescence where variations in the ring pattern likely correlate to cell crack locations. Most cracks appear to be near interconnect wire locations where the oxygen quenching leads to dips in the outer perimeter of the rings near the wire locations. In a few examples, diagonal cracks show bright lines in the center of the cells where fluorophores are diffusing through the cracks from the rear encapsulant and where oxygen has not diffused in from the cell perimeter to quench that fluorescence.

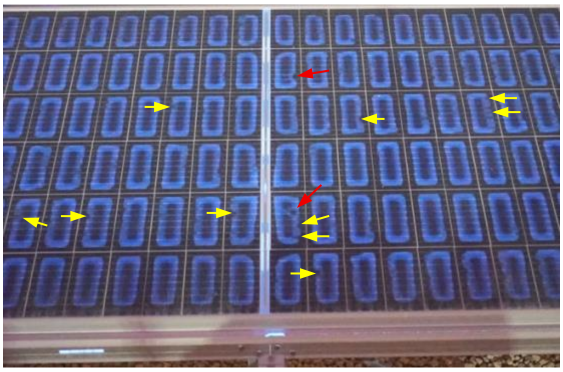

Fig. 6: UVF image of a TOPCon panel where breaks and variations in the ring patterns likely correspond to cell cracks. Yellow arrows show cracks that may lie underneath busbars, while red arrows show cracks that propagate between busbars. Panels installed in 2022 at a fixed tilt southward of 22 degrees. PR = 96.0%.

3.4 Hot Spots

Figure 7 shows a UVF image of a PERC panel with no visible fluorescence anywhere except near the junction boxes and the perimeter frame. We assume the fluorescence has evolved preferentially in these locations due to resistive heating in the junction boxes and due to regions near the frame running hotter than elsewhere. The competing kinetics of fluorescence activation from heat and fluorescence quenching from oxygen diffusion through glass penetrations and edges give rise to complex patterns.

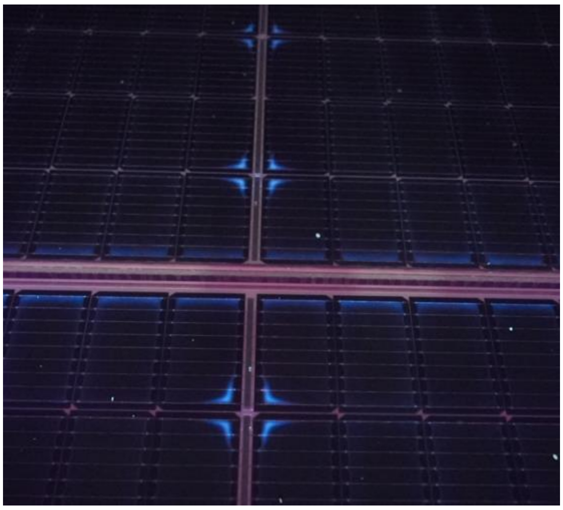

Fig. 7: UVF image showing the effect of hotter regions near the junction boxes and the perimeter of a PERC solar panel. The competing kinetics of fluorescence activation from heat and fluorescence quenching from oxygen diffusion through glass penetrations and edges give rise to complex patterns. Panels installed in 2018.

Figure 8a shows frameless PERT panels where some clamping positions where shifted after some years of operation and where there may be local heating near the clamp positions. The regions around both the old and new clamping positions shows visible browning above the white regions at the perimeter of the panels. The glass surface was manually scrubbed to verify that the discoloration was not due to residue on the top surface of the glass. Possible causes of the discoloration are due to hotter internal panel temperature under the clamp positions or diffusion of some chemical species from the polymer used in the clamps. Figures 8b and 8c show UVF images of the panels where the browned regions fluoresce strongly but where there is little other fluorescence in the panel. The fluorescence appears quite strong over the cell regions close to the clamps, and it is possible that the strong fluorescence correlates to hot spot regions.

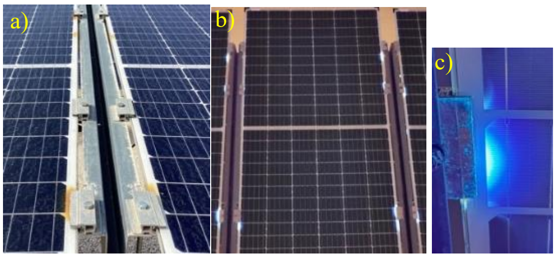

Fig. 8: a) RGB image of frameless PERT panels where some clamp positions had been shifted after some years of field operation; b) a UVF image of the same panels, and c) a closeup UVF image near a clamp position. Panels were installed in 2020.

Finally, we show in Figure 9 a UVF image of the rear side of a Series 4, First Solar CdTe panel installed for >10 years in Ohio. Strong fluorescence is seen along both edges of the bussing wire near the edge of panel. We assume that some local heating had occurred in this location, but do not understand the origin of the heating or the reliability/performance impacts.

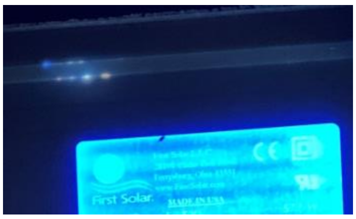

Fig. 9: a) UVF image of the rear side of a Series 4 First Solar panel showing strong fluorescence along a bussing wire, potentially due to local heating (poor TCO connection?).

4 DISCUSSION

As a field testing technique, UVF suffers from its high dependency on bill of materials, panel design, installation location, and panel history. Encapsulants that have no UV absorbing additives do not fluoresce unless fluorophores diffuse from other layers. When fluorophores are present, it can take years of field exposure for sufficiently strong fluorescence to evolve. Oxygen diffusion barriers such as rear glass can reduce the effectiveness of seeing cracked cells. However, the strengths of UVF lie in its high throughput, non-contact nature, and ability to image problems not otherwise seen by EL and thermal IR imaging. The data presented above demonstrate that even for the most challenging cases of relatively new glass/glass panels, useful defect imaging can occur.

Despite the rear glass acting as an oxygen diffusion barrier, the diffusion of oxygen from panel edges and junction box penetration still occurs in glass/glass panels, as does the diffusion of oxygen from the rear encapsulant layer to the front encapsulant layer both in the gaps between cells as well as through cracks in the cells. For most silicon based panels, such sealing failures may not represent a significant durability problem, and in the context of UVF imaging, may present an opportunity for more informative imaging of other defect types where oxygen ingress has occurred. However, in more sensitive thin-film panels such as those based on Perovskites, such sealing failures may be catastrophic, and their detection critical. Our observation here of oxygen possibly diffusing preferentially down the scribe lines of the monolithically integrated thin film cells points to a potential problem deserving attention.

While the successful imaging here of the superstrate type CIGS thin-film panels is promising for UVF imaging of thin-film panels, we note that the vast majority of monolithically integrated thin-film panel produced to date (CdTe panels from First Solar) are of the superstrate variety with no encapsulant to image from the front side except in the narrow regions between scribe lines. The emerging field of Perovskite PV is of varied designs with most monolithically integrated panels having a superstrate front cell, while the Perovskite on Si-wafer designs are more promising for front-side UVF imaging with encapsulant between the cells and the front glass. Our finding here of successful UVF imaging from the rear side may find application in superstrate type thin-film panels depending on their bill of materials. While high throughput UVF imaging by pole-mounted or drone-mounted camera imaging may not obviously be applicable to rear-side imaging, such rear side imaging may still be conveniently performed by systems that are hand held or mounted to vehicles, robots, and even drones, especially for tracker systems that could be tilted to nearly vertical for better access to the rear side.

The overall trend over the last decade for glass/glass panels of using encapsulants with no UV absorbers bodes poorly for universal application of UVF to such panels, but our findings here give promise that for some significant number of GWs of panels, UVF will find useful applications. In particular, based on our finding here in Figures 7, 8, and 9 and in Buerhop's investigations [5], the imaging of hot spots may be effectively performed even in panels with no fluorescence elsewhere in the panel. Operations and Maintenance groups and field testing companies can use UV flashlights to assess any site for UVF imaging potential, and then where applicable follow up with high throughput imaging tools [6].

A summary of the different panel problems that may be visible with UVF imaging in glass/glass panels is shown in Table I with very rough estimates of the probability that UVF can see the problem and amount of field exposure time needed for the fluorescence to be strong enough to image the problem.

Table I. UVF effectiveness for defects in glass/glass panels

Problem	UVF Imaging Probability	Field exposure time needed
Encapsulant BoM variation	High	0-3 yrs
Local heating	High	0-1 yrs
Sealing failures	Med	2-5 yrs
Cracked Cells	Low	2-5 yrs

5 CONCLUSIONS

Despite the relatively few examples in the literature of UVF being used to characterize glass/glass solar panels, we have found multiple examples of useful applications over a range of different PV technologies in panels fielded for 5-10 years. We demonstrated detection of 1) front encapsulant bill of material variation between panels of the same model number, 2) sealing failure at the panel perimeter edges and at the junction box penetrations, 3) possible hot spot heating near junction boxes, frames, clamping positions, and 4) cell cracking. We also demonstrated useful imaging of the rear side for three panel types.

The emerging technology of Perovskite solar cells is particularly sensitive to sealing failures, and the ability of UVF to image such failures from either the front or rear sides could be helpful for both product development after chamber testing and for field testing.

6 REFERENCES

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