Low-cost Defect Detection of Solar Cells by Electroluminescence Imaging

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I declare that, apart from properly referenced quotations and citations, this thesis is my own work and complies with Murdoch University’s academic integrity commitments.

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Abstract

Solar panels experience a reduction in efficiency as they age due to the variable physical conditions they are exposed to throughout their lifetime, transport and installation. This exposure, due to a combination of effects such as thermal cycling and moisture, can cause a number of defects in the panels, including: cracks in, and non-uniform degradation of, the photoactive material; breakages in the current collectors; and contact finger interruptions (Mansouri 2012, Spertino, Ciocia et al. 2015).

It is therefore of great interest to detect and monitor this degradation process in order to be able to determine with greater precision, the total lifetime of the cells, as the trend of cell cost as a fraction of the module cost declines (Blakers 2015).

Several technologies exist to assess the degradation of solar panel, I-V curves, lock-in-thermography imaging and its derivatives and electroluminescence (EL) imaging. I-V curves are generated by flashing the panel with light and recording the power output that results. Lock-in-thermography looks at the heat generated by the panel and those areas that are defective, such as local short circuits, that dissipate onto the module some of the power generated (Breitenstein, Bauer et al. 2007).
EL works by reversing the role of the panel by putting power through it and making it behave as a light emitting diode instead of a photodiode (Petraglia and Nardone 2011). A typical EL setup is shown in Figure 1.1. The power is supplied by a current source (A) and Norton Resistance (B) to the solar panel (photodiode, C). The camera (D), operates on an independent circuit.

**Figure 1.1: Typical EL setup**

EL imaging, while an effective method of fault detection, is expensive due in part to the camera sensor technologies used, such as thermally stabilised charge coupled devices (CCD) and Indium-Gallium-Arsenide sensors (Petraglia and Nardone 2011, Parlevliet 2016).

This thesis presents a low cost apparatus for EL imaging of standard silicon solar panels and the image post processing techniques necessary to interpret the panel defects.
Background

Solar Cell Defects & Degradation

Solar cells degrade because of their exposure to the variable physical and chemical components of the environment in which they operate and during transport. Expansions and contractions during thermal cycling are a major cause of post installation defects. It induces the induction of cracks that enable further degradation by exposing the insides of the panel to moisture and other chemical effects leading to corrosion of the active material. Hail and other physical stresses can cause similar patterns of degradation because hey too cause cracks. Cracks due to improper handling in transportation and installation also account for a large proportion of cracks (Spertino, Ciocia et al. 2015) further exacerbating the degradation process.

For the commercial testing of EL testing apparatus, faults in the solar panels is typically induced either via the application of a high mechanical load (Mansouri 2012) and/or thermal stresses, rather than using pre-weathered panels so as to more easily correlate the defects. However we used pre-weathered panels due to their availability.

Principles of Electroluminescence

Electroluminescence occurs when the voltage drop over the panel approaches the open circuit voltage (Voc) of the panel and recombination occurs across the
p-n junction (Mansouri 2012), giving off light of the same spectrum as the panel absorbs. This light correlates to the function of the panel and can be detected by cameras sensitive to that spectrum. The resulting images can then be used to measure the function of the panel. For Silicon panels this is in the 950-1300 nm range (Petraglia and Nardone 2011). As the EL effect starts when the forward voltage drop across the panel is equal to the Voc, the supply voltage must be greater (a value of 130% Voc is suggested (Mansouri 2012)) to overcome the internal resistance of the power supply, which is dependant on the power supply used. Smaller power supplies used for small modules require minimal, if any, compensation.

The light emitted from the solar cell falls on to a sensor and an image is constructed from the data, with a region high brightness corresponding to high emission and a region of low intensity corresponding to a region of low emission. The emission levels in turn are correlated directly to the level of photo-activity of the cell. As a result of this principle, EL imaging is able to detect a wide variety of defects that occur as a result of weather exposure as well as induced defects like physical stress and thermal cycling, popular in research.

**Electroluminescence Imaging**

To be usable for EL a camera sensor must have some overlap in its absorption spectrum with the emission spectrum of the panel to be imaged, the greater the overlap the brighter the image will be. For silicon panels this requirement rules out the use of standard light photographic cameras (Petraglia and Nardone 2011), because they include an infrared blocking filter to reduce IR blur and
silicon cells emit most strongly in the near IR (NIR) region (figure 1.2). Cameras that are deliberately sensitive to the NIR, cameras that have had their IR filter removed and cameras with specially designed sensors are therefore potential candidates for EL work.

![Absorption & Emission spectra of Sensor and Panel types](chart.jpg)

**Figure 2.1: Absorption & Emission spectra of Sensor and Panel types (Parlevliet 2016).**

There are several adjustable or selectable parameters of a camera that are applicable in EL imaging and used to combat low signal amplitude, namely the exposure time, focal ratio (f-stop) and sensitivity (ISO).
Increasing the exposure time allows more light to hit the sensor resulting in increased detail in low light conditions. This tactic does have an upper limit beyond which the image will become whitewashed. Mansouri (2012) suggests that exposure does have a point of diminishing returns, but Petraglia and Nardone (2011) recommend “very long exposures”. Long exposures also increase the total time the panel spends dissipating power and therefore may necessitate allowing the panel to cool down before imaging again.

Use of a wide aperture (low f), will allow the camera to gather more light and get a brighter image; however focusing the camera by adjusting the distance to the panel will be required. This in turn affects the area able to be imaged (Petraglia and Nardone 2011, Mansouri 2012). However, not all cameras have an adjustable aperture.

The camera’s ISO should be set as high as possible without inducing too much noise, so as to maximise the brightness of the image. Some of the noise can be removed with the use of image processing tools like Photoshop or GIMP (Petraglia and Nardone 2011).

Thus the ideal sensor has a high overlap with the emission spectra of the types of panels to be imaged and is capable of long exposures with a high ISO and a wide aperture.
**Operating conditions**

Apart from the initial transition from not emitting to emitting, which exhibits nonlinear transitional behaviour, the relation between electroluminance and current, and therefore power, is linear.

While increasing the delivered current will result in a brighter image, care must be taken to avoid supplying too much power for too long, as overheating of the solar cell may occur posing a personal thermal safety risk and possibly further irreparable damage to the cell (Petraglia and Nardone 2011) as well as distorted images (Mansouri 2012). This risk is further exacerbated by the use of programmable power supplies, where it is possible to set the voltage or current. The supply is expected to power panels that have degraded i.e. where the actual values of the Voc and short circuit current (Isc) may vary significantly from their nominal values and therefore the knee of the IV curve may be in a different place. Misjudging the value of Voc could risk an unknown amount of power delivery to the panel. Controlling power by monitoring the current therefore provides a much finer control of power \( P \propto i \cdot \log(i) \) instead of \( P \propto v \cdot a^v \) for some \( a \), where \( a \) is function of the diode parameters) and limits the current to a threshold that ensure safe operation of the equipment.

EL is typically conducted in as dark an environment as possible to increase the signal to noise ratio (SNR) of the resulting image, as the panels do not give off a large signal amplitude and so it is easily lost if there is external interference (Petraglia and Nardone 2011).
Advantages of Electroluminescence

Electroluminescence imaging produces images that correlate directly to the function of the panel, so that apart from enhancing the image to increase the brightness, there is no further interpretation of the image required to determine where the panel is functioning. As expected brightness correlates to function, and panel area loss of function to power loss (Mansouri 2012). Some inference may be needed to determine the cause of the power loss, but assessing the function is simple. As such EL can detect a wide range of defects and their effects on the power loss can be estimated by eye.

Disadvantages of Electroluminescence

Due to the exotic nature of the sensors used, the cost of equipment for EL imaging can be significant (Petraglia and Nardone 2011). The use of cheaper sensors comes at the cost of less spectral overlap between the camera and the cell and can make the sensitivity of the camera a primary concern. This loss of sensitivity also greatly increases the susceptibility of the image to interference from external light sources.

The requirement to provide the panels with power necessitates the use of large power supplies in order to image large panels or strings of panels. This adds further to the issue of cost and has safety implications for the operation of panels where the Voc and Isc are unknown.

Low Cost Electroluminescence

The choice of sensors when money is limited is severely restricted, as commercial solutions cost tens of thousands of euros (Petraglia and Nardone 2011).
However as long as there is an overlap between the absorption spectrum of the camera and emission spectrum of the panel, EL can work.

The use of optical filters may be used to improve the image signal-to-noise ratio (Köntges, Siebert et al. 2009), however it may reduce the signal by an unacceptable amount.

To compensate for the low brightness of the images, various image post process techniques may be applied to overcome brightness and noise related issues (Petraglia and Nardone 2011).
Aim

The aims of this thesis are to:

• Build a self-contained, low-cost EL imaging apparatus capable of imaging standard commercial solar panels, utilising cheap commercially available equipment where possible. The apparatus should be simple, intuitive and safe for the end user to operate. Additionally it is desired to be light and able to be operated wirelessly to ease use for field operation.

• Use the apparatus to image and diagnose defects in a variety of solar panels. Verify and document the operation of the apparatus and any image post processing techniques used.

• Evaluate the effectiveness, measured as the scope, quality and confidence of diagnoses, of the process using the apparatus.

• Investigate the commercial viability of the apparatus.
**Materials**

Table 4.1: Bill of materials.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Cost</th>
<th>Percent of total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller (μC)</td>
<td>Raspberry Pi (3B+)</td>
<td>$139</td>
<td>1.65%</td>
</tr>
<tr>
<td>Camera</td>
<td>Raspberry Pi NoIR (IR sensitive), 8MP</td>
<td>$41</td>
<td>0.5%</td>
</tr>
<tr>
<td>Case</td>
<td>3D printed plastic</td>
<td>Made in house</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μC information cable</td>
<td>Cat5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μC power cable</td>
<td>USB A to micro USB</td>
<td>$20</td>
<td>0.24%</td>
</tr>
<tr>
<td>Power supplies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>Aglient 6692A (0-60V, 0-110A) DC</td>
<td>Retail price ~$8000</td>
<td>94.9%</td>
</tr>
<tr>
<td>Infrared optical filters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000nm long pass</td>
<td>Hoya RM100</td>
<td>$95 (incl. ship.)</td>
<td>1.13%</td>
</tr>
<tr>
<td>1000nm -10nm FWHM band pass</td>
<td>Edmund Optics</td>
<td>$135.50</td>
<td>1.61%</td>
</tr>
<tr>
<td>Power cables and screw terminals</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen in table 4.1 the microcontroller used is the Raspberry Pi 3B+ because it is cheap, readily available and has camera add-ons available and its
processor, an ARM cortex-A53, is widely supported by familiar libraries and frameworks.

The camera chosen is the RaspberryPi NoIR, the standard camera add-on for the RaspberryPi with the infrared short pass filter removed. It was chosen because there were no modifications required for the camera to detect the near infrared, the portion of the spectrum measured by electroluminescence. Like the RaspberryPi, it is also cheap and readily available. While the spectral sensitivity characteristics are not published beyond 700nm (Sony 2011), it is a CMOS based camera and is advertised as suitable for NIR imaging and the sCMOS curve in figure 2.1 was used to determine that there was some spectral overlap between the camera and silicon panels.

A case for the camera was designed in Google Sketchup and printed using MakerBot.

The power supplies used were (SMALL 30W,) an 180W Escort EPS-6030T and a 6.6kW Aglient 6692A for the large panels.

Two filters, a Hoya RM100 and a “traditional coated 1000nm band pass interference filter” from EdmundOptics were used. The RM100 is a long pass, IR passing filter allowing all of the near IR to pass while blocking the visible spectrum. The EdmundOptics filter is a band pass optical filter centred about 1000nm with a 10nm full width half max. The filters were chosen to maximize
the camera absorption as a product of the solar cell's emission, the filter's absorption and the camera's sensitivity.

Additionally a Cat5 cable and a USB-A to microUSB cable were used for communications and power from a laptop, and various cables for power transmission to the solar panels.
Method & Design

Chassis

A case was made to house the camera, microcontroller and cabling. It was designed in Google Sketchup and 3D printed with MakerBot. Its primary purpose was to stabilise and provide support for the camera and microcontroller allowing the camera to be exposed.

One flaw of the design was that the lights of the Ethernet controller on the microcontroller were facing the same direction as the camera. This was worked around by placing a cloth over the Cat5 cable’s terminus. In hindsight this could have been avoided by having the camera on the top side of the chassis, so the lights from the Ethernet controller were not aligned with the camera hence causing reflections off the laminate of the solar cells.

Image Server & Microcontroller Configuration

To enable remote control of the camera, a simple web service was written which enabled varying the camera parameters of interest, namely ISO and exposure time, and allowed the operator to take images and display them. Additionally “ssh” was used as the remote command line to launch the web service and to invoke the inbuilt camera utility “raspistill” for exploration of the camera’s capability.

The service was written in D using the “Vibe.d” web framework and “pyd”, a D library for interoperating with python, to embed python using the “picamera”
library to control the camera. The microcontroller is powered by a USB A to USB micro from a laptop and communicates with a Cat5 cable over Ethernet. It would have been possible to enable WiFi and use the standard supply that comes with the microcontroller to enable wireless control, but the cabled approach was sufficient for the purposes of this thesis. Enabling wireless control would also have made the device much less secure and enabling multiple clients to connect to the system simultaneously that would break the assumption of the software that only one client is connected at any given time.

The Raspberry Pi’s camera was enabled by running “sudo raspi-config” and, after putting in the super user’s password, navigating to the camera option and enabling it.

The D language compiler LDC version 1.1.0-beta2-linux-arm (LDC Developers2016) was used as the beta3 of same release series has a regression that stopped the use of 3rd party libraries (any releases since 1.1.0-beta4 should also work).

The following packages were installed with “get-apt install”

- libevent-dev
- libssl-dev
- libpython2.7-dev

A new dub project was initialised in the directory “picamserve” with “bin/dub init picamserve” with the following directory structure

- picamserve /dub.json - see Appendix A.
• picamserv /source/app.d – see Appendix B
• picamserv /views/index.dt – see Appendix C
• picamserv /public/images/

The program was built with “dub build –compiler=/bin/ldc2” and ran to listen on port 8081 to be connected to by the user.

I-V Curve and Electroluminescence Imaging

The larger solar panels’ IV curves were taken with a SPIRE 5600SLP Flash Tester and their nominal Voc and Isc were recorded, to serve as a reference point for the power loss due to degradation, and to estimate the power requirement of the panels.

To test the functionality and capability of the apparatus several series of images of the following solar panels were taken in a dark room (to minimise external light interference):

• Two small 4W panels (model SR-4M) with a 30W supply as an initial test.
• A poly-crystalline silicon cell (panel name “p312”)
  ▪ A power sweep to test image intensity/clarity with power
  ▪ A series at full power to test stacking images in software
  ▪ A distance sweep to determine the focus/image quality
  ▪ A series close up covering the panel to get a high resolution
• A mono-crystalline panel (p112)
• A multi-crystalline panel (p412)

Image Post Processing

Images of all but the first SR-4M panel (SR0958112) were post processed in GIMP/Photoshop to increase the brightness as high as possible and vary the contrast to analyse the image, as the signal amplitude was too low to observe without enhancement.

Except where noted, all colour images were enhanced with either a single brightness & contrast layer with the brightness set to maximum or multiple brightness & contrast layer with the brightness set to maximum and the contrast set so as not to enhance background noise.

Black and white images were enhanced with the brightness technique as described above, converted to grey and inverted.
Testing the effectiveness of the apparatus

All images were taken with ISO800 with a 1.75s exposure as this combination resulted in the greatest brightness. The Raspberry Pi NoIR while theoretically capable of ISO1600 and 6s exposure is not capable of both simultaneously: an ISO1600 exposure is imitated to 0.5s exposure in sports mode and the longer exposures are limited to low ISOs. This is a firmware limitation, not a limitation of the camera and should be easy to change for the vendor.

SR-4M type panels

Two small SR-4M panels (SR0958112 and SR0957180) were photographed in a closed cabinet to test the capability of the camera for the purpose of EL imaging.

Table 6.1: Nominal I-V characteristics of the SR-4M type panels.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Rated Power</td>
<td>4W</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>10.8V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>0.51A</td>
</tr>
<tr>
<td>Max power voltage</td>
<td>8.9V</td>
</tr>
<tr>
<td>Max power current</td>
<td>0.45A</td>
</tr>
</tbody>
</table>
Figure 6.1.1: SR-4M panel SR0958112

A photograph of panel SR0958112 (Figure 6.1.1) was taken at full resolution of 2592 x 1944 pixels with a supply of 10.0V, 3A. Of note are, the four panels on the bottom left that are mostly dark, the patches of dark scattered elsewhere on the panel and the non-uniform illumination of the cells.
Figure 6.1.2: SR-4M panel SR0957180

Panel SR0957180 (Figure 6.1.2) was imaged under the same conditions as Figure 6.1.1, and shows a much further progressed state of degradation. The overall brightness is significantly lower prior to post processing; there is more blotching, most obvious in the areas corresponding to visible delamination (bottom left two cells on the right and second bottom right in the middle). The cell third from the top on the left appears to have suffered conduction breaking fractures throughout. There is also a fracture visible on the lower left cell, which is consistent with a commercial scan taken of the panel 5 years prior (Figure 6.1.3).
The voltage scan (Figure 6.1.3) clearly shows that most of the individual cells have experienced a drop in open circuit voltage and some are non-functional. Note also the crack on the cell between y=180 to 200 mm and x=40 to 60mm, which is consistent with Figure 6.1.2.

The preliminary tests show that the camera is capable of producing images that show defects on the cells with reasonable resolution that are consistent with previous analysis of the panels.
**Polycrystalline panel p312**

The IV curve of panel p312 was taken using a SPIRE 5600SLP Flash Tester and the operating characteristics were recorded in Table 6.2 and Figure 6.2.1.

**Table 6.2: I-V Characteristics of p312**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal open circuit voltage</td>
<td>43V</td>
</tr>
<tr>
<td>Nominal short circuit current</td>
<td>3.35A</td>
</tr>
<tr>
<td>Measured open circuit voltage</td>
<td>42.75V</td>
</tr>
<tr>
<td>Measured short circuit current</td>
<td>3.14A</td>
</tr>
<tr>
<td>Max power voltage</td>
<td>33.33V</td>
</tr>
<tr>
<td>Max power current</td>
<td>2.47A</td>
</tr>
</tbody>
</table>

**Figure 6.2.1: IV curve of p312 taken by SPIRE 5600SLP Flash Tester.**
From Table 6.2 the voltage as suggested by Mansouri (2012) to be 130% of the open circuit voltage is 55.57V. However the power supply used topped out at 9A, 54V.

![Image](image.png)

**Figure 6.2.2 Luminance-Current curve of p312**

Figure 6.2.2 shows luminance as a function of current for panel p312. There is some transitional behaviour between 5A and 6A corresponding to the Voc threshold of the panel but beyond 6A the relationship is very linear. This suggests that the optimal operating current is somewhere between 5A and 6A, except that the images were still extremely dark and so the maximum available current was as no thermal safety concerns arose from the operating the equipment at 9A.
Due to the low brightness of the images, it was decided to test the effectiveness of stacking images in software. While this technique does average out some of the noise and does result in a brighter image it does not result in any more visible information and is, as suggested by (Petraglia and Nardone 2011), “possible but not necessary”.

We can see from figure 6.2.3 that panel p312 suffers from a significant proportion of underperforming cells with a variety of defects: almost all cells show less luminance further from the busbars; some busbars have detached completely (second and third form the bottom on the right). However at this resolution and size it is not possible to see fine-grained details of why a given cell is underperforming, but for the purposes of assessing the photovoltaic activity of the panel, it suffices.
Figure 6.2.4: Depth sweep in 20cm increments of p312.

As the Raspberry Pi NoIR is fixed focus at infinity, and therefore cannot be used to correct for changes in distance from the imaged object, it is necessary to determine the image characteristics experienced at different distances. Figure 6.2.4 shows a series of images taken at 5 cm to 105 cm in increments on 20 cm of
the higher luminance bottom left portion of Figure 6.2.3, rotated 90 degrees clockwise.

As the camera moves further from the panel fine detail is lost and gives way to more macro features with a greater degree of blurriness and demonstrates that this is an unavoidable trade-off, albeit one that is completely under the control of the user.

Figure 6.2.5: EL image of p312 with an RM100 optical filter, forward-lit (left) and backlit (right) by compact fluorescent lights.

Given the stringent interference requirements of almost complete darkness, the use of an optical filter was explored. Figure 6.2.5 shows an EL image of panel p312 with a low level of external light interference which was post processed by two brightness & contrast filters, a grey scale conversion and an inversion layer to enhance image clarity (the darker sections corresponding to higher level of EL
activity). While the RM100 filter did allow imaging at low levels of light interference, the reduction in signal amplitude suffered at the cost of maintaining the signal to noise ratio, and was ultimately not worthwhile.

The images taken with the Edmund Optics filter had no image signal, due to spectral mismatch between the camera, panel and filter and the very tight bandpass nature of the Edmund Optics filter (10nm full width half max). Whether images of sufficient brightness could be produced with similar filters but of a different bandpass cannot be determined due to the lack of published spectral sensitivity data for the camera in the region of interest.

Figure 6.2.6: Superimposed EL on full visible light spectrum image of panel p312.
To better visualise the regions of EL activity close up visible light and EL images were taken and superimposed in software (Figure 6.2.6). The signal free (i.e. black) regions of the EL image were assigned an alpha value of zero, a brightness & contrast layer was applied, and the whole EL image was added on top of the light image with the weight of each image adjusted to suit.

While the brightest regions of Figure 6.2.6 are in close proximity to the bus bars, there are holes visible, most clearly around the bottom bus bar of the second cell from the left on the top, which appears to correlate with the crystal structure of the cell.

![Image](image_url)

*Figure 6.2.7: EL on edge-detection light image.*

To further investigate the apparent correlation with the crystal structure, an EL on edge-detected light image was constructed by running an edge detector over the light image (convolution with the magnitude of the Sobel gradients) and
multiplying it by the brightness & contrast enhanced EL image. Unfortunately the edge detector picked up the fingers (the regular grid pattern) of the cells much more strongly than the crystal structure (the irregular patterns), however they are still visible.

From figure 6.2.7 it is possible to see that in the regions further away from the bus bars the EL activity does seem to correlate with the crystal structure, although a better image enhancement algorithm should be pursued in order to make that more clear. Also visible is a section of finger disruptions (right cell lower bus bar in the middle) that does not have an associated section of EL inactivity probably due to its proximity to the bus bar.

**Multicrystalline panel p412:**

As with panel p312 the I-V characteristics were taken using the SPIRE 5600SLP Flash Tester and are given in Table 6.3 and Figure 6.3.1.

**Table 6.3: I-V Characteristics of p412**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Voc</td>
<td>25.8838</td>
</tr>
<tr>
<td>Measured Isc</td>
<td>2.56785</td>
</tr>
<tr>
<td>Max power Voltage</td>
<td>20.9243</td>
</tr>
<tr>
<td>Max power Current</td>
<td>2.3657</td>
</tr>
</tbody>
</table>
Figure 6.3.1: I-V curve of p412

Figure 6.3.2: Close up EL image of panel p412.

An EL image of panel p412 was taken and post processed with 3 brightness & contrast layers, to compensate for the lower image brightness. As with panel p312 there are significant variations within the cell, some of which appear to
correlate with the crystal structure. The EL activity is higher in regions closer to the bus bars.

**Mono-crystalline panel p112:**

As with p312 the I-V characteristics were taken using the SPIRE 5600SLP Flash Tester.

**Table 6.4: I-V Characteristics of p112**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Voc</td>
<td>33.0756</td>
</tr>
<tr>
<td>Measured Isc</td>
<td>4.90054</td>
</tr>
<tr>
<td>Max power Voltage</td>
<td>26.009</td>
</tr>
<tr>
<td>Max power Current</td>
<td>4.4573</td>
</tr>
</tbody>
</table>
Figure 6.4.1: Close up EL of p112 with contact finger interruptions.

As is expected from mono-crystalline cells, panel p112 does not exhibit high frequency variations within cells due to a varied crystal structure, as there is only a single crystal. It does however exhibit the bus bar proximity variations as seen with the previous panels, as well as contact finger interruptions as the dark vertical lines in Figure 6.4.1.
Figure 6.4.2: Figure 9 from (Mansouri 2012) "Contact finger interruptions in a mono-crystalline silicon cell"

Under the assumption that the cells in Figures 6.4.2 & 6.4.3 are of similar size the low cost EL apparatus developed for this thesis provides similar resolution and clarity to the commercial apparatus used in Mansouri (2012).
Figure 6.4.3: EL image of panel p112.

Figure 6.4.4: Figure 17 of (Spertino, Ciocia et al. 2015)
An image taken at a greater distance from the solar panel (Figure 6.4.4) was taken to use as a point of comparison to a commercial image of a panel (Figure 6.4.5). While the low cost apparatus does produce an informative image, it does so with a much greater amount of noise, lower pixel count and resolution, and is only able to cover a portion of the panel. These differences may be overcome by stitching together a series of images in software to reconstruct the full panel. This was not done due to time constraints.
Discussion

The camera parameters that resulted in the highest brightness image were ISO 800 and 1.75s exposure, due to a limitation of the firmware of the camera. The camera is capable of ISO1600 and a 6s exposure, but not at the same time. Almost all of the resulting images were very dark, even at full power of the power supply.

A very low signal amplitude made the use of filters to remove light interference less useful because it is more effective to remove sources of noise, by imaging the cells in as dark a room as possible. Any attempt to improve the signal to noise ratio with a filter came at the expense of the signal amplitude.

If a firmware update to the camera were to make it possible to get a 6s exposure at ISO 1600, it would enable using less power to achieve a comparable image or get higher brightness & contrast raw images that could be further enhanced in software.

Despite this limitation the camera is able to produce images that clearly show the diverse range of defects in all of the tested cells, with a reasonable contrast and resolution with the use of post processing.

Despite the fixed focus nature of the camera used, it can be used to image entire panels in one go with reasonable resolution to detect underperforming sections.
of the panel. These can then be imaged at a closer range to look at the finer detail.

Mansouri’s (2012) guideline of 130% of Voc was reasonably accurate for the large power supply, but not for the smaller supply, which had negligible output impedance.
**Future work**

Due to time constraints, panel availability and power supply output, the EL apparatus only tested only silicon panels. EL should also work with other solar cell technologies like Cadmium-Telluride, Copper-Indium-Gallium-Selenide so it would be good to test them, despite their small market share (Blakers 2015), to demonstrate the effectiveness of the apparatus on a range of types of panels.

While the use of optical filters with the current apparatus is not worthwhile because of the loss of signal intensity, it should be very simple for the camera firmware vendor to enable long exposures with higher ISOs as the camera is capable of those setting (just not simultaneously). Doing so may make the use of optical filters, like the RM100, worthwhile to enable EL imaging in environments other than almost total darkness, such as night time imaging using filters to overcome light pollution.

While the panels used in this experiment were severely degraded it would be useful to test the apparatus on panels still in use for energy production.

Testing panels that are known to be broken in a particular way would enable direct characterisation of the defect.

Testing with suitable cameras with different capabilities to the Raspberry Pi NoIR would allow the effectiveness of other low cost cameras to be determined.
Conclusion

The apparatus produced for this thesis was self contained and low cost ($430 discounting the computer used for post-processing) with the exception of the power supply ($8000) and able to diagnose defects in a variety of panel types with a reasonable degree of confidence and is consistent with the literature. The commercial viability of the project hangs in the balance of offsetting the cost of the power supply and the amount of demand.

The camera performed well but for larger panels the dominant cost factor will be the power supply. While this is unlikely to be a major concern for universities that have an electrical department, because they will have capable power supplies, cables and access to three-phase power sockets where necessary as part of their teaching, other institutions and individuals will be much less likely to have access to power supplies capable of powering rooftop solar panels.

Given the significant relative cost of the power supply a camera firmware update to allow a 6s exposure at ISO 1600 could potentially reduce the requirements of the power supply leading to a significant reduction of the cost of performing EL imaging of solar panels, but the cost will still likely be dominated by the power supply.

To deal with the issue of the high cost of the power supply one possible business approach is to rent the equipment as the need to continually monitor panel
degradation is unlikely to be high unless the organisation has a very large number of panels.

Taking the EL images of the panels in as dark a room as possible is crucial to ensuring a high SNR as noise significantly impedes post processing and in turn the analysis of the image. The use of a filter to increase the SNR results in an image-destroying loss of signal amplitude and therefore necessitates the photography be done in near total darkness. This has a significant impact on the potential applications of the apparatus, relegating its use to either darkroom photography, for moveable panels, or night-time photography for panels that cannot be moved. The night-time photography may still suffer if there is significant light pollution.

The EL imaging apparatus is able to image standard commercial solar panels. The fixed lens of the camera did not prove to be a significant problem, rather it presented a trade-off between fine detail and panel coverage per image. It is also a far cheaper option than commercial alternatives, although the cost will still be dominated by the power supply.
Acknowledgements

I would like to thank the following people for their invaluable contributions:

David Parlevliet, my supervisor, for his insight and explanations of the intricacies of solar panels among many other topics.

The Murdoch University Engineering technical staff, Jeff Laava, David Morrison, Will Stirling and Mark Burt, for their help organising and manufacturing equipment.

Sönke Ludwig, Ellery Newcomer and Dave Jones for providing excellent open source libraries.

Reference:


Sony (2011). IMX081PQ,IMX091PQ,IMX111PQ.

Appendix

A – Build configuration
{
  "name": "thesis",
  "description": "PiCam Camera Controller",
  "copyright": "Copyright © 2016, nicholaswilson",
  "authors": ["nicholaswilson"],
  "dependencies": {
    "vibe-d": "~>0.7.19",
    "pyd": "~>0.9.8"
  },
  "versions": ["VibeDefaultMain"]
}

B – Server source code
import vibe.d;
import std.conv;
import std.path;
import std.file;
import std.algorithm;
import std.stdio;
import std.array;
import std.string;
import std.socket;
import std.process;
import pyd.pyd;
import pyd.embedded;

struct CamInfo
{
  static int pictureNum;
  static int exposure; // in microseconds
  static int iso;     // max 1600
  static string exmode = "off";
  static int exposure_compensation = -24; // < + 25
  static InterpContext ictx;
}
shared static this()
{
  auto cwd = getcwd();
  printf("%s\n", cwd.toStringz);
py_init();
auto router = new URLRouter;
router.get("/", &index)
  .post("/settings", &postSettings)
  .post("/picture", &getPicture)
  .get("*", serveStaticFiles("./public/"));
auto settings = new HTTPServerSettings;
CamInfo.ictx = new InterpContext();
CamInfo.ictx.py_stmts("import picamera");
CamInfo.ictx.py_stmts("from fractions import Fraction");
CamInfo.ictx.cam = CamInfo.ictx.py_eval("picamera.PiCamera(framerate=Fraction(1,6))");

CamInfo.ictx.cam.setattr("resolution", CamInfo.ictx.py_eval("cam.MAX_RESOLUTION");)
  settings.port = 8081;
  settings.bindAddresses = [(new InternetAddress(InternetAddress.ADDR_ANY,8081)).toAddrString()];
  listenHTTP(settings, router);
}

void index(HTTPServerRequest req, HTTPServerResponse res)
{
  string exposure = CamInfo.exposure.to!string;
  string iso = CamInfo.iso.to!string;
  auto images = dirEntries("public/images",SpanMode.breadth)
    .filter!(e => e.isFile)
    //7..$ -> remove "public/
    .map!(f => f.name[7..$]).array.sort()
    //.filter!(n => n.extension.equal(".jpg"))
    ;
  writeln(images);
  res.render!("index.dt", images, iso, exposure);
}

void postSettings(HTTPServerRequest req, HTTPServerResponse res)
{
  CamInfo.iso = req.form["iso"].to!int;
  CamInfo.exposure = req.form["exposure"].to!int;
  res.redirect("/");
}

void getPicture(HTTPServerRequest req, HTTPServerResponse res)
{
  printf("getPicture %d:
", CamInfo.pictureNum);
  auto where = "/home/pi/picamserve/public/images/%04d.jpg".format(CamInfo.pictureNum ++);
printf("\tsetting ISO");
   CamInfo.ictx.cam.setattr("iso", py(to!int(CamInfo.iso)));
   printf(" - Set\n\tsetting shutter_speed");
   CamInfo.ictx.cam.setattr("shutter_speed", py(to!int(CamInfo.exposure)));
   CamInfo.ictx.cam.setattr("exposure_mode", py(CamInfo.exmode));
   CamInfo.ictx.cam.setattr("brightness",py(75));
   CamInfo.ictx.cam.setattr("exposure_compensation",py(CamInfo.exposure_compen- 
   sation));
   writefln(" - Set\ntcaptive\nto %s ...
",where);
   CamInfo.ictx.py_stmts("cam.capture("%s")".format(where));
   printf("\t...done.\n");
   res.redirect("/");
}

C – Web page
doctype html
html
   head
      title PiCam Controller
   body
      p Camera Settings
      form(action="/settings", method="POST")
         //input(type="radio", name="filter", value="default") //- ignored for now
      p Iso
      input(type="text",name="iso",value=iso)
      p Exposure Time ( in microSeconds, max 6000000 )
      input(type="text",name="exposure", value=exposure)
      p
      input(type="submit",value="Submit")

      form(action="/picture",method="POST")
         input(type="submit", value="Take Picture")

   -foreach(s; images)
      img(src=s)