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Investigation of Photoconductive Properties of Passivated Emitter Rear Cell Silicon Photovoltaic Cells Using Atomic Force Microscopy

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Investigation of Photoconductive Properties of Passivated Emitter Rear Cell Silicon Photovoltaic Cells Using Atomic Force Microscopy

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B.S. University of Connecticut, 2013

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Master of Science Thesis

Investigation of Photoconductive Properties of Passivated Emitter Rear Cell Silicon Photovoltaic Cells Using Atomic Force Microscopy

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Chapter 1. Introduction

1.1 Background

The modern world requires a large amount of energy and, as concerns about the sustainability and environmental impact of fossil fuels rise, renewable energy sources become more and more necessary to provide the energy needed. As sunlight is readily available, photovoltaic energy has been one of the main sources of renewable energy pursued. Today, global demand for photovoltaic energy is on the rise. Measured by net installed capacity, photovoltaic energy is currently the fastest growing energy technology [1]. Just in 2017, 98 GW of additional photovoltaic capacity were installed worldwide, bringing the current cumulative installed photovoltaic capacity to over 400 GW [1].

As photovoltaic energy continues to grow in importance, investigation into the degradation of photovoltaic cells is crucial so that the stability and performance of solar cells can be improved over time. In this work, atomic force microscopy measurements are explored which can be used in the future to investigate the degradation of solar cells.

Many materials have the ability to collect solar energy and act as photovoltaic cells. Some of these materials are silicon (both amorphous and crystalline), Cadmium Telluride (CdTe), Copper-Indium-Gallium-Diselenide (CIGS), perovskites, and many organic thin films [2]. Silicon solar cells are the oldest type of solar cells and are well established in the photovoltaic industry [3], [4]. Crystalline silicon is the market leader for commercial solar cells [3]. In 2017, crystalline silicon solar cell technologies made up more than 90% of overall photovoltaic cell production [2]. According to the International Technology Roadmap for
Photovoltaic Results 2017 (ITRPV-17) report, more than 70% of crystalline silicon solar cells are made with Aluminum Back Surface Field (Al-BSF) technology [5].

### 1.2 Aluminum Back Surface Field (Al-BSF) solar cells

Al-BSF solar cells make up the majority of photovoltaic cells currently made [2], [5]. These cells can be made using both multicrystalline (mc-Si) and monocrystalline (mono-Si) silicon and have average stabilized efficiencies between 18 and 20% [5]. The highest efficiency for a screen-printed Al-BSF cell was reported to be 20.29% in 2017 [6].

The Aluminum back surface field refers to a type of back surface passivation of p-type silicon solar cells [7]. This passivation method was first introduced in 1972 [7] and involves a two-step process in which the back of a cell is coated with aluminum paste and the cell is then annealed [7]. During the annealing, silicon diffuses into the aluminum, leaving vacancies in the silicon which aluminum then fills. When the cell cools, silicon diffuses out of the aluminum and recrystallizes, leaving an Aluminum doped back surface field (BSF) layer [8], [9]. This technique has been optimized for high throughput industrial manufacturing and, in industrial settings, is accomplished by a screen printing process to coat silicon with aluminum and a short in-line anneal above the Al-polySi eutectic temperature in a belt furnace [7], [10].

The BSF layer is used to increase the collection of minority carriers by creating a p⁺-p high low junction at the back of the solar cell. This junction sets up an electric field in the same direction as the electric field of the n-p junction at the front of the silicon solar cell. This electric field causes minority carriers to be slowed down and eventually accelerated back against the diffusion gradient [11]. Carriers will drift back towards the bulk of the cell and have an increased
chance of being collected [12]. This technique can increase the short circuit current of a cell, decrease the dark current, and ultimately increase the cell’s efficiency [11].

Al-BSF technology is currently the most widely used technique for passivation of p-type Si solar cells due to its simplicity, low cost, and high throughput capability [7][13]. However, the performance of Al-BSF solar cells can be limited by high back-surface recombination velocities and low back-surface reflectance. In addition, full area Al-BSF can warp thin wafers, which can prevent the creation of cheaper thinner cells [13]. These issues can be addressed by the use of Passivated Emitter Rear Cell (PERC) technology.

1.3 Passivated Emitter Rear Cell (PERC) technology

PERC technology was first described in 1983 in a University of New South Wales final grant report [14]. A PERC solar cells is an adaptation of the Al-BSF cell that incorporates a dielectric film stack on the rear surface between the silicon and aluminum layers. Laser or chemical etching methods are used to create windows (or vias) in the dielectric layer to allow a local aluminum back surface field to form in these regions upon annealing. Figure 1 shows the

![Figure 1: Cross-section diagrams of a) Al-BSF cell and b) PERC cell. Adapted from Kumar [17]](image)
difference between Al-BSF and PERC structures. Figure 2 shows the region around a PERC cell local back surface field (BSF) in more detail. Figure 2(a) is a scanning electron microscope (SEM) image of a PERC via region with features identified (adapted from [15]). The local BSF is not visible in the image but is shown by a dashed outline. This figure shows the terminology of the features of the via region that will be used for the rest of the thesis. Research will be done primarily around the bulk silicon/aluminum back electrode/BSF triple junction. Figure 2(b) is a compilation of AFM deflection images showing the topography of an Al-polySi region. The BSF is not visible in the topography.

The PERC design provides the advantages of decreased rear surface recombination (due to the dielectric surface passivation and reduced metal/semiconductor contact area) and increased rear surface reflection[16][14]. Because of these advantages, PERC solar cells are able to achieve a higher efficiency than Al-BSF cells. In 2017, the average stabilized efficiency of PERC cells in mass production was found to be between 21 and 22% [5].
One of the advantages of PERC technology over other non-Al-BSF cell technologies is that PERC cells can be made with much the same industrial process as Al-BSF cells, with only a couple of extra steps to add cost. Two additional steps are required for PERC processing: a rear-surface passivation step which adds 3.21 $-cents/wafer and laser contact opening which adds a processing cost of 2.08 $-cents/wafer [17]. Figure 3 shows a simplified comparison of the cell manufacturing process between Al-BSF and PERC cells [14].

![Figure 3: Simplified processed diagram for Al-BSF (above) and PERC (below). Where there is only one level, both types of cells are processed. From Green [14].](image)

Because PERC cells require only a couple of extra processing steps, PERC cells can be made at only a moderate increase in cost over Al-BSF cells. In addition, manufacturers of Al-BSF cells can transition to PERC cell manufacturing with the addition of only a couple of processing steps and produce more efficient solar cells.

Due to its high efficiency and only moderate increase in cost over Al-BSF, PERC technology has been increasing in commercial production in the last years. ITRPV-17 predicts that PERC cell production will reach 40% around 2020 and will eventually overtake Al-BSF production[5]. Because of the importance of PERC cell technology, there is interest in researching the performance and degradation of PERC cells under different conditions. As the length scale for many of the processes involved in photovoltaic power generation, including generation of charge carriers and exciton dissociation, occur over only nanometers, it is
important to be able to measure performance of these cells at the nanoscale [18]. Atomic Force microscopy can be used for this purpose.

### 1.4 Atomic Force Microscopy

Atomic force microscopy (AFM) was invented in 1986 [19]. The technology is based upon the measurement of forces between a microcantilever and a sample created by the proximity of the cantilever tip to the surface of the sample [19][20]. Figure 4 shows the basic components of an AFM setup.

![Diagram of AFM components](image)

**Figure 4: Simplified diagram of important AFM components**

The most common type of atomic force microscopy measures the topography of a sample through one of two main modes – contact (or static) mode and dynamic mode. Contact mode works with a constant deflection setpoint. The cantilever tip is scanned across the sample in contact with the surface. A laser is reflected off the back of the cantilever. Where the sample is flat, the laser reflection hits the center of a photodiode. When the topography changes, the cantilever is deflected from its setpoint. When the cantilever is deflected, the position of the laser reflection changes and is detected by the photodiode. A feedback loop changes the z position of
either the cantilever tip or the sample to bring the deflection back to the setpoint and the laser reflection back to the center of the photodiode. The shift in z position is recorded as the topography[20]–[22].

In dynamic mode, the cantilever is oscillated close to its resonance frequency or a harmonic. Force between the cantilever and the surface will change the resonant frequency of the lever. The amplitude and the phase of the oscillation are also affected. In a common type of dynamic mode, amplitude modulation AFM with intermittent contact (aka tapping mode), the amplitude of the cantilever oscillation is kept at a setpoint. When the amplitude changes, the height of the tip or sample is changed to return it to the setpoint and the change in z position is recorded for the topography [19]–[21].

However, AFM can be used for the measurement of properties of a sample besides topography. Over time, AFM has evolved to be able to measure many different material properties at the nanoscale with different measurement techniques [20]. Some of the techniques that have been used to investigate photovoltaics include electrostatic force microscopy (EFM) [23], time resolved electrostatic force microscopy (trEFM) [23], and Scanning Kelvin Probe Force Microscopy (SKFM) [24].

Conductive Atomic Force Microscopy (cAFM) is one of the more common AFM methods used in photovoltaic research. cAFM is a mode of atomic force microscopy that measures current flowing at a tip sample nanojunction while simultaneously recording topography of the sample [21]. A conductive cantilever tip is used for this method. When a conductive sample is scanned in contact mode, an electrical circuit is produced between the tip and the sample. Any current flowing through this circuit can be measured by the AFM [3], [21].
Because current and topography are measured simultaneously in cAFM, this mode allows current information to be directly correlated with the sample structure on a nanometer scale [3].

1.5 Photovoltaic Performance Parameters

In investigations of photovoltaic cells, it is useful to be able to compare properties measured at the nanoscale with those measured at the macroscale. A common way of measuring photovoltaic properties at the macroscale is through the use of the photovoltaic performance parameters short circuit current ($I_{SC}$), open circuit voltage ($V_{OC}$), fill factor (FF), maximum power ($P_{max}$), and current and voltage at maximum power ($I_{MP}$ and $V_{MP}$ respectively). These properties are all related to the current-voltage (IV) curve of a photovoltaic cell, as shown in Figure 5 (adapted from [25]).

![IV diagram showing $I_{SC}$, $V_{OC}$, $P_{max}$, and Fill Factor (FF). Also shown are current at maximum power ($I_{MP}$) and Voltage at maximum power ($V_{MP}$). Figure adapted from [25].](image)
It is of interest, then, to collect these parameters at the nanoscale. This can be done at a single point by placing a conductive AFM tip at the point and varying the bias applied to the sample while measuring the resultant current to collect an IV curve [26]. The photovoltaic parameters can then be calculated from this curve. However, as electrical properties can vary over very small areas, it would be more useful to be able to map these parameters for entire areas at the nanoscale. Recently developed AFM techniques have made mapping photovoltaic parameters at the nanoscale possible, as will be discussed in the following section.

### 1.6 AFM Methods to Map Photovoltaic Performance Parameters

#### 1.6.1 Photoconductive Atomic Force Microscopy (pcAFM)

In 2007, Coffey et al. reported a technique called photoconductive atomic force microscopy (pcAFM) that combined cAFM with sample illumination. This technique allowed Coffey et al. to study and map the photocurrent of an organic photovoltaic cell produced under illumination. The light intensity dependence and the surface bias dependence of the photocurrent were also studied. Additionally, Coffey et. al used pcAFM to map the short circuit current of a MDMO-PPV:PCBM cell by taking a pcAFM image with no sample bias applied [27].

Since pcAFM was introduced, it has become a common AFM mode used to determine the electrical response of solar cells [28]. It has been used to study the photocurrent generated by organic photovoltaic blends [27], CdTe/CdS solar cells[26], [29] CIGS (Cu(In,Ga)Se$_2$) solar cells [30] CZTS (Copper Zinc Tin Sulfide) solar cells [31], and perovskite solar cells [32]. It has also been used to develop new techniques, such as the technique of photoconductive AFM spectroscopy discussed below [26]. However, pcAFM has not before been used to measure the photocurrent of a PERC silicon solar cell.
In this work, pcAFM is used to measure the photocurrent of a PERC silicon cell triple junction as a function of position and as a function of light intensity.

### 1.6.2 Photoconductive Atomic Force Microscopy Spectroscopy

In 2015, Kutes et al. developed photoconductive atomic force microscopy spectroscopy (pcAFMs), a method that enables one to take a series of pcAFM scans at different voltages and calculate an IV curve for each pixel. Figure 6 shows a sequence of images taken by Kutes et. al and shows how plotting the current from each scan as a function of voltage can be used to develop an IV curve for two different pixels. This procedure is repeated for each pixel in order to calculate an IV curve for every pixel in an image. $I_{SC}$, $V_{OC}$, FF, and $P_{max}$ can then be calculated from the IV curve and mapped for each pixel [26]. This method was demonstrated by Kutes et. al on microstructured CdTe/CdS solar cells. It was observed that enhancements and reductions in certain photovoltaic parameters were correlated with certain grains and grain boundaries but were independent of topography. While previous studies (including Coffey’s pcAFM study [27]) had observed the nanoscale variation of photovoltaic performance, Kutes et al.’s experiment marked the first time that the variation of traditionally

![Figure 6: Formation of IV curves using sequence of pcAFM images. The figure shows the formation of IV curves for two pixels from a stack of pcAFM images at different voltages. [26]](image)
macroscale performance parameters such as $V_{OC}$, $P_{max}$, and FF were mapped at the nanoscale [26].

pcAFMs has been used to study the variation of photovoltaic parameters at the nanoscale for CdTe/CdS [22], [26] and for CH$_3$NH$_3$PbI$_3$ hybrid perovskite thin film solar cells [33]. However, pcAFMs has not yet been used to study the variation of photovoltaic parameters for silicon solar cells. In this work, pcAFMs will be used to study the variation of photovoltaic parameters at the bulk silicon/aluminum back electrode/back surface field triple junction of a PERC silicon solar cell.

1.6.3 Direct $V_{OC}$ mapping

Though pcAFMs is useful for studying photovoltaic performance parameters at the nanoscale, the method is time consuming and has limited voltage resolution [26]. In order to map the open circuit voltage without these limitations, Atamanuk et al. has developed a direct $V_{OC}$ mapping technique that allows one to directly map $V_{OC}$ with a single scan using a user generated proportional-integral-derivative (PID) feedback loop [29]. This feedback loop adjusts the electrical bias applied to the sample in order to maintain a setpoint current of zero. The resulting sample bias is then recorded as $V_{OC}$. During a direct $V_{OC}$ measurement, the PID feedback loop is used at the same time as a separate feedback loop measuring the sample height, so the $V_{OC}$ of a sample can be measured simultaneously with the sample topography [29].

Atamanuk et. al have used direct $V_{OC}$ mapping to investigate the variation of the $V_{OC}$ of a CdTe/CdS cell at the surface of the cell. The method was also used to investigate the $V_{OC}$ through a volume of a solar cell by combining direct $V_{OC}$ mapping with computed tomographic AFM, in which AFM images are acquired during progressive surface milling [29].
Direct $V_{OC}$ mapping has been used to investigate the $V_{OC}$ of a CdTe/CdS solar cell as a function of lateral position and as a function of depth. In this experiment, direct $V_{OC}$ mapping will be used to investigate the $V_{OC}$ of a triple junction as a function of lateral position, but also as a function of light intensity.

1.7 Scope of this work

The aim of this work is to use the methods of pcAFMs, pcAFM and direct $V_{OC}$ mapping to map performance parameters of a PERC silicon solar cell at a triple junction with the long-term goal of investigating the effect of degradation on the structure and photovoltaic performance of this region. Classically macroscale performance parameters are investigated at the nanoscale so that future nanoscale measurements can be compared to measurements of performance parameters taken at the macroscale of whole solar cells. Direct mapping of $I_{SC}$ and $V_{OC}$ are also used to investigate the effect of light intensity on $I_{SC}$ and $V_{OC}$ of the solar cell.

1.8 References


Chapter 2. Mapping photovoltaic performance parameters of Passivated Emitter Rear Cell solar cells at the nanoscale

2.1 Abstract

Silicon solar cells are the market leaders in the solar cell industry with crystalline silicon comprising over 90% of commercial photovoltaic (PV) cell production [1]. It is predicted that by 2020, Passivated Emitter Rear Cell (PERC) solar cells will make up about 40% of silicon solar cell production[2]. With the importance of PERC cells in the global PV market growing, investigation into the performance and degradation of PERC cells is crucial. Degradation concerns for PERC cells include light induced degradation (LID), light/elevated temperature induced degradation (LeTID) and passivation layer stability[3]. Special interest is paid to the triplejunction between the bulk silicon, the aluminum back electrode, and the local back surface field (BSF), as this region could display all of these types of degradation. In this work, this region is studied using photoconductive Atomic Force Microscopy spectroscopy (pcAFMs), which allows photovoltaic performance parameters short circuit current ($I_{SC}$), open circuit voltage ($V_{OC}$), maximum power ($P_{max}$), current and voltage at maximum power ($I_{MP}$ and $V_{MP}$) and Fill Factor (FF) to be mapped at the nanoscale[4]. Results show that the local BSF region of the PERC cell is clearly visible in calculated property maps of PV performance parameters and can be compared to the surrounding bulk silicon. These results are initial studies on nondegraded PERC cells and will be compared to future samples that have been subjected to accelerated aging treatments to study the degradation of PERC cells at the nanoscale.
2.2  Introduction

Passivated Emitter Rear Cell (PERC) solar cells are increasing in usage in the photovoltaic market. It is predicted that they will make up 40% of silicon solar cell production by 2020 [2]. PERC cells are very similar to the most widely used type of solar cell - the Aluminum back surface field (Al-BSF) cell. However, where Al-BSF cells have a back-surface field (BSF) that covers the entire rear surface of a solar cell, PERC cells have a dielectric passivation layer over the rear surface with windows (vias) cut into it so that a local BSF forms at only these select locations. This technique has the benefits of decreased rear surface recombination and increased rear surface reflectivity, and ultimately yields a higher efficiency than is possible in Al-BSF [5], [6]. The average efficiency for a monocrystalline Al-BSF cell is about 20% while the average efficiency for a monocrystalline PERC cell is between 21 and 22% [2]. However, the PERC cell also has some additional degradation concerns over Al-BSF, namely LID and passivation layer stability [3].

Light induced degradation (LID) in silicon solar cells refers to a loss in the silicon cell efficiency observed during illumination [7]. Several LID mechanisms have been observed in crystalline silicon [7][8], but the earliest described and the most completely understood is the formation of a carrier-lifetime reducing boron and oxygen complex (BO complex) composed of one substitutional boron atom and two interstitial oxygen atoms during light exposure [9]. Though this complex forms in all oxygen-rich boron-doped silicon materials [9], it is more important in PERC than in Al-BSF cells because, in Al-BSF cells, the minority carrier lifetime is limited by rear surface recombination. In PERC, rear surface recombination is reduced, so the minority carrier lifetime is limited by the bulk lifetime which, in turn, is affected by the formation of the BO complex [3]. As increasing bulk lifetimes are obtained, LID effects gain in
Instability of the passivation layer is also a major concern for PERC cell efficiency as the passivation layer between the bulk silicon and the rear aluminum layer is the main advantage of PERC over Al-BSF. Dielectric passivation layers deposited on the surface of silicon wafers have been observed to change over time under the influence of elevated temperature and illumination. The layers degraded both in darkness and illumination, though stronger illumination accelerated the degradation [10]. Similar degradation of the passivation layer in commercial PERC cells is a concern and must be investigated.

Atomic force microscopy (AFM) methods can be useful for investigations of photovoltaic cells because they can be performed on the scale at which many photovoltaic processes occur, and become some modes of AFM, such as conductive atomic force microscopy (cAFM), can be used to relate material properties to the material’s structure by measuring the topography and other material properties simultaneously. AFM also allows investigation into a very small area, so that a specific region of a sample can be measured at the nanoscale.

In this experiment, the triple junction, a region of a PERC solar cell including the aluminum back electrode, the bulk silicon, and the local BSF layer, as shown in Figure 2(a), is examined. The triple junction is investigated using photoconductive atomic force microscopy spectroscopy (pcAFMs), a technique which allows the measurement of classically macroscale photovoltaic parameters at the nanoscale. These parameters are commonly used in industry to assess photovoltaic cells. They are derived from a current-voltage (IV) curve that can be taken by
measuring the current through a sample when sweeping through a range of voltages. Parameters measured with the IV curve include [4], [11], [12]:

- Short circuit current ($I_{SC}$) – the current when there is zero bias applied to the sample
- Open circuit voltage ($V_{OC}$) – the bias that needs to be applied for the current to be zero (in other words, the bias at which the cell goes from power generating to power shunting.)
- Maximum power ($P_{max}$) – the maximum power that a solar cell can have according to its IV curve. It can be calculated from current and voltage on the IV curve using the equation: $P_{max} = I x V \left| \frac{d}{dx}(I_{SC} x V_{OC}) = 0 \right.$
- Voltage at maximum power ($V_{MP}$) – The voltage applied to the cell at the point in the IV curve where the solar cell has maximum power
- Current at maximum power ($I_{MP}$) – The current at the point in the IV curve where the solar cell has maximum power
- Fill factor (FF) – a measure of the quality of the solar cell. It is the ratio of maximum power density ($P_{max}$) to the theoretical power density ($P_t$) and can be calculated using the ratio $\left(\frac{I_{MP} x V_{MP}}{I_{SC} x V_{OC}}\right)$. FF is used as a critical metric for manufacturers and researchers for characterizing the efficiency of a PV power source.

In order to map these parameters at the nanoscale, pcAFMs requires the mapping of photocurrent at a range of sample voltages. A series of photocurrent images is taken of the same area with increasing sample bias. With this series, one can calculate an IV curve for a pixel in the area by plotting the measured current for that pixel from each image against the bias applied to
the sample during that image. This can be done for each pixel. Using these IV curves, one can then calculate photovoltaic performance parameters for each pixel and map them.

2.3 Materials and Methods

2.3.1 Sample Preparation

The PERC p-type cell investigated was produced by Dupont Silicon Valley Technology center as part of a 15.5 x 15.5-cm mini module cell (Figure 7(a)) with the cell specifications given in the table in Figure 7(b).

![Image of solar cell](image)

**Figure 7:** a) 15.5 cm x 15.5 cm mini module produced by Dupont Silicon Valley Technology Center and b) specifications for mini module. Specification table from [3] in which the same cells were used.

To prepare the sample for AFM imaging, the sample was fractured and the edge was smoothed using a Triple Ion Beam Cutter by Dr. Bryan Huey and Dr. Oleg Kolosov. The edge was smoothed due to concerns about sharp topography changes around the triple junction that made AFM imaging difficult. SEM images taken of a non-smoothed sample (Figure 8) showed regions where the Al-polySi region was missing after fracture and also regions where the Al-polySi region was present, but where there was a large drop between the silicon region and the
back contact. Both of these produced regions which could not be imaged with AFM due to too
great changes in topography.

The edge smoothing process produced a sloped but smoothed sample edge that could be
easily imaged with AFM and that included the Aluminum back electrode, the bulk silicon and
the Al-polySi region around a triple junction. Figure 9 shows the sample after sloping (a), as well
as a diagram of the sample after sloping from a top view, showing the Al-polySi region (b) and a
side view showing the approach of the AFM cantilever (c).

Figure 8: SEM images of vias in passivated layer in fractured PERC silicon sample. a) A region
where the Al-polySi region has been destroyed during fracture. b) An Al-polySi region which is
raised but has a dip in the electrical contact next to it. Both of these images show examples of
large topography differences which can interfere with AFM imaging.

Figure 9: Silicon sample after smoothing a) plan-view picture of sample from above after
smoothing. b) plan-view schematic of sample from above after slope cutting showing Al-PolySi
region. b) cross section schematic of sample showing location scanned during experiment.
The sample was mounted on a clear glass slide using phenyl salicylate (also known as salol) with the absorber side facing down so light could hit the absorber from below. A streak of silver paint ran from the underside of the sample (touching one of the silver contacts) to a magnet which could be connected to the AFM tip holder, allowing a circuit to be formed between the AFM tip and the sample when mounted.

2.3.2 Equipment setup

All AFM images were taken with an MFP-3D AFM (Asylum Research) operated in air. The system was mounted on an optical microscope (Nikon TE-2000) with a 40X objective lens (Plan Achromat, 0.65 numeric aperture), which enabled illumination from below during AFM scanning on the top surface of the sample. The light source is a focused, unfiltered XPE Gen3 LED (CREE). Current detection was done with an Asylum Research ORCA Cantilever Holder. pcAFMs images were taken with a conductive diamond coated silicon tip (Nanosensors, CDT-NCHR) with a nominal 225-610 kHz resonance frequency and a nominal 23-225 Nm\(^{-1}\) force constant.

2.3.3 pcAFMs measurements

pcAFMs measurements were done by taking photocurrent images under illumination at applied sample biases from -3 V to 1 V at 200 mV increments. IV curves and resulting performance parameters for each pixel were calculated using a MATLAB code which plotted the measured current of each pixel against the sample voltage, calculated an IV curve using a polynomial fit, and calculated the performance parameters from the resulting curves. Due to the setup of the experiment, measured voltage had to be multiplied by -1 to calculate for IV curves. Calculations also account for about a 70 pA offset necessary to account for background noise.
from the instrument. In addition, preliminary IV curve investigations with Excel found that flat regions in an IV curve, where current response of the cell had leveled out or where current response had gone beyond the measurement range of the AFM, interfered with the calculation of a polynomial fit for IV curves of the BSF and bulk silicon regions. For this reason, only measurements taken from -2 V to 0.2 V were used with the MATLAB code.

2.4 Results and Discussion

In order to map the photovoltaic performance parameters of the triple junction, pcAFMs images were taken at a sequence of sample biases from -3 V to 1 V. The resulting pcAFMs images are shown in Figure 10. Note that the active quadrant for power generation is technically with negative biasing to the sample due to the experimental configuration. The bias is therefore inverted throughout this work to correspond to conventional solar cell analyses with power generation in the 1st quadrant (positive bias and positive current).

MATLAB code was used to calculate a wide range of photovoltaic parameters for each pixel and to map them as a function of position, extending the work of Kutes et al. onto this new
material system. The resulting property maps for FF, $I_{SC}$, $I_{MP}$, $V_{MP}$, $V_{OC}$ and $P_{max}$ are presented in Figure 11 in relation to an IV curve as (a) through (f) respectively. Each property map is connected to its respective location on the IV curve. A height map of the same region showing the topography is also presented for comparison (g). There are two features that are immediately apparent when comparing the topography and the property maps. First, there is a large region visible in all of the property maps that is not visible in the topography. This is outlined by a dashed red line in Figure 11(f). From the location around the Al-polySi, this is theorized to be the back surface field (BSF). Second, there are two horizontal streaks near the top of the property maps (outlined with a black dashed line on Figure 11(f)) that appear to align with topographical features with the height (outlined in blue on Figure 11(g)). These are assumed to be due to topography related artifacts and are not considered in the discussion of individual property maps. There is also topography variation in the Al-polySi region of the area, as can be seen on the right hand side of the height image. Measurements in the Al-polySi region in the property maps are also expected to be affected by topography artifacts. For this reason, analyses of individual property maps focus primarily on the bulk silicon (outlined in white in 11(f)), the BSF region (outlined in red in 11(f)) and a portion of the aluminum back electrode (outlined in purple in 11(f)). In measurements of the BSF and bulk silicon regions, the AFM cantilever acts a local back electrode so that the BSF and bulk silicon act like a silicon cell with and without a back surface field respectively. Measurements on the back electrode represent measurements of the
parameters of the whole PERC sample, as the conductive back electrode collects current from the entire area of the sample. Analyses of individual property maps are described below.

Figure 11: Photovoltaic parameter maps for FF (a), $I_{sc}$ (b), $I_{MP}$ (c), $V_{MP}$ (d), $V_{OC}$ (e), and $P_{max}$ (f) shown in relation to IV curve (center) [11]. Topography map of same region also shown for comparison with parameters maps (g). Parameter maps show a solid region that is not visible in the topography, as seen outlined in red in (f). Maps also show a region whose response appears to be a topography artifact of the scan, represented by the black dashed region in (f) and the corresponding blue dashed region in (g). Measured regions of the bulk silicon and back electrode are also seen in (f), outlined in white and in purple respectively.
2.4.1 Discussion of Each Parameter

*Short Circuit Current (I_{SC})*

A property map of the I_{SC} at the triple junction is shown in Figure 12(a). Because the measured I_{SC} on the aluminum back electrode is orders of magnitude higher than the actual Si photovoltaic, it is difficult to visualize the short circuit currents of the bulk silicon or the BSF region on a linear scale in the same field of view. Accordingly, log I_{SC} is plotted instead in Figure 12(b). Figure 12(c) shows a histogram of Figure 12(b). From the log plot and the histogram, we can see that the I_{SC} of the bulk silicon appears to be between 100 and 316 pA (between $10^2$ and $10^{2.5}$), though there are regions that are closer to around 30 pA ($10^{1.5}$). The I_{SC} of the BSF region varies more than that of the bulk silicon. While the majority of the region varies between about 315 pA and 2500 pA ($10^{2.5}$ and $10^{3.4}$ pA), there are small regions with I_{SC} down to around 30 ($10^{1.5}$) pA. A short circuit current displayed as 0 (black contrast) actually indicates that a realistic value could not be determined, due to unrealistic curve-fitting solutions for that pixel to the IV spectra acquired from the sequence of images in Figure 10.

Because the aluminum back electrode is very conductive and covers the rear of the cell, current measured at this electrode represents current from the properly assembled complete cell. This is as opposed to the bulk Si or BSF regions, where the AFM conducting probe acts as a local back electrode during measurement and thus measures the more local current at a single point. For this reason, measurements at the back electrode can be most directly related to the performance parameters for the bulk sample. Unfortunately, the I_{SC} for the back electrode is above the 20 nA measurement limit for the current detector in the AFM. Therefore, an exact I_{SC} cannot be determined with AFM-based resolution, as the measurement is simply off-scale. This
makes sense as PERC solar cells are expected to have $I_{SC}$'s well above 20 nA. For instance, Deng et al. measured the short circuit current density ($J_{SC}$) of one PERC cell to be 40.51 mA/cm² [13]. Based on the entire area of the sample in this experiment (0.43 cm²), if our sample has a similar $J_{SC}$ then a short circuit current of 17.5 mA is expected, almost 3 orders of magnitude higher than the upper limit for the AFM system.

This limit of measured current affects the calculated $I_{SC}$ of the electrode, but also the value of any parameter whose calculation at the electrode involves currents higher than the current detector limit. This includes the calculated values of $I_{MP}$, $V_{MP}$, $P_{max}$, and the fill factor. Therefore, the calculation of all of these parameters for the electrode is considered to be affected by the limited current and so considered erroneous. The trends are not unreasonable, but the absolute values are almost certainly incorrect. The calculation of $V_{OC}$, as it measures the voltage where the current is 0 pA, is not affected by the current limit and will be discussed in the next section.

**Figure 12:** pcAFMs mapping of $I_{SC}$. a) map of calculated $I_{sc}$ of triple point, b) map of log $I_{SC}$ of triple point, and d) histogram of log $I_{SC}$ map at triple point.
Open Circuit Voltage ($V_{oc}$)

The calculated $V_{oc}$ property map in Figure 13(a) has more discrete values for bulk silicon and the BSF than the $I_{sc}$ does. Bulk silicon has a $V_{oc}$ value of about 0.2 V, which can also be seen in the peak at 0.2 V in the $V_{oc}$ histogram in Figure 13(b). The BSF region has a $V_{oc}$ of about 1.3 V, though there is some variation in the region between 1 and 1.4 V. This can be seen in the $V_{oc}$ histogram in Figure 13(b) which has a wide peak that ranges from about 1 to 1.4 but is highest at 1.3 V. The $V_{oc}$ for the exposed aluminum back electrode is approximately 0.5 V, as can be seen by the distinct peak around 0.5 V in the $V_{oc}$ histogram. This can be compared to the $V_{oc}$ measured in whole PERC cells in literature, as in the measurement of a 22.61% efficiency cell by Deng et al. Deng et al. measured the $V_{oc}$ of the cell to be about 685 mV[13]. While this is higher than the measured value of about 500 mV seen in this experiment, similar variations have been reported as a result of experimental conditions, such as temperature, in silicon solar cells [14]. Additionally, since the cell measured by Deng et al. was produced by another solar cell company, it is expected that there would be some variation in $V_{oc}$ between the cells[13]. Further experimentation will have to be done between cells of the same type and at the same experimental conditions to make a more accurate comparison. However, the fact that the measured and literature values are within experimental and sample variation gives one confidence in the ability of pcAFMs to accurately calculate the $V_{oc}$ for a PERC sample. Other peaks in the histogram can be accounted for by currents detected in the Al-polySi region.
Maximum Power ($P_{\text{max}}$)

The maximum power property map is seen in Figure 14(a). The maximum power is plotted on a log scale due to the large range of values in the field of view. Bulk silicon has a low maximum power between 3 and 10 ($10^{0.5}$ and $10^1$) pW as can be seen in Figure 14(a) and also in the small peak between 0.5 and 1 log pW on the histogram in Figure 13(b). The BSF region has a much stronger maximum power, with $P_{\text{max}}$ consistently ranging from ~100 pW to 3000 pW ($10^2$ to $10^{3.5}$). The $P_{\text{max}}$ measured at the electrode was about 4000 pW ($10^{3.6}$). However, the $P_{\text{max}}$ is calculated based on current measurements, which, as seen for $I_{\text{SC}}$ above, are limited to a ceiling of 20 nA by the AFM. Therefore, the calculated $P_{\text{max}}$ for the electrode is expected to be much less than its real value.
Current and Voltage at maximum power ($I_{MP}$ and $V_{MP}$)

As $P_{max}$ can be calculated by the equation $P_{max} = I_{MP} \times V_{MP}$, current and voltage at maximum power ($I_{MP}$ and $V_{MP}$ respectively) were also mapped. Maps of these parameters are also in Figure 14, along with histograms of these maps. The variation in $P_{max}$ is largely due to the current at maximum power, as the current shows a larger variation than does the voltage at maximum power. The bulk silicon has $I_{MP}$ values ranging from 10 to 100 ($10^1$ to $10^2$) pA, most commonly approximately 40 pA ($10^{1.6}$) according to the $I$ at $P_{max}$ histogram. The BSF region has $I_{MP}$ varying from 100 pA up to 2500 pA ($10^2$ to $10^{3.4}$ pA). The peak in the histogram around $10^{4.3}$ can be attributed to the $I_{MP}$ of the electrode. As explained above, the calculated $I_{MP}$ is affected by current measurements limited by the instrumentation. The peak at $10^1$ can be attributed to spuriously calculated values for regions affected by topography artifacts, especially in the polyAl-Si region of the cell.

The voltage at $P_{max}$ has less variation, as anticipated since this value generally ranges less than an order of magnitude. $V_{MP}$ values are seen as distinct peaks on the $V$ at $P_{max}$ histogram in Figure 14(f). The bulk silicon region has a value of about 0.2 V, based on the broad peak low on the histogram. The BSF region has a peak around 1.1 V, the prominent peak at the center. The aluminum back electrode has a peak at 0.5 V on the histogram, which is expected to be erroneous due to the impact of the current detector measurement limit on $P_{max}$. Other peaks at 1.5, 1.7, and 2 are artifacts, resulting from distinct positions on the Al-BSF regions.
Figure 14: a) map of log $P_{\text{max}}$ of triple junction, b) histogram of log $P_{\text{max}}$, c) map of log $I$ at $P_{\text{max}}$, d) histogram of log $I$ at $P_{\text{max}}$, e) map of $V$ at $P_{\text{max}}$, and f) histogram of $V$ at $P_{\text{max}}$. 
**Fill Factor**

The calculated fill factor for the bulk silicon is about 30%, based on the property map and histograms of Figure 15(a) and (b). The fill factor of the BSF region is much higher. The fill factor of the BSF region is predominantly between 70 and 100% with a peak around 90%, as can be seen in the broad peak around 90% in the fill factor histogram. Such a high fill factor is expected for a commercial grade solar cell. One area of the BSF region, outlined in red in Figure 15(a), has a much lower fill factor, between 0 and 30%. However, as this is in the same region where several lines of unrealistic (0 pA) measurements were seen in the current in Figure 12, this may be due to curve fitting errors in the calculation of the fill factor parameter in this area. The fill factor for the electrode is about 30%. This is low in comparison to what is expected from a commercial PERC cell, which would be expected to have a fill factor around 70-80% [12]. However, as shown in Figure 11, the calculation of fill factor depends on $I_{SC}$, which is limited by the measurement limit of the AFM, as discussed above. Therefore, the magnitude of the fill factor is erroneous for this area, while the concept is sound.

![Figure 15: pcAFMs mapping of Fill Factor (FF). a) map of calculated FF of triple junction, b) histogram of FF map at triple junction.](image)
2.4.2 Discussions of performance at distinct regions of PERC cell

In general, the back surface field region exhibits higher values for photovoltaic performance parameters than does the underlying bulk silicon. The reason for this difference is related to the function of the BSF in decreasing the recombination of minority carriers at the surface of the silicon near the rear electrode. [15]. As discussed by Von Roos, the decrease in recombination leads to a higher number of carriers being available for collection at zero voltage, thus a higher short circuit current. There is also a decrease in dark current, and thus a higher open circuit voltage[15]. A higher $I_{SC}$ and $V_{OC}$ will result in a higher value also for $P_{max}$, (which can be calculated from the equation $P_{max} = FF \times I_{SC} \times V_{OC}$), and thus for the parameters $I_{MP}$ and $V_{MP}$ as well. The fill factor is dependent on the shape of the IV curve as well. Fundamentally, though, measurements at the BSF layer by the AFM probe more closely mimic the full cell except for the final Al electrode layer, as compared to measurements on bare bulk Si which are effectively missing a back passivating layer.

2.4.3 Benefits and Challenges with pcAFMs

In this experiment, pcAFMs has been shown to give nanoscale maps of photovoltaic performance parameters that can be compared to measurements taken at the macroscale. However, several concerns have also been noted with pcAFMs. Kutes noted that the technique is time consuming, since a number of scans must be completed at distinct sample biases to determine a reasonably accurate IV curve for each pixel [4]. The $V_{OC}$ and correspondingly the fill factor, $P_{max}$, and associated photovoltaic metrics necessarily depend on the number of scans taken and the range of biases assessed. Thus, for a moderate number of scans, the voltage resolution is limited and if more voltage resolution is desired, the experiment will take a longer
time. In addition, some positional drift tends to occur over a number of consecutive scans, which requires additional time for image processing to align corresponding pixels [4].

Another concern is that, since pcAFMs depends on the calculation of an IV curve, anything that interferes with that calculation can change the calculated parameters. For example, as discussed above, any measurements beyond the available range of the current detector can especially throw off IV analyses. Localized outlier values, noise, etc. may also be an issue even if they only occur in a single image frame. For example, the graph in Figure 16 shows IV curves for three pixels in a vertical line in an IV sequence taken of bulk silicon from -1 to 1 V (images not shown here). While pixels at positions (102,155) and (102, 156) (of the 512 x 256 scan area) show similar IV curves of a normal shape and have very similar $V_{OC}$ values, pixel (102,154) does not. For that pixel, one outlying point in the curve (from one scan at ~0.6V) drastically changes the curve and the calculated $V_{OC}$ value. $V_{OC}$ for this pixel appears to be much lower than the others, while in reality it may be higher. Other parameters such as $P_{max}$ would similarly be affected by low-sampling-density along the voltage axis and/or occasional local measurement errors.

![IV Curve for pixel in bulk silicon](image)

**Figure 16:** Point by point IV curves for three pixels in bulk silicon showing the effect of an outlier value on calculated parameters.
This dip in the IV curve may be related to vertical dropouts or downward spikes that are sometimes seen in IV curves taken by commercial IV curve tracers. These are due to an intermittent electrical connection, such as a jostled test lead [12]. It is conceivable that the dips in the IV curve seen here are due to brief breaks in the electrical circuit. Since the measurement is based on an AFM cantilever adjusting its height in response to changes in deflection (force), the local resistance can indeed change e.g. causing a lower current than would be expected for a specific voltage. Obviously, there are several solutions to correct for such calculation artifacts. In future investigations, multiple images at a single bias could be acquired and then their results averaged, though this would increase experimental time accordingly. After the fact, even with the data acquired here, each image (at a distinct bias) could also be smoothed and/or outlier pixels could simply be flagged as unmeasurable (for that specific instance). The I/V spectra per pixel from consecutive images could be smoothed as well. But since each of these procedures would influence the values at the well-measured pixels, it is scientifically more appropriate to analyze the raw data.

2.5 Conclusion

Photovoltaic performance parameters $I_{SC}$, $V_{OC}$, $P_{max}$, FF, $I_{MP}$ and $V_{MP}$ have been mapped using the technique of photoconductive atomic force microscopy spectroscopy (pcAFMs). Analysis of these maps has revealed a clear distinction between the local back surface field (BSF) around a PERC via and the surrounding bulk silicon, though no difference is seen in the sample topography. The bulk silicon has lower $I_{SC}$ and $V_{OC}$ than the BSF region, and thus a lower $P_{max}$, $I_{MP}$, and $V_{MP}$. It also exhibits a lower fill factor, around 30%, while the BSF region yields around 90% as expected for a commercial-grade solar cell like those studied here. There is more variation in BSF parameters as well, especially $I_{SC}$ and $I_{MP}$. 
Performance parameters were also calculated for the aluminum back electrode. The $V_{OC}$ calculated for the aluminum back electrode was similar to that measured for a whole PERC solar cell in the literature, giving experimental confidence that this method could be used to accurately calculate $V_{OC}$. However, the other performance parameters could not be calculated accurately at the back electrode as the current at the back electrode was beyond the measurement limit of the AFM for a number of points on the IV curve. This was expected, given the sample size, as current measured at the electrode was collected over the entire area of the sample. Thus, for many of the pcAFM based property maps, the $I_{SC}$ and max power differences are qualitatively relevant but necessarily inaccurate quantitatively.

Though pcAFMs proved effective in mapping photovoltaic performance parameters, there are some concerns with the method, including the long duration of experiments, possibly limited voltage resolution, positional drift, and the accuracy of performance parameters calculated from IV curves that may be influenced by instrumental artifacts.

2.6 References


Chapter 3 – Direct Measurement of Open Circuit Voltage and Short Circuit Current in Passivated Emitter Rear Cell Solar Cells

3.1 Abstract

Passivated Emitter Rear Cell (PERC) solar cells are expected to make up 40% of silicon solar cell production by 2020[1]. Investigation into the performance and degradation of these solar cells is therefore important. Light Induced Degradation (LID) is a major concern in crystalline silicon solar cells[2]–[5]. LID is seen as a decrease in the solar cell short circuit current (I_{SC}) and open circuit voltage (V_{OC}) [5]. Therefore, investigation into the I_{SC} and V_{OC} of a solar cell can yield information about the degradation of the cell. In this experiment, I_{SC} and V_{OC} were directly mapped at the nanoscale at a region of a PERC solar cell which included the aluminum back electrode, the bulk silicon, and the local back surface field (a triple junction). From these measurements, it was calculated that at the light intensity of the experiment, the I_{SC} of the bulk silicon was about 50 pA and the I_{SC} of the local BSF was primarily between 150 and 200 pA. The V_{OC} for the bulk silicon was about 1 V and the V_{OC} for the BSF region was about 1.4 V. These measurements were taken on unaged samples as initial measurements and can be compared, in the future, to measurements on samples that have undergone accelerated aging treatments.

3.2 Introduction

Light Induced Degradation (LID) can be characterized as a decrease in the short circuit current (I_{SC}) and open circuit voltage (V_{OC}) of a silicon solar cell [5]. As discussed in the previous chapter, I_{SC}, V_{OC} and other photovoltaic performance parameters can be mapped at the nanoscale using pcAFMs, a technique that uses a series of pcAFM images at different voltages to
create IV curves for each pixel of an area and calculates performance parameters for each pixel from the curve.

However, the pcAFMs method has several downsides, especially when measuring $V_{OC}$. First, using this method, voltage resolution is determined by the number of image frames and the voltage range [6]. Therefore, with a moderate number of images, the voltage resolution is limited. Second, because many images are required to create IV curves for each pixel, the method can be very time consuming, especially if a high voltage resolution is desired. Third, because the method relies on many images, the method is susceptible to positional drift over many consecutive images [6]. Fourth, because the parameters are calculated from an IV curve with current values drawn from each scan, parameter calculations can be affected by a single low or high point on any of the many scans.

Because of these issues, direct measurement of performance parameters such as $I_{SC}$ and $V_{OC}$ is preferred to pcAFMs. AFM methods are available which make possible the direct reading of either $I_{SC}$ and $V_{OC}$ in a single scan.

$I_{SC}$ can be directly measured using photoconductive atomic force microscopy (pcAFM) which combines illumination with conductive atomic force microscopy (cAFM) [7]. Essentially, when one scans a sample using cAFM under illumination and with no bias applied, the resulting photocurrent map will represent the short circuit current (the current flow when zero bias is applied to a sample.) For the sake of distinction between the techniques of pcAFMs and pcAFM, for the remainder of this thesis pcAFM-based results will be referred to as direct $I_{SC}$ mapping.

Based on a very recent development at UConn, $V_{OC}$ can also be directly measured based on a user-generated proportional-integral-derivative (PID) feedback loop to maintain open circuit
conditions (i.e. to maintain a setpoint of zero current) [8]. This feedback loop is used in addition to the feedback used for height during scanning, so direct \( V_{OC} \) mapping can record open circuit voltage and topography simultaneously. Additional electronics can be implemented to directly map \( P_{max} \) and the corresponding \( I_{MP} \) and \( V_{MP} \) as well, but hereafter only complementary direct \( I_{SC} \) and \( V_{OC} \) imaging is addressed. In particular, \( I_{SC} \) and \( V_{OC} \) are directly mapped at a bulk silicon/back electrode/BSF triple junction for a shallow-angle cross-sectioned PERC cell.

### 3.3 Materials and Methods

#### 3.3.1 Sample Preparation

Sample preparation followed the procedure described in Chapter 2, Section 2.3.1.

#### 3.3.2 Equipment setup

All AFM images were taken with an MFP-3D AFM (Asylum Research) operated in air. The system was mounted on an optical microscope (Nikon TE-2000) with a 40X objective lens (Plan Achromat, 0.65 numeric aperture), which enabled illumination from below during AFM scanning on the top surface of the sample. The light source is a focused, unfiltered XPE Gen3 LED (CREE). Current detection was done with an Asylum Research ORCA Cantilever Holder. All images were taken with a conductive diamond coated silicon tip (Nanosensors, CDT-NCHR) with a nominal 225-610 kHz resonance frequency and a nominal 23-225 Nm\(^{-1}\) force constant.

#### 3.3.3 Short circuit current mapping

\( I_{SC} \) mapping was done using direct \( I_{SC} \) mapping (pcAFM). The sample was illuminated from below while the current and topography were measured using cAFM from above.
3.3.4 Open circuit voltage mapping

V_{OC} mapping was done by setting up a PID feedback loop in the Asylum Software which would vary the bias applied to the sample in order to get the current to maintain a setpoint value of zero. Specific instructions on the method for setting up and running a PID loop to measure V_{OC} are included in Appendix 1. As in the previous chapter with pcAFMs, due to the setup of the sample and biasing configuration, the voltage must be flipped for V_{OC} measurements. Accordingly, this has been implemented with the voltage results throughout this chapter, so that they correspond to conventional positive open circuit voltages.

3.4 Results and Discussion

3.3.1 Results of Direct Mapping of I_{SC} and V_{OC}

Figure 17 displays directly acquired maps of I_{SC} and V_{OC}, along with simultaneously acquired height images from each area. The images were taken at slightly different angles but in essentially the same area. As seen with pcAFMs in the previous chapter, the local BSF region is especially visible in the V_{OC} image, and not at all apparent in the topography since it relates to local dopants and carrier concentrations independent of the surface morphology.
Direct Short circuit current ($I_{SC}$) mapping

The bulk silicon exhibits a directly measured short circuit current ranging from about 10 to 100 pA, primarily around 50 pA. The BSF region yields a stronger short circuit current, ranging from 50 pA to above 1400 pA. Within the BSF region, the strongest $I_{SC}$ occurs in a few locations which have $I_{SC}$ as large as 1400 pA (1.4 nA) with more common values centered
around 50 to 200 pA. These are revealed by the image profile displayed in Figure 18(b), obtained along the overlain red line in Figure 18(a).

**Figure 18:** Line graph showing high $I_{sc}$ values at distinct locations for the BSF. The red line overlain in the $I_{sc}$ map (a) identifies the location from which the data profile in (b) is extracted.

**Direct Open Circuit Voltage ($V_{OC}$) mapping**

The directly acquired $V_{OC}$ performance map in Figure 19(a) shows that bulk silicon has a $V_{OC}$ around 1 V while the BSF region has a $V_{OC}$ around 1.4 V. There is an abrupt step between these regions, as seen in the profile in Figure 19(b) along the red line overlain in Figure 19(a).

**Figure 19:** Line graph $V_{oc}$ values in bulk silicon and in BSF. The red line in the $V_{OC}$ map (a) shows the location line from which the graph in (b) is taken.
3.3.2 Direct $V_{oc}$ measurement of entire BSF region

After it was confirmed that $V_{oc}$ could be directly mapped, direct $V_{oc}$ mapping was used to map the entirety of the local BSF around one Al-polySi region of the PERC cell. Figure 20(a) shows one such representative local BSF. Figure 20(b) presents 21 separate direct $V_{oc}$ images, stitched together to make the overall map. The images were stitched together using a MATLAB code, which is included in this work as Appendix 2. The images were acquired over several days, resulting in slight variations in the baseline signal for each scan. There are also occasional scanning artifacts from previous scans, appearing as darker or lighter rectangular areas. Nevertheless, several important observations can be made. First, an obvious BSF region is apparent in the $V_{oc}$ images around the entire Al-polySi via that is not apparent in the corresponding topography Figure 20(c). The width of the BSF region varies from around 1μm at

![Figure 20: Direct $V_{oc}$ mapping of entire BSF region. (a) shows the location of the BSF region in relation to the surrounding area. (Image adapted from [9]) (b) shows direct mapping of the entire BSF region. The topography of the same region (c) is included for comparison.](image)
its thinnest point on the right side of the diagram to about 3 μm in some of the lower images.
Also, in all images, the $V_{OC}$ of the BSF region is higher than that of the surrounding bulk silicon.

### 3.4.2 Comparison with pcAFM

Results obtained via direct $I_{SC}$ and $V_{OC}$ mapping were compared to measurements taken of the same region with pcAFMs.

$I_{SC}$ comparison

Figure 21 shows the comparison between directly mapped $I_{SC}$ (a) and the $I_{SC}$ calculated using pcAFMs (b). The directly measured $I_{SC}$, like the calculated $I_{SC}$ from pcAFMs, has a fairly consistent value for bulk silicon and a more varied range for the BSF region. The specific regions of relatively higher and lower $I_{SC}$ in the BSF are also consistent between the direct $I_{SC}$ and pcAFMs calculated $I_{SC}$ maps. However, $I_{SC}$ values calculated by pcAFMs tend to be greater than those measured using direct $V_{OC}$ mapping. Furthermore, direct mapping is both less susceptible to scan related artifacts (horizontal lines in the data) and it appears to provide better lateral resolution (more distinct local variations). For instance, the $I_{SC}$ of a few sub-micron areas in the BSF region jump to an $I_{SC}$ of $\sim$1.4 nA as compared to a nearby mean signal of just 50 pA. The signal per pcAFMs is much more spatially uniform. As discussed in the last chapter, these observations are most likely explained by error induced during curve fitting of pcAFMs data and image drift during sequential images, respectively.
$V_{OC}$ comparison

Figure 22 shows the comparison between the directly mapped $V_{OC}$ and the pcAFMs calculated $V_{OC}$ at the triple junction. The $V_{OC}$ mapped by direct $V_{OC}$ measurement shows that bulk silicon has a $V_{OC}$ around 1 V and that the BSF region has a $V_{OC}$ around 1.4 V. The directly mapped $V_{OC}$ of the BSF region is in good agreement with that calculated with pcAFMs, as the calculated $V_{OC}$ for the BSF region is about 1.3 V. However, the $V_{OC}$ of bulk silicon does not agree as well. The $V_{OC}$ of bulk silicon, as mapped using direct $V_{OC}$ mapping, is about 1 V. On the other hand, the $V_{OC}$ of bulk silicon as calculated using pcAFMs is only about 0.3 V. More broadly, though, as with the $I_{SC}$ data the $V_{OC}$ data from each method is qualitatively equivalent.
Discrepancies

As discussed above, there are several discrepancies between the \( I_{\text{SC}} \) and \( V_{\text{OC}} \) values measured by direct \( I_{\text{SC}} \) and \( V_{\text{OC}} \) mapping and those calculated using pcAFMs. There are a couple possible explanations for this. As discussed in the previous chapter, pcAFMs depends on the polynomial fit of experimental points, which can be affected by several different factors. Calculated curves in pcAFMs may under- or over- estimate the values of \( I_{\text{SC}} \) and \( V_{\text{OC}} \). Direct \( I_{\text{SC}} \) and \( V_{\text{OC}} \) mapping, on the other hand, rely on the AFM setup and correctly accounting for offsets inherent in the system. More research will have to be done by future students to determine specific reasons for these discrepancies.

3.5 Conclusion

This chapter has shown the successful direct mapping of \( I_{\text{SC}} \) and \( V_{\text{OC}} \) at a bulk silicon/aluminum back electrode/BSF triple junction. Direct \( V_{\text{OC}} \) mapping of an entire BSF layer
was also demonstrated. The BSF region was observed to completely surround the Al-polySi region of the PERC cell and to vary from 1 to 3 μm in width. The BSF region was also observed to have a higher $V_{OC}$ than bulk silicon.

Results from direct $I_{SC}$ and $V_{OC}$ mapping were compared with those acquired from pcAFMs for the triple junction. Directly mapped $I_{SC}$ had, in general, a lower value than that calculated with pcAFMs. The directly mapped $V_{OC}$ and the calculated $V_{OC}$ from pcAFMs were very similar for the BSF region. However, values of $V_{OC}$ for bulk Si differed, as pcAFMs measured the $V_{OC}$ of bulk Si as 0.3 V and direct $V_{OC}$ mapping measured it as about 1 V. More research should be done to determine the reason for the differences in mapped and calculated $I_{SC}$ and $V_{OC}$.

Direct $I_{SC}$ and $V_{OC}$ mapping can be used to map $I_{SC}$ and $V_{OC}$ of PERC samples at the nanoscale more quickly and without curve fitting concerns of pcAFMs and so is preferred to the pcAFMs method of photovoltaic parameter calculation. In the next chapter, direct $I_{SC}$ and $V_{OC}$ mapping are used to investigate the dependency of these two performance parameters on illumination in PERC solar cells. Future research can use these techniques to study the effect of degradation on these photovoltaic performance parameters.

3.6 References


Chapter 4: Investigation into the light intensity dependence of short circuit current and open circuit voltage in Passivated Emitter Rear Cell solar cells.

4.1 Abstract

The light intensity dependence of photovoltaic parameters short circuit current ($I_{SC}$) and open circuit voltage ($V_{OC}$) is investigated using direct $I_{SC}$ and $V_{OC}$ Atomic Force Microscopy (AFM) scanning under different intensities of light. Slopes of the photovoltaic parameter vs. intensity plots for each pixel of an AFM image are then mapped as a measure of the parameter’s dependence on light. The resulting maps showed a slope of around $1 \log \text{pA}$ per relative intensity unit for $I_{SC}$ and around $0.5 \text{ V}$ per relative intensity unit for $V_{OC}$. These findings agree with previous experimental findings at the macroscale which found that both $I_{SC}$ and $V_{OC}$ increased with increasing light intensity.

4.2 Introduction

Solar cells are used year-round, but the intensity and angle of light incident on them changes over time. Light levels and angles change throughout a day due to the rotation of the earth and change seasonally due to the elliptical orbit of the earth around the sun [1]. Because solar cells will be used under many light conditions, it is important to look at the dependence of the performance of solar cells on light intensity.

Numerous setups have been used for studying the light intensity dependence of solar cells. Setups for measurement of the intensity dependence of solar cell performance can vary in both illumination mode and measurement method.
Two illumination regimes are common in light intensity state experiments – steady state illumination, and quasi-steady state illumination. With steady state illumination, light intensity is held steady at one level while photovoltaic performance parameters are measured. The light intensity is then increased or decreased for subsequent measurements in order to measure the response of a solar cell to different intensity levels. With quasi-steady state (Qss) illumination, a light pulse is used that is varied very slowly compared to the effective minority carrier lifetime of the wafer being measured [2]. Because the light pulse monotonically increases or decreases slowly with respect to the effective minority carrier lifetime of the wafer, the sample is seen as essentially at a steady state at each point [3]. The performance of the cell can thus be measured throughout the increase or decrease of the light pulse to get a measure of the photovoltaic performance at every light level of the pulse. The Qss illumination regime has been used to investigate both the photoconductance [2] and the open circuit voltage [4] of a solar cell as a function of illumination in the methods quasi steady state photoconductance (QssPC) and quasi steady state open circuit voltage (QssV\textsubscript{OC}, also known as Suns-V\textsubscript{OC}) respectively. The Qss illumination regime is widely used because, since less than 1 μA of current is drawn from a solar cell during this experiment, the effect of series resistance on the method is negligible [5]. Calculations have shown that corrected measurements from QssPC and QssV\textsubscript{OC} data can be directly related to true steady state measurements [3].

Methods of photovoltaic parameter measurement in light intensity dependence experiments also vary. While measurements can be made at the macroscale using instruments such as source meters [6], light intensity dependence of solar cell performance has also been investigated at the nanoscale using Scanning Kelvin Force Microscopy (SKFM) and photoconductive Atomic Force Microscopy (pcAFM). Snaith et. al used SKFM to look at the
light intensity, temperature and thickness dependence of open circuit voltage \( (V_{OC}) \) in solid state dye sensitized solar cells [7]. Coffey, in his introduction of pcAFM, looked at the intensity dependence of the photocurrent at zero bias of polymer/fullerene solar cells [8].

Crystalline silicon solar cells are the market leaders in the photovoltaic industry, comprising more than 90% of photovoltaic cells made in 2017 [9], [10]. Passivated Emitter Rear Cell (PERC) type solar cells are anticipated to be the market leaders in silicon solar cell technology by 2022 [11]. Therefore, research into the light dependency of crystalline silicon solar cells, especially PERC type cells, is important. Previous studies have looked at the incident intensity dependence of silicon solar cell parameters at the macroscale [6], [12]. This experiment investigates the light dependency of local short circuit current \( (I_{SC}) \) and open circuit voltage \( (V_{OC}) \) of a PERC cell at the nanoscale using Direct \( I_{SC} \) and Direct \( V_{OC} \) mapping with steady state illumination at different light levels. Direct \( I_{SC} \) mapping (pcAFM) is a technique that combines illumination with conductive AFM (cAFM) in order to measure the photocurrent of a solar cell [8], while direct \( V_{OC} \) mapping is a method of measuring \( V_{OC} \) using cAFM and an additional Proportional-Integral-Derivative (PID) feedback loop which changes the sample bias during a scan to maintain a set current [13]. Measurements are taken at a triple junction of bulk silicon, the aluminum back electrode, and the back surface field (BSF) in a PERC solar cell in order to determine the difference between the light dependence of the BSF and the bulk silicon of the cell.

4.3 Materials and Methods

4.3.1 Sample Preparation

Sample preparation followed the procedure described in Chapter 2, section 2.3.1.
4.3.2 **Equipment Setup**

All AFM images were taken with an MFP-3D AFM (Asylum Research) operated in air. The system was mounted on an optical microscope (Nikon TE-2000) with a 40X objective lens (Plan Achromat, 0.65 numeric aperture), which enabled illumination from below during AFM scanning on the top surface of the sample. Current detection was done with an Asylum Research ORCA Cantilever Holder. All AFM images were taken with a conductive diamond coated silicon tip (Nanosensors, CDT-NCHR) with a nominal 225-610 kHz resonance frequency and a nominal 23-225 Nm⁻¹ force constant.

4.3.3 **Short circuit current mapping**

Direct $I_{SC}$ mapping was done using photoconductive AFM (pcAFM). The sample was illuminated from below while the current and topography were measured using cAFM from above.

4.3.4 **Open circuit voltage mapping**

Direct $V_{OC}$ mapping was done by setting up a PID feedback loop in the asylum software which varied the bias applied to the sample in order to maintain a current setpoint of zero pA. Specific instructions on the method for setting up and running a PID loop to measure $V_{OC}$ are included in Appendix 1.

4.3.5 **Illumination**

The light source used for illumination in this experiment is a focused, unfiltered XPE Gen3 LED (CREE) with a maximum light output of about 280 lm. Light levels for the experiment with the right triple junction in Figure 20 were controlled using an Agilent 33120 A
Function/Arbitrary Waveform Generator. The voltage output was connected to the LED power source to establish light levels at 0%, 20%, 40%, 60%, 80%, and 100% based on DC drive biases up to 5V. Light levels for a complementary experiment, at the left triple junction in Figure 20, were equivalently controlled using independent or combined ND4 and ND8 neutral density filters. All intensity-dependent measurements are relative and are referred to as a percentage of the peak light intensity for complete illumination (100% LED power with no neutral density filtering).

4.4 Results and Discussion

4.4.1 \(I_{\text{SC}}\) and \(V_{\text{OC}}\) mapping as a function of light intensity

Direct \(I_{\text{SC}}\) and \(V_{\text{OC}}\) measurements were acquired at 6 different light levels between 0 and 100% of the full intensity of the light source, as shown in Figure 23. These images are located at the right triple junction of one Al-polySi region of a PERC solar cell.

![Figure 23: Sequences of \(I_{\text{SC}}\) (upper sequence) and \(V_{\text{OC}}\) (lower sequence) maps taken as a function of light intensity.](image-url)
MATLAB code was used to extract the $I_{SC}$ and $V_{OC}$ results for each pixel as a function of intensity. The slope of each parameter was then mapped and analyzed. Figure 24(a) presents the log of the $I_{SC}$ vs Intensity slope in units of log pA per relative intensity unit. Figure 24(b) displays the slope of the $V_{OC}$ vs Intensity results linearly, as there is a much smaller range of slopes and a log scale is not needed. Figure 24(c) illustrates the corresponding topography.

![Graphs of I_{SC} and V_{OC} slope vs light intensity.](image)

Figure 24: Maps of $I_{SC}$ and $V_{OC}$ slope vs light intensity. The log slope of $I_{SC}$ vs intensity map is plotted in (a). the slope of $V_{OC}$ vs intensity map is plotted for (b). The topography of the region is illustrated in (c).

$I_{SC}$ vs Light Intensity

The most common $I_{SC}$ vs light intensity slope for pixels in the silicon and BSF regions of the triple junction was 1 ($10^0$) log pA per arbitrary relative unit, though there were a number of pixels with higher slopes (from about 2.5 to 6 or from $10^{0.4}$ to $10^{0.8}$ log pA per relative intensity unit) and were also pixels with lower slopes (approaching 0 log pA per relative intensity units). Since the photocurrent of all silicon should increase with increasing light intensity, a slope of zero or below is an unrealistic solution. Therefore, the two regions that had low slopes approaching zero will be discussed further. There are two distinct regions in the bulk silicon that exhibit very small slopes in the log $I_{SC}$ vs light intensity curve. Both regions also exhibit
apparently zero slope on the $V_{oc}$ vs light intensity map as well and are outlined on the $V_{OC}$ map in red and white respectively. The region in red can be attributed to the effect of previous scans, as will be discussed in the next section. The other thin region with low slope, outlined in white, appears to surround the BSF region. Interestingly, the BSF region appears to have approximately the same $I_{SC}$ vs intensity slope as the bulk silicon. Only the edge of the BSF region differs.

$V_{OC}$ vs Light Intensity

The slope of $V_{OC}$ vs intensity is fairly uniform for most of the bulk Si and BSF regions of the triple junction. The slope is about 0.5 V per arbitrary light intensity unit for all of the silicon in the imaged region. Like the $I_{SC}$ map, the $V_{OC}$ map in Figure 24(b) also shows two regions with very small slope. One is due to the effect of previous measurements and the other outlines the BSF region.

The low slope region outlined in red in Figure 24(b) but visible in both the $I_{SC}$ and $V_{OC}$ maps is due to the effect of a previous set of measurements. As the light intensity scans were taken from 0 to 100% peak light intensity, this effect slowly dissipated. This can be seen clearly in the $V_{OC}$ image sequence shown in Figure 23. As the previous scan effect dissipates, that region slowly decreases in intensity as the rest of the intensity increases. That region, thus, has a negative slope where the surrounding area does not. This was not an effect of the voltage, but of the continuing scans, which can be seen by a comparison of $V_{OC}$ maps of the region at zero light intensity at the beginning and the end of the experiment, shown in Figure 25. At the beginning of the experiment, at zero light intensity, a strong dark region can be seen at the right side of the
scan. At the end of the experiment, after the sequence of images in Figure 23(b) was taken, another scan taken at zero light intensity does not have this region.

![V$_{oc}$ at zero light intensity](image)

**Figure 25:** Comparison of $V_{oc}$ maps taken with no illumination at the beginning (a) and the end (b) of the experiment described above.

The other low slope region, outlined in white in Figure 24(b) appears to be the edge of the BSF region of the sample. Interestingly, the BSF region itself has a similar slope to the rest of the silicon. However, the edge of the BSF region has a smaller slope with respect to light intensity than does the rest of the silicon for both $I_{SC}$ and $V_{OC}$.

A second $V_{OC}$ vs light intensity experiment was conducted on the left triple junction of the same region to see if this same pattern appeared. This sequence was taken with light levels of 100%, 25%, 12.5%, and 3.2% using neutral density (ND) filters. MATLAB code was used in order to plot $V_{OC}$ vs intensity and map the resulting slope, with similar results. Again, there was a slope of 0.5 for $V_{OC}$ vs. light intensity for all of silicon and, again a curve with a smaller slope, that outlines the BSF region. A comparison of the $V_{OC}$ vs intensity slope maps for the two triple
points is shown in Figure 26. It is possible that this effect is due to drift during an image sequence. For instance, in the $V_{OC}$ sequence of images shown in Figure 23, the $V_{OC}$ of the BSF region is higher than that of the bulk silicon. If drift occurred so that in later images the bulk silicon was measured in pixels that in earlier images had measured the BSF region, the slope of $V_{OC}$ vs intensity would be negative for those pixels. However, further experimentation is needed to confirm this.

![Figure 26: Comparison of $V_{OC}$ vs Intensity slope for Right Triple Junction (a) and Left Triple Junction (b).](image)

### 4.4.2 Comparison to literature

Previous studies on the light intensity dependence of $I_{SC}$ and $V_{OC}$ in silicon on the macroscale found that $I_{SC}$ increased in direct proportion with light intensity while $V_{OC}$ increased only slightly [6], [12].

The findings of this experiment are in agreement with the results shown in the literature in that both $I_{SC}$ and $V_{OC}$ were shown to increase with increasing light intensity. However, as the
exact intensity of the light source is unknown, and the LED used as a light source in this
eperiment would have a different spectrum than the solar simulator used in many macroscale
experiments, an exact comparison cannot be made between these experimental results and the
literature. Future research with a light source matching that of macroscale measurements is
needed to compare these results to those taken at the macroscale.

4.5 Conclusion

Short circuit current ($I_{SC}$) and open circuit voltage ($V_{OC}$) were analyzed as a function of
relative light intensity at the bulk silicon/aluminum back electrode/BSF triple junction of a
PERC solar cell. The slope of the parameter vs intensity curve was mapped for both $I_{SC}$ and $V_{OC}$
as a measure of the light intensity dependence of the parameter. In general, both $I_{SC}$ and $V_{OC}$
increased with increasing light intensity. This finding agreed with experiments conducted on
silicon solar cells at the macroscale. However, as the light source used in this experiment was
different from that used in macroscale measurements, measurements taken in this experiment
could not be directly compared to literature values.

The light intensity dependence (as measured by the slope of each parameter vs intensity
curve) is similar between the bulk silicon and BSF regions of the solar cell. However, the edge of
the BSF region had lower values than either the bulk silicon or BSF regions in both the log $I_{SC}$ vs
intensity curve and the $V_{OC}$ vs intensity curve. This was seen for $V_{OC}$ in two different regions. It
is possible that this is due to drift between images in the experiment, but further experimentation
is needed to confirm this.

Direct $I_{SC}$ and $V_{OC}$ mapping can be used to investigate the light intensity dependence of
performance parameters at the nanoscale. These methods can be used in future research to relate
measurements taken in PERC cells at the nanoscale to QssVOC measurements taken at the macroscale in studies of the effect of degradation on solar cell parameters. However, a calibrated light source will need to be used to make this possible.

4.6 Resources


Chapter 5 – Conclusions and Future work

5.1 Introduction:

In this thesis, photovoltaic performance parameters, especially short circuit current (I_{SC}) and open circuit voltage (V_{OC}) were investigated at the nanoscale at the bulk silicon/aluminum back electrode/back surface field (BSF) triple junction of a passivated emitter rear cell (PERC) silicon solar cell. In this chapter, conclusions and future work based upon these experiments will be discussed. The chapter will conclude with the long-term goal of this experiment and the next steps towards that goal.

5.2 Measurement of photovoltaic performance parameters using photoconductive atomic force microscopy spectroscopy (pcAFMs)

5.2.1 Conclusions

Photovoltaic performance parameters I_{SC}, V_{OC}, P_{\text{max}} (maximum power), I_{MP} (Current at maximum power), V_{MP} (Voltage at maximum power), and FF (Fill Factor) were calculated and mapped over a 3 x 3 μm region at a bulk silicon/back aluminum electrode/BSF triple junction in a PERC solar cell using pcAFMs. The performance parameters were successfully mapped and showed the back surface field (BSF) at the triple junction though it was not present in the topography. Values of each of the performance parameters seen in the bulk silicon of the cell and in the back surface field were discussed.

Concerns about the accuracy of the calculation for some points were noted. It was observed that points outside the instrument range would interfere with the polynomial fit of the
data over many scans required for the calculation of the performance parameters. Single outliers and regions of constant data could also interfere with the fit. Due to this concern, the long duration of any pcAFMs experiment, and the limited voltage resolution inherent in the pcAFMs method, direct methods of measuring performance parameters were pursued.

5.2.2 Future work

Results from this experiment suggest that future work should look into the best procedure to use to ensure an accurate determination of the IV curve for each pixel of a map when using pcAFMs. Some steps that could be taken include removing data points above the measurement threshold of the instrument, as was done in Chapter 2 and optimizing the curve fitting parameters such as polynomial order. Potential methods to deal with outlier data points include taking multiple images at each voltage or removing the outlier points as part of the MATLAB program. However, increasing the number of scans taken would increase the experimental time and smoothing the data or removing outliers would change the measured data. Direct methods of mapping performance parameters are therefore preferred to pcAFMs.

5.3 Measurement of $I_{SC}$ and $V_{OC}$ at triple junction of PERC cell using direct $I_{SC}$ and direct $V_{OC}$ mapping

5.3.1 Conclusions

In Chapter 3, $I_{SC}$ and $V_{OC}$ were mapped directly using pcAFM (called direct $I_{SC}$ mapping in this experiment) and direct $V_{OC}$ mapping. $I_{SC}$ and $V_{OC}$ of a PERC silicon solar cell triple junction were successfully mapped with these methods, with the benefits over pcAFMs that only one AFM scan was required for each image and that calculations were not required for the final
data. This method was used to map the entire BSF around one Al-polySi region in the PERC solar cell.

Directly mapped $I_{SC}$ and $V_{OC}$ were compared to $I_{SC}$ and $V_{OC}$ maps calculated with pcAFMs in Chapter 2. While broadly there was agreement between the maps, in that both showed the BSF region having higher values for both $I_{SC}$ and $V_{OC}$, there were also discrepancies between the maps. The $I_{SC}$ calculated by pcAFMs tended to be higher than that directly mapped and, while the $V_{OC}$ of the BSF region was very close between the two methods (about 1.3 V using pcAFMs and about 1.4 V using direct $V_{OC}$ mapping), the $V_{OC}$ of the bulk silicon did not agree as well. The $V_{OC}$ of the bulk silicon was about 0.3 V as measured using pcAFMs and about 1 V using direct $V_{OC}$ mapping. These discrepancies may be due to curve fitting issues associated with pcAFMs mapping, as discussed in Chapter 2, but may also be related to potential offsets inherent in AFM measurement not properly accounted for in either pcAFMs or Direct $I_{SC}$ or $V_{OC}$ measurement. Further research is needed to determine the exact reason for these discrepancies.

5.3.2 Future work

Future research should look into the reason for the discrepancy between pcAFMs and direct $I_{SC}$ and $V_{OC}$ mapping methods. In addition, as the direct reading of performance parameters is preferred to calculation with pcAFMs, direct reading of other performance parameters, such as $P_{max}$, should be taken at the triple junction.

5.4 Investigation of light intensity dependence of short circuit current and open circuit voltage

5.4.1 Conclusions
Chapter 4 investigated the light intensity dependence of the $I_{SC}$ and $V_{OC}$ of a PERC silicon cell bulk silicon/aluminum back electrode/BSF triple junction. A Direct $I_{SC}$ and a Direct $V_{OC}$ sequence of images were taken at different light levels and the $I_{SC}$ and $V_{OC}$ responses for each pixel were plotted against light relative intensity. The slope of the $I_{SC}$ (or $V_{OC}$) curve as a function of light intensity was mapped over the triple junction region as a measure of the light dependency of the $I_{SC}$ or $V_{OC}$ at each point. Results agreed with macroscale experiments of the light intensity dependence of the $I_{SC}$ and $V_{OC}$ of silicon in that both $I_{SC}$ and $V_{OC}$ increased with light intensity [1], [2]. However, a calibrated light source would be needed to compare the exact values of the nanoscale measured $I_{SC}$ and $V_{OC}$ to those at the macroscale.

The BSF and bulk silicon had similar light intensity dependence, as shown in both the log $I_{SC}$ vs intensity and the $V_{OC}$ vs intensity slope maps. However, the edge of the BSF region had a lower slope in both maps. This may be due to positional drift over a sequence of images. However, further experimentation is needed to confirm this.

5.4.2 Future research

As mentioned above, further research should include investigation into whether positional drift during a sequence of images causes a lower sloped region between the BSF and bulk silicon regions. Beyond that, similar experiments should be done with a calibrated light source with a spectrum similar to that used for macroscale experiments so that results can be compared to measurements at the macroscale. Another possible avenue of investigation suggested by this experiment is the dependency of $I_{SC}$ and $V_{OC}$ on temperature at the nanoscale. Previous studies done at the macroscale investigated the effects on these parameters of both light
intensity and temperature in order to see what the environmental effects on the cell would be [1], [2]. It would be interesting to see the effects of temperature on the solar cell at the nanoscale.

5.5  Aim of research and next steps

As described above, the investigations in this thesis have suggested several areas of future research. However, the overall aim of this research was to test AFM methods on PERC solar cells around the bulk silicon/back aluminum electrode/BSF triple junction which could be used in future research to look at PERC cells before and after degradation to determine what degradation does to the performance of the cell at the nanoscale. The triple junction was measured as this region is an area of special concern in PERC degradation as it could potentially show effects from Light Induced Degradation (LID), light and elevated temperature degradation (LeTID) and passivation layer instability[3]. Methods are used which calculate photovoltaic performance parameters often used at the macroscale so that nanoscale measurements can be compared with macroscale measurements taken on whole solar cells. The light intensity dependence of $V_{OC}$ was investigated at the nanoscale to compare to macroscale quasi steady state $V_{OC}$ ($QssV_{OC}$ or $Suns-V_{OC}$) measurements. Kerr has explained how $QssV_{OC}$ can compared to steady-state $V_{OC}$ measurements [4]. Therefore, the nanoscale steady-state $V_{OC}$ vs intensity measurements should be able to be compared to the $QssV_{OC}$ measurements often used to measure solar cells at the macroscale.

As the methods in this thesis have proved successful in measuring performance parameters at the nanoscale on a PERC cell and in measuring the light dependence of both $I_{SC}$ and $V_{OC}$, future research will include the use of these techniques to investigate the performance of PERC solar cells around the bulk silicon/aluminum back electrode/BSF triple junction before and after degradation to see the impact of degradation on solar cell performance at the nanoscale.
5.6 **Resources**


Appendix 1. Step by Step Method for Direct $V_{oc}$ Measurement

1. Open Programming > XOP Tables > Aliases (Figure 27(a))
   On the Alias Panel, open the “User” tab (Figure 27(b))
   a. In the first row,
      i. Type “Current” under UserAlias.I
      ii. Type “InputFast” under UserAlias.d
      iii. Type Enter
   b. In the second row
      i. Type “SurfaceBias” under UserAlias.I
      ii. Type “Output.C” under UserAlias.d
      iii. Type Enter
   c. At the bottom of the panel
      i. Click “Write”
      ii. Click “Read”

2. Open “All” tab of Alias panel and scroll to the bottom to make sure that the channels that you typed in the User tab are visible (Figure 27(c)).

3. Close the Alias Panel
4. Open Programming > Crosspoint Panel (Figure 28(a))
5. In the CrosspointPanel
   a. Click the dropdown menu “Load Settings” and select “DoIV” (Figure 28(b))
   b. Click the dropdown menu “InB” and select “BNCIn0” (Figure 28(c))
   c. Click the “Write Crosspoint” button

Figure 27: Alias panel: (a) Menu path to Alias menu, (b) “User” tab of Alias panel, (c) “All” tab of Alias menu, showing Current and SurfaceBias channels.
i. You should see new line on the Sum and Deflection Meter labelled “User 0”

d. Click lock next to “No Auto Change Crosspoint” so that it turns red. (Figure 28(d))

6. Close Crosspoint Panel

7. Open Programming > XOP Tables > PISLoops (Figure 29(a))
   a. Fill in the fields under PIDSLoop[5].d as shown in (Figure 29(b))
   b. Notes:
      i. The setpoint -0.035 V leads to a setpoint of 70 pA in the system. This setpoint was chosen instead of 0 to account for the about 70 pA offset observed in the system. The value here should depend on the system being used
      ii. The range used for OutputMin and OutputMax will depend on the range that you want the system to look at. Use a range that you believe contains the V_{OC} you want to look at.
      iii. You do not have to change the “Status” field (row 13). It will automatically change when the loop is started or stopped.
   c. Click “Write”
      i. The setpoint in the PIDSLoop5 should change to -3.5e-002V
      ii. User 0 and Samp Volt on the Sum and Deflection Meter will go to -2
d. Do NOT close the PIDSLoop window

8. Open AFM Controls > Other > Realtime Name Panel (Figure 30(a))

9. On the Realtime Name Panel (Figure 30(b))
   a. In the “Name” box across from User In 0 Gain, type “SurfaceBias”
   b. Click Enter
   c. The “Force” box below the “Name” box will be auto filled with “Surfa”
   d. The “Abbrev.” box below the “Force” box will be auto filled with “Su”
   e. Close the Realtime Name Panel

Figure 29: PIDS Loop Panel: (a) Menu path to PIDS Loop Panel, (b) PIDS Loop panel filled out with parameters for direct \( V_{oc} \) measurement under PIDS Loop 5.

Figure 30: Realtime Name Panel: (a) Menu path to Realtime Name Panel, (b) Realtime Name Panel filled out with SurfaceBias, Surfa, and Su in the boxes outlined in red.
10. In Master Channel Panel
   a. Click on “5” tab
   b. Click “Input” dropdown menu and select “SurfaceBias” at the bottom (Figure 31)
   c. If want Trace and Retrace data, click “Capture & Display” dropdown menu and select “Both”

![Master Channel Panel](image)

Figure 31: Master channel panel, showing SurfaceBias on the Input dropdown menu.

11. When ready to do direct V<sub>OC</sub> scanning
   a. Click “Start” on PIDS Loop panel
      i. Dot next to “Start” should show green
      ii. “Status” field should show 1
      iii. Note: may need to click stop and start a couple times for this to happen

12. Final notes
   a. You should play around with scan speed and scan size to find what gives you the best results. Scanning can be slow and 0.1-0.4 Hz worked well for different scans. Scan sizes between 3 and 5 μm were used for these experiments.
   b. If you want to change the parameters in the PIDS loop, you may need to change (or at least retype) two fields before hitting write instead of just the one you want to change.
   c. This method was done with Asylum Research version 12. Some specifics here may vary for different versions.
   d. At times, the V<sub>OC</sub> feedback loop fails to establish the setpoint zero current within the available voltage range, especially when the scan starts at a very conductive region. Two ways to deal with this are:
      i. Change the scan region slightly so the scan does not start on a conductive region
      ii. Try increasing the range of the voltages allowed by changing the OutputMin and OutputMax values
Appendix 2. Matlab code for Image Compilation

{%ImageCompiler
%Prep work -
%Make image stacks for all of tabs you want to compile.
%Use ImageJ - Concatenate stacks (uncheck 4D option)
% - Crop all at once so same size
% - Stack to images
% - Save images - Deflection as Def
% - SurfaceBias as Surf
% - Current as Cur
% - Height as Hg
% NOTE: Currently need to save as RGB tif images for code
% to work - in future, should edit image so that 8-bit can
% work so can add color
%Change Saving section at bottom so don't overwrite any other saves
%NOTE: Currently issue with saving - need to fix

close all
clear

%Writing code assuming images same size (for loop purposes) - will change
%if necessary

%ImportImages
Def1 = imread('Def1.tif');
Def2 = imread('Def2.tif');
imshow(Def1)
figure, imshow(Def2)

%Choose subregions of each image
[sub_Def2,rect_Def2] = imcrop(Def2);  %choose part of image in common
[sub_Def1,rect_Def1] = imcrop(Def1);  %crop for second image must be larger than first

%display sub images
figure, imshow(sub_Def2)
figure, imshow(sub_Def1)

%Do normalized cross correlation and find coordinates
%Display cross correlation as graph - peak where images are best
%c=normxcorr2(sub_Def2(:,1),sub_Def1(:,1));
figure, surf(c), shading flat

%Find Total offset between images

%offset found by correlation
[max_c,imax] = max(abs(c(:,)));
[ypeak,xpeak] = ind2sub(size(c),imax(1));
corr_offset = [(xpeak-size(sub_Def2,2))
                (ypeak-size(sub_Def2,1))];
%relative offset of position of subimages
rect_offset = [(rect_Def1(1)-rect_Def2(1))
             (rect_Def1(2)-rect_Def2(2))];

%total offset
offset = corr_offset+rect_offset;
xoffset = offset(1);
yoffset = offset(2);

%making coordinate system
CombinedDeflection = uint8(zeros(4000,7000,3));

%putting 1st image in coordinate system
%to put in, must be integer value - hence round
[R1,C1,~]=size(Def1);
xbegin1 = round(1+300);
xend1 = round(C1+300);
ybegin1 = round(1+300);
yend1 = round(R1+300);
CombinedDeflection(ybegin1:yend1,xbegin1:xend1,:)=Def1;
figure, imshow(CombinedDeflection);

%putting 2nd image in coordinate system

[R2,C2,~]=size(Def2);
xbegin2 = round(1+300+xoffset);
xend2 = round(C2+300+xoffset);
ybegin2 = round(1+300+yoffset);
yend2 = round(R2+300+yoffset);
CombinedDeflection(ybegin2:yend2,xbegin2:xend2,:)=Def2;
figure, imshow(CombinedDeflection);

%Putting together coordinate registry
ImageOffsets = zeros(25,2);
ImageOffsets(2,1) = yoffset;
ImageOffsets(2,2) = xoffset;

for n = 3:19
    xbegin1 = xbegin2;
    xend1 = xend2;
    ybegin1 = ybegin2;
    yend1 = yend2;

    a = n-1;
    b = n;

    file1 = 'Def';
    file2 = '.tif';
aName = strcat(file1,num2str(a),file2);
bName = strcat(file1,num2str(b),file2);

%import images
Def1 = imread(aName);
Def2 = imread(bName);
figure, imshow(Def1)
figure, imshow(Def2)

%Choose subregions of each image
[sub_Def2,rect_Def2] = imcrop(Def2);  %choose part of image in common
[sub_Def1,rect_Def1] = imcrop(Def1);  %crop for second image must be larger than first

%display sub images
figure, imshow(sub_Def2)
figure, imshow(sub_Def1)

%Do normalized cross correlation and find coordinates
%Display cross correlation as graph - peak where images are best correlated

c = normxcorr2(sub_Def2(:,:,1),sub_Def1(:,:,1));
figure, surf(c), shading flat

%Find Total offset between images
%offset found by correlation
[max_c, imax] = max(abs(c(:)));  
[ypeak, xpeak] = ind2sub(size(c),imax(1));
corr_offset = [(xpeak-size(sub_Def2,2))
                 (ypeak-size(sub_Def2,1))];

%relative offset of position of subimages
rect_offset = [(rect_Def1(1)-rect_Def2(1))
               (rect_Def1(2)-rect_Def2(2))];

%total offset
offset = corr_offset+rect_offset;
xoffset = offset(1);
yoffset = offset(2);

%Putting 1st image in coordinate system
CombinedDeflection(ybegin1:yend1,xbegin1:xend1,:)=Def1;
figure, imshow(CombinedDeflection);

%Putting 2nd image in coordinate system
[R2,C2,~]=size(Def2);
xbegin2 = round(xbegin1+xoffset);
xend2 = round(xend1+xoffset);
ybegin2 = round(ybegin1+yoffset);
yend2 = round(yend1+yoffset);

CombinedDeflection(ybegin2:yend2,xbegin2:xend2,:)=Def2;
figure, imshow(CombinedDeflection);
% Putting coordinates in coordinate registry
ImageOffsets(n,1) = yoffset + ImageOffsets(n-1,1);
ImageOffsets(n,2) = xoffset + ImageOffsets(n-1,2);

close all
end

% Putting together figure of Current Images

% making coordinate system
CombinedCurrent = uint8(zeros(4000,7000,3));

for n = 1:19

% Import Image
file1 = 'Cur';
file2 = '.tif';
Name = strcat(file1,num2str(n),file2);
CurrentImage = imread(Name);

% Putting Image into coordinate system
[R,C,~] = size(CurrentImage);
xbegin = round(1+300+ImageOffsets(n,2));
xend = round(C+300+ImageOffsets(n,2));
ybegin = round(1+300+ImageOffsets(n,1));
yend = round(R+300+ImageOffsets(n,1));

CombinedCurrent(ybegin:yend,xbegin:xend,:)=CurrentImage;

close all
end

figure,imshow(CombinedCurrent)

% Putting together figure of SurfaceBias Images

% making coordinate system
CombinedSurfBias = uint8(zeros(4000,7000,3));

for n = 1:19

% Import Image
file1 = 'Surf';
file2 = '.tif';
Name = strcat(file1,num2str(n),file2);
SurfBiasImage = imread(Name);

% Putting Image into coordinate system
[R,C,~] = size(SurfBiasImage);
xbegin = round(1+300+ImageOffsets(n,2));
xend = round(C+300+ImageOffsets(n,2));
ybegin = round(1+300+ImageOffsets(n,1));
yend = round(R+300+ImageOffsets(n,1));

CombinedSurfBias(ybegin:yend,xbegin:xend,:)=SurfBiasImage;

end

figure,imshow(CombinedSurfBias)
yend = round(R+300+ImageOffsets(n,1));

CombinedSurfBias(ybegin:yend,xbegin:xend,:) = SurfBiasImage;

close all
end

figure, imshow (CombinedSurfBias)

% Putting together figure of Height Images

% Making coordinate system
CombinedHeight = uint8(zeros(4000,7000,3));

for n = 1:19

  % Import Image
  file1 = 'HgXY';
  file2 = '.tif';
  Name = strcat(file1,num2str(n),file2);
  HeightImage = imread (Name);

  % Putting Image into coordinate system
  [R,C,~] = size(HeightImage);
  xbegin = round(1+300+ImageOffsets(n,2));
  xend = round(C+300+ImageOffsets(n,2));
  ybegin = round(1+300+ImageOffsets(n,1));
  yend = round(R+300+ImageOffsets(n,1));

  CombinedHeight(ybegin:yend,xbegin:xend,:) = HeightImage;

  close all
end

figure, imshow (CombinedHeight)

close all

% Saving

figure, imshow (CombinedDeflection)
figure, imshow (CombinedCurrent)
figure, imshow (CombinedSurfBias)
figure, imshow (CombinedHeight)

saveas(CombinedDeflection,'CombinedDeflection.jpg');
saveas(CombinedCurrent,'CombinedCurrent.jpg');
saveas(CombinedSurfBias,'CombinedSurfBias.jpg');
saveas(CombinedHeight,'CombinedHeight.jpg');
save Offsets ImageOffsets