SPATIALLY RESOLVED OPTO-ELECTRIC MEASUREMENTS OF PHOTOVOLTAIC MATERIALS AND DEVICES

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DECLARATION:

In accordance with the Rule G4.6.3, I hereby declare that the abovementioned thesis is my own work and that it has previously not been submitted for assessment to another University or for another qualification.

Signed: _________________________

Date: _________________________
This is dedicated to my uncle, Johannes Moloto.
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Summary

The objective of this study is to characterize and analyse defects in solar cell devices. Materials used to fabricate solar cells are not defects free and therefore, there is a need to investigate defects in cells. To investigate this, a topographical technique was developed and employed which uses a non-destructive methodology to analyse solar cells.

A system was built which uses a technique based on a laser beam induced current (LBIC). LBIC technique involves focusing light on to a surface of a solar cell device in order to create a photo-generated current that can be measured in the external circuit for analyses. The advantage of this technique is that it allows parameter extraction. Parameters that can be extracted include short-circuit current, carrier lifetime and also the external and internal quantum efficiency of a solar cell.

In this thesis, LBIC measurements in the form of picture maps are used to indicate the distribution of the localized beam induced current within solar cells. Areas with low minority carrier lifetime in solar cells are made visible by LBIC mapping. Surface reflection intensity measurements of cells can also be mapped using the LBIC system developed in this study. The system is also capable of mapping photo-generated current of a cell below and above room temperature.

This thesis also presents an assessment procedure capable of assessing the device and performance parameters with reference to I-V measurements. The dark and illuminated I-V characteristics of solar cells were investigated. The illuminated I-V characteristics of solar cells were obtained using a defocused laser beam. Dark I-V measurements were performed by applying voltage across the cell in the dark and measuring a current through it. The device parameters which describe the behaviour of I-V characteristic were extracted from the I-V data using Particle Swarm Optimization (PSO) method based on a one-and two-diode solar cell models.
Solar cells of different technologies were analysed, namely, single-crystalline (c-Si) and multicrystalline (mc-Si) silicon, Edge-defined Film-fed Growth Si (EFG-Si) and Cu(In,Ga)(Se,S)\textsubscript{2} (CIGSS) thin film based cells. The LBIC results illustrated the effect of surface reflection features and material defects in the solar cell investigated. IQE at a wavelength of 660 nm were measured on these cells and the results in general emphasised the importance of correcting optical losses, i.e. reflection loss, when characterizing different types of defects. The agreement between the IQE measurements and I-V characteristics of a cell showed that the differences in crystal grains influence the performance of a mc-Si cell.

The temperature-dependence of I-V characteristics of a CIGSS solar cell was investigated. The results showed that, for this material, the photo response is reduced at elevated temperatures. In addition to LBIC using a laser beam, solar spectral radiation was employed to obtained device performance parameters. The results emphasised the effect of grain boundaries as a recombination centres for photogenerated hole-pairs.

Lastly, mesa diode characterizations of solar cells were investigated. Mesa diodes are achieved by etching down a solar cell so that the plateau regions are formed. Mesa diodes expose the p-n junction, and therefore mesa diode analysis provides a better way of determining and revealing the fundamental current conduction mechanism at the junction. Mesa diodes avoid possible edge effects. This study showed that mesa diodes can be used to characterize spatial non-uniformities in solar cells.

The results obtained in this study indicate that LBIC is a useful tool for defect characterization in solar cells. Also LBIC complements other characterization techniques such as I-V characterization.

**Keywords:** Solar cell, defects, LBIC, current-voltage characteristics
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Chapter 1

Introduction

1.1. The use of photovoltaics

Solar cells are semiconductor devices capable of converting solar radiation into electric energy. In contrast to many traditional forms of generating electrical power, i.e. coal-fired power, the conversion of solar energy is achieved without emission of air-pollutants. Since the discovery of the photovoltaic (PV) effect by the French scientist Edmund Becquerel in 1839, solar cell conversion efficiencies have improved. New techniques and materials to efficiently utilize the full solar radiation can revolutionize photovoltaic technology. The successful commercialisation of crystalline solar cell technologies has demonstrated the promise of PV applications. Other technologies exploiting thin films and also organic semiconductors have emerged as promising strategies for lowering the cost of PV energy. The reported cell production increased from 10 MW/yr in 1980 to about 1200 MW/yr in 2004 recorded under the Standard Test Conditions (1000 W/m², AM 1.5 and 25°C cell temperature) [1].

Although crystalline silicon solar cells dominate PV market, the shortage of silicon and the high expenses of silicon crystals have accelerated the need to develop alternative materials for PV applications [2]. The potential of multicrystalline silicon (mc-Si) materials for large scale terrestrial PV application is recognized. However, the use of polycrystals in processing solar cells introduces inhomogeneous performance of the solar cell due to the different grain sizes and the distribution of grain boundaries (GBs). The density of impurities present within the bulk material and at the GBs can impede with the photo-generated carriers leading to the recombination of carriers [3]. In addition to the material defects, surface defects can
degrade the performance of a solar cell. Photons are reflected off the surface defect, resulting in fewer photons reaching the cell for the generation of current carriers. To investigate performance limiting effects in solar cell wafers fabricated from materials such as mc-Si, characterisation techniques are needed.

1.2. The objectives of this study

The objectives of this investigation are to characterize performance limiting defects in solar cells. The primary aim was to develop a topographic technique for quantitatively analysing defects in solar cells and also an assessment procedure capable of assessing the current-voltage characteristics of cells. This study used the Light Beam Induced Current (LBIC) and I-V characterisation systems developed at NMMU for indoor measurements. The LBIC system provided information about the distribution of defects in solar cells. In addition, assessment of device performance parameters was possible using the I-V characterisation system.

1.3. Outline

Chapter 2 presents the fundamentals of solar cell principles and operations. The description is based on how solar radiation is utilized by semiconductor materials. Emphasis is given to p-n junction solar cells and their I-V characteristics. The fundamental equations and device parameters used for describing I-V characteristic of ideal and non-ideal solar cells are presented.

Chapter 3 describes the scanning techniques and their applications on PV devices. The descriptions include the principles of non-destructive technique such as LBIC. The fundamental equations for calculating quantum efficiency of solar cells are also described.

In chapter 4, the description and the methodology of the LBIC system developed, is given. The layout of how the LBIC system can be used to determine quantum efficiency of solar cells is described. Also presented is the description of the dark and illuminated I-V characterisation systems used in this study.
Chapter 5 presents and discusses the LBIC results obtained on different solar cell technologies. The cells investigated included crystalline silicon cells and thin film Cu(In,Ga)(Se,S)\textsubscript{2} solar cells. The quantum efficiency measurements of the cells are presented and analysed.

In chapter 6, the procedure for fabricating mesa diodes for the characterisation of solar cells is discussed. The purpose of mesa diode development was to illustrate the usefulness of the procedure to determine the spatial distribution of device parameters and defects in solar cells. The solar cells investigated were mc-Si and EFG-Si solar cells. The LBIC results of solar cell mesa diodes were measured and analysed. In addition, the I-V characteristics obtained of mesa diodes for the analysis of the electronic transport properties are discussed.

1.4. References


Chapter 2

Principles and Operations of Solar cells

2.1. Introduction

The common types of solar cells are based on the photovoltaic (PV) effect, which occurs when light falling on a semiconductor device produces a potential difference across the p-n junction. When this happens and a device is connected to a load, electrical power is generated and a current can flow in an external circuit. This chapter discusses the operating principles of solar cells, focusing more on the p-n junction and current-voltage (I-V) characteristics of solar cells. Crystalline silicon solar cells are examples of p-n homojunction devices and thin-film solar cells based on CuInGa(Se,S)_2 alloys as absorber layer form p-n heterojunction cells.

The performance and device parameters of p-n junction devices describing the behaviour of I-V characteristics of the devices are mentioned in this chapter. The I-V characterisation of solar cells and modules can be performed under illumination or under dark conditions. Illuminated I-V characterisation is used mainly for determining performance parameters, e.g. open-circuit voltage, short-circuit current, output power, fill factor and the efficiency of the cell. On the other hand, dark I-V characterisation yields information regarding diode parameters and parasitic resistances.

2.2. The p-n junction

When a uniformly doped n-type (excess of conduction electrons) semiconductor material is joined to a uniformly doped p-type semiconductor, the configuration produces the p-n junction. The difference in carrier concentration causes electrons to diffuse from the n-type to the p-type and holes move from the p-type to the n-type.
During redistribution, the carriers near the junction edge of the two materials diffuse away leaving behind ionized atoms. Electrons on the n-region leave behind a positively charged ion, and holes on the p-region leave behind a negatively charged ion. This process establishes a space charge region (SRC) around the junction [1].

2.2.1. Homojunction structure

In a p-n homojunction, for example silicon, one side is altered to form p-type and other side n-type. Terrestrial p-n homojunction solar cells have a single energy band-gap, $E_g$. Photons entering a solar cell having energy less than $E_g$ of the cell material, make no contribution to the generation of current. However, photons with energy equal or greater than $E_g$ will contribute to the efficiency of the cell, but some with much higher energy than the $E_g$ will be lost as heat. The design of the p-n junction device can affect the efficiency of the device. This includes factors such as the distribution of dopants on either side of the junction, purity of the semiconductor material, and the depth of the junction below the surface of the device. Fig. 2.1(a) shows a schematic of a typical p-n homojunction solar cell connected to a load. The corresponding energy diagram under light illumination is also shown in Fig. 2.1(b). Incident photons with enough energy will excite the electrons from the valence band (VB) to the conduction band (CB), resulting in electrons taking part in the conduction process. The presence of the built-in electric field ensures that the minority carriers created within a diffusion length of the junction drift to the region where they become majority carriers. If an external load is connected, as shown in Fig. 2.1(a) carriers will flow externally constituting a current through the load.
An equivalent ideal solar cell under illumination can be represented by a current source $I_L$ connected in parallel with a diode, as shown in Fig. 2.2 (solid lines). The corresponding I-V characteristic is described by the Shockley solar cell equation as [2]

$$I = I_0 \left[ \exp\left(\frac{qV}{k_B T}\right) - 1 \right] - I_L$$

(2.1)

with

$$I_0 = qA n_i^2 \left[ \frac{1}{N_A \tau_n} + \frac{1}{N_D \tau_p} \right]$$

(2.2)
Equation 2.2 corresponds to the reverse saturation current which depends on the doping concentration. The terms in equations 2.1 and 2.2 are:

\[ I = I_0 \left[ \exp \left( \frac{q(V + IR_s)}{n_1 kT} \right) - 1 \right] - I_0 \left[ \exp \left( \frac{q(V + IR_s)}{n_2 kT} \right) - 1 \right] - \frac{(V + IR_s)}{R_{sh}} \]  

(2.3)

with:  
\[ I_0_1 = \text{the ideal diode saturation current.} \]
\[ I_0_2 = \text{the non-ideal diode saturation current.} \]
$n_1$ and $n_2$ = diode ideality factors. When $n=1$ (ideal case) and $n>1$ (non-ideal)

$V$ = the measured voltage across the terminals of the cell

When a solar cell is under dark conditions, its I-V characteristic differs from the illuminated characteristic. Therefore, equation 2.3, can be written as

$$I = I_{01} \left[ \exp \left( \frac{q(V - IR_s)}{n_1 kT} \right) - 1 \right] + I_{02} \left[ \exp \left( \frac{q(V - IR_s)}{n_2 kT} \right) - 1 \right] + \frac{(V - IR_s)}{R_{sh}}$$

(2.4)

where $V$ is the applied voltage.

The dark I-V characteristic of a solar cell at lower current levels is influenced by the shunt resistance and therefore, $R_{sh}$ can be accurately determined. In this case the recombination process in the SCR is predominant and the ideality factor, $n_2 \approx 2$ [3]. This implies that, in equation 2.4, the second and third terms dominate. At the mid current levels, the ideal case is predominant yielding $n_1 \approx 1$ and the first term in equation 2.4 dominates. At higher current range the effect of series resistance is predominant and $n_2 \approx 2$.

2.2.1.1. Device performance parameters

The I-V characteristic of a solar cell based on a one-diode model is considered. Equation 2.3 can be rewritten to describe the characteristic of a one-diode model:

$$I = I_L - I_{0} \left[ \exp \left( \frac{q(V + IR_s)}{nkT} \right) - 1 \right] - \frac{(V + IR_s)}{R_{sh}}$$

(2.5)

In the ideal case, i.e. $R_{sh}$ is taken to be infinite and $R_s$ is neglected, the short circuit current $I_{sc}$ is equal to the photo-generated current $I_L$. If no load is connected to an
ideal solar cell, the open circuit voltage \( V_{oc} \) can be measured at the terminals. Therefore, from equation 2.5, \( V_{oc} \) is given by

\[
V_{oc} = \frac{k_B T}{q} \left[ \ln \left( \frac{I_{sc} - \frac{V_{oc}}{R_{sh}}}{1} \right) - \ln I_0 \right]
\] (2.6)

and if \( R_{sh} \) is assumed to be infinite, then \( R_{sh} \gg \frac{V_{oc}}{I_{sc}} \) and \( \left[ \frac{I_{sc}}{R_{sh}} - \frac{V_{oc}}{R_{sh}} \right] > 1 \), therefore equation 2.6 becomes:

\[
V_{oc} = \frac{k_B T}{q} \ln \left( \frac{I_{sc}}{I_0} \right)
\] (2.7)

The output power of the cell is defined by, \( P = IV \) and therefore the cell generates the maximum power \( P_{max} \) at a maximum voltage \( V_{max} \) and maximum current \( I_{max} \). The fill factor \( FF \) of the cell, which is the area under the I-V characteristic of the cell, can be defined as:

\[
FF = \frac{P_{max}}{I_{sc} V_{oc}}
\] (2.8)

and the conversion efficiency \( \eta \), of a solar cell can be conveniently calculated as:

\[
\eta = \frac{P_{max}}{E \times A}
\] (2.9)

where \( E \) is the irradiance of the incident light and \( A \) is the area of the cell.

2.2.2. Heterojunction structure

The p-n heterojunction or heteroface device is formed when two semiconductor materials of different band-gap \( E_g \) are joined together. The most common
heterojunction devices are based on thin film technology. For example, solar cells based on alloys CuInSe$_2$, Cu(In,Ga)Se$_2$, and Cu(In,Ga)(Se,S)$_2$ or CIGSS form heterostructures. The advantage of thin film solar cells in general is their ability to absorb more light, even though multiple junctions are required to improve their optical thicknesses. Fig. 2.3(a) illustrates the CIGSS solar cell heterojunction device structure. The corresponding energy band diagram is shown in Fig. 2.3(b). The fabrication of a typical cell is briefly described as follows [4]. A Molybdenum (Mo) back contact (~ 1 $\mu$m) is deposited on a soda lime glass substrate. Se diffuses from the growth of p-type CIGSS, forming a MoSe$_2$ layer on top of Mo layer. CIGSS was grown as a p-type absorber layer, followed by an n-type CdS layer with band gap of 2.5 eV grown on the absorber layer to reduce collection losses. Transparent conducting oxides such as i-ZnO layer is then grown as a window layer, followed by another oxide, ZnO:Al, which serve as the antireflective coating. CIGSS solar cells that were used in this study had CIGSS alloys prepared by temperature controlled selenization and sulphuration processes. Cu$_x$(In,Ga) was first annealed with diluted H$_2$Se in Ar mixture. The sample was finally sulphurized in a diluted H$_2$S in Ar.

**Figure 2.3:** (a) Structure of CIGSS solar cell, and (b) the corresponding energy diagram of the cell.
In the CIGSS alloy, Ga and/or S increases the band gap causing the conduction band to rise. This can cause the electrons to tunnel from the n-type CdS and recombine with the holes from the p-type CIGSS side. The other possible recombination mechanisms in CIGSS solar cell include recombination due to tunnelling at the CdS/CIGSS interface, and in the SCR [5].

The I-V characteristics of the CIGSS solar cells may be described with the saturation current \( I_0 \) thermally activated and may be defined as

\[
I_0 = I_{00} \exp \left( -\frac{E_a}{n k_B T} \right)
\]  \hspace{1cm} (2.10)

where the pre-factor \( I_{00} \) depends on the recombination mechanism dominating \( I_0 \) and is temperature dependent, \( E_a \) is the activation energy. \( E_a \approx \phi_h \) for recombination at the CdS/CIGSS interface, where \( \phi_h \) is the barrier height.

The open circuit voltage \( V_{oc} \) can be derived from equations 2.1 and 2.12 as [6]:

\[
V_{oc} = \frac{E_a}{q} - \frac{n k_B T}{q} \ln \left( \frac{I_{00}}{I_L} \right)
\]  \hspace{1cm} (2.11)

2.3. Summary

The basis of solar cell operation is the p-n junction formed between n-type and p-type semiconductor materials with the same lattice structures. The formation of p-n homojunction between materials with same band gap was discussed. Also p-n heterojunction formed between n-type CdS and p-type CIGSS semiconductors having different band gaps were presented. In addition, the one-and two- diode models used to describe the I-V characteristics were presented.
Device performance parameters such as $I_{sc}$, $V_{oc}$ and $P_{max}$ which are obtainable from the illuminated I-V characteristic, were used to calculate $FF$ and $\eta$ of the device. Also the effect of parasitic resistances on I-V characteristic of a solar cell, was briefly mentioned.

2.4. References


Chapter 3

Scanning techniques and applications

3.1. Introduction

The physics of a p-n junction solar cell has been described in the preceding chapter. In that chapter it has been mentioned that a basic understanding of p-n junction solar cell operation can be gained by interpreting its current-voltage characteristics. In addition, device and performance parameters describing I-V characteristics of solar cells and modules can be used for quality control during production and also to provide insights into the operation of the devices.

This chapter presents methods that can be used for further investigation into the opto-electrical characterisation of solar device performances. Scanning measurement techniques provide a direct link between the spatial non-uniformity of the cell material inherent in solar cells and their overall performance. Scanning and mapping tools which are mostly used in photovoltaic applications in recent studies include electron beam induced current (EBIC) [1], solar light beam induced current (S-LBIC) [2] and laser beam induced current (LBIC) [3], to name a few. These techniques are tools for mapping the distribution of possible irregularities due to the presence of impurities in solar cells.

This chapter starts with a brief background of equations describing the generation of photo-current. A summary of the scanning techniques is also given. Although EBIC is as important as other scanning techniques, this study focuses on the light beam induced current methods. The basic principles governing the light beam induced current method and the application of the method are presented in this chapter. The applications of LBIC method include computing both external and internal quantum efficiency of solar cell devices.
3.2. Current at a monochromatic wavelength

When a monochromatic light of wavelength $\lambda$ is incident on the front surface of a solar cell device, a photo-generated current can be obtained. For an abrupt p-n junction solar cell device with uniform doping, mobility and lifetime of carriers on each side of the junction, generation of photo-current can occur in both quasi neutral zones and also in the space charge region (SCR). Therefore, the total photo-generated current density at a given $\lambda$ can be expressed [4]:

$$J(\lambda)=J_n(\lambda)+J_p(\lambda)+J_{SCR}(\lambda)$$  \hspace{1cm} (3.1)

where:

- $J_n(\lambda)$ is the photo-generated current density in the n-region at $\lambda$.
- $J_p(\lambda)$ is the photo-generated current density in the p-region at $\lambda$.
- $J_{SCR}(\lambda)$ is the photo-generated current density in the SCR at $\lambda$.

3.3. Scanning techniques

The applications of scanning analysis techniques in solar cell devices include detection of surface features and material defects. These techniques are very useful for mapping spatial distribution of induced current on solar cells and are described in the following sections. Since their operation is based on local injection of minority carriers, the measurement closely imitates the operation of a solar cell.

3.3.1. EBIC

EBIC is a scanning technique that employs an electron beam to induce a current within a semiconductor material. In solar cell devices EBIC is used to obtain current maps depicting the characteristics of the device, e.g. the presence of extended defects such as grain boundaries (GBs) and material dislocations. Since the scanning electron
microscope (SEM) is a convenient source of an electron beam, most EBIC techniques are performed using a SEM. The resolution of the topographical image is determined by the size of the electron cloud generated in the sample by the impinging electron beam, and it depends upon the accelerating voltage of the electrons. The limitations for this technique include the fact that it can only be used to study small areas of a solar cell whereas other techniques such as S-LBIC and LBIC can be used to map the whole wafer. On the other hand, the advantage of EBIC is its capability to analyse shallow and deep level recombination centres [5].

3.3.2. S-LBIC

S-LBIC is a technique that uses solar radiation as light source to induce a current within a sample which may be used as a signal for generating maps that illustrate characteristics of the sample. Vorster et al [2] developed a system that uses a collimated beam of sunlight as a beam probe. In addition, the S-LBIC measurements performed at high intensity with full solar spectrum radiation can give a measure of the uniformity of solar devices that are intended for concentrator photovoltaic applications. As it will be seen in Chapter 5 that the S-LBIC technique can also be employed to obtain a photo-generated current across multicrystalline solar cells.

3.3.3 LBIC

LBIC is a scanning analysis that uses a laser beam probe as a light source. Although many LBIC designs uses laser light of monochromatic wavelength, Sites developed a system that employs multiple wavelengths guided through a single mode optical fibre [6]. Recent studies have demonstrated LBIC measurements that can be performed at high intensities with a beam diameter approaching 1 μm [7, 8]. Limitations of LBIC systems include the inability to obtain a beam spot size of less than 1 μm and since the technique uses an optical beam as probe wavelength also limit LBIC resolution. Also the resolution is limited by the diffusion length of the minority carriers in the material and hence the divergence of the beam leads to an effective spot size which increases within the material as it is absorbed [9]. In addition, the depth of the analysed layer is shallow typically several tens or hundred of microns, depending on
the wavelength used. Therefore, only a small fraction of the generation volume in which the electron-hole pairs are created can be analysed.

3.4 Principle of LBIC

When a light beam penetrates a semiconductor, electron-hole pairs are created with energies near the band-gap of the host material. By electrically contacting the host semiconductor material under LBIC test, which is done by ohmic contacts, current carriers can be collected, amplified and analysed. The light is scanned across the sample in a raster pattern while measuring the photo-generated current as a function of position and eventually a topographical image of the current of the sample is produced. In the analysis stage, the current distribution in a solar cell device is interpreted as variations of contrast in an LBIC image. LBIC is sensitive and responsive to current carrier recombination. For example, in defect areas where there are low levels of induced current, an LBIC image will appear dark compared to other areas without defects. Such locations can act as recombination centres. Defects can occur at the surface of the device or as extended defects such as grain boundaries (GBs), which are electrically active. Often GBs in LBIC images are identified as dark irregular lines in multicrystalline solar devices.

3.5 Applications of LBIC

3.5.1 Effect of a grain boundary on a LBIC signal

This section presents a brief summary illustrating the effect of a grain boundary on the LBIC contrast. As mentioned in the preceding section, a GB appears darker in LBIC maps. A number of reviews have discussed LBIC characterisation of GBs, for example a reader is referred to Marek [9], Naury [10], Donolato [11] and Dimassi [12]. Fig. 3.1 shows schematic diagrams adopted for describing LBIC observations at a GB in a multicrystalline solar cell. Fig. 3.1(a) shows a light beam irradiance incident on a typical mc solar cell. In (b), the typical LBIC linear scan across a GB is illustrated. In this figure, high levels of LBIC signals indicate higher efficiency of a cell performance whereas a lower LBIC signal, i.e. at GB, shows low cell efficiency. It can be mentioned that the influence of GBs on LBIC profile differs.
This is due to different electrical activities of GBs which depend on the content of the impurities present in the GBs [13].

![Diagram of a multicrystalline solar cell](image)

(a)

**Figure 3.1:** (a) Schematic of a multicrystalline solar cell. Also shown is the incident light beam. (b) Line scan profile across a GB on a solar cell.

Returning to Fig. 3.1(a), the photo-generated current $I(x)$ due to a defect such as GB can be expressed as [9]:

$$ I(x) = I_0 - I^\ast(x) $$

(3.2)

where:

- $I_0$ is the background current, i.e. current at a large distance from the GB.
- $I^\ast(x)$ is the current due to the presence of the GB.

The related contrast $C$ of LBIC scans is given in terms of:
3.5.2 Quantum efficiency

The quantum efficiency (QE) measurement is a very useful tool for the optimization of solar cells and PV modules. QE refers to how well the device utilizes the incident photons to generate an electrical current. Note, however, that the conditions under which QE measurements can be performed are different to actual operating conditions of a real solar cell. Thus, QE measurements can be obtained using a monochromatic light beam, while a practical solar cell operates under conditions involving the full solar spectrum. Two measures of QE are external (EQE) and internal (IQE) quantum efficiency. EQE and IQE can be described by referring to Fig. 3.2 below.

**Figure 3.2**: Sketch of a solar cell illustrating the optical losses.

Fig. 3.2 illustrates the scheme adopted for describing reflection and transmission of light beam on a solar cell. When a beam of light is incident on to the front surface of a solar cell, not all photons are absorbed into the cell. Part of the beam is reflected at the antireflective coating (ARC). Part is reflected at the back contact and part is transmitted through the cell. The intensity of light close to the surface of a cell can be
described by the absorption equation given by Beer’s Law, which states that the intensity $I_{\text{depth}}$ of the light at the depth $x$ in the semiconductor device, is expressed as:

$$I_{\text{depth}}(x) = I_{\text{light}} e^{-\alpha x}$$  \hspace{1cm} (3.4)

where $I_{\text{light}}$ is the intensity of the light before entering the surface of the device, and $\alpha$ is the absorption coefficient of the device at the specific wavelength. Incident photons with lower energy than the band gap of the host won’t contribute directly to the photo-generated current. Photons with energy greater than or equal to the band gap will contribute to the photo-generated current. These photons contribute to the spectral response (SR) of the device, which is the ratio of the photo-generated current $I_{\text{photo}}$ in amperes produced by the solar device over the incident radiant power, $I_{\text{light}}$. The SR, which is also known as the collection efficiency at each wavelength $\lambda$, is such that $SR = SR(\lambda)$. Therefore, mathematically, $SR$ can be expressed as:

$$SR(\lambda) = \frac{I_{\text{photo}}(\lambda)}{I_{\text{light}}(\lambda)}$$  \hspace{1cm} (3.5)

EQE is defined as the ratio of the photo-generated current per unit time to the number of photons incident on the device per unit time. It is a function of SR and therefore, from equation 3.5 it follows that EQE can be given as:

$$EQE(\lambda) = SR(\lambda) \frac{hc}{e\lambda}$$  \hspace{1cm} (3.6)

where $h$ is the Planck’s constant, $c$ the speed of light and the electron charge $e$.

It is obvious from equation 3.6 that EQE includes the effect of optical losses such as reflection ($R_{\text{front}}$ and $R_{\text{back}}$) away from the cell and transmission through the cell. However, it is useful to look at the QE of the light that remains after the reflected and transmitted light has been lost. IQE refers to the efficiency with which photons that are not reflected or transmitted through the cell can give rise to the photo-generated
current carriers. Thus, experimentally, the IQE can be obtained through the light reflectance and the SR. Therefore, IQE can be derived as:

\[
IQE(\lambda) = \frac{1}{1 - R(\lambda)} \times \frac{I_{\text{ph}}(\lambda)}{I_{\text{light}}(\lambda)} \times \frac{hc}{e\lambda} \tag{3.7}
\]

where \( R(\lambda) \) is the reflection coefficient at wavelength \( \lambda \), which is the ratio incident power to the reflected intensity.

From equations 3.6 and 3.7, IQE can be written in terms of EQE as follows;

\[
IQE(\lambda) = EQE(\lambda) \times \frac{1}{1 - R(\lambda)} \tag{3.8}
\]

It will be seen in Chapter 5 that employing equations 3.6 and 3.8, EQE and IQE values of crystalline and thin-film solar cells can be obtained from LBIC measurements, respectively.

### 3.6 Summary

The main objective of this chapter was to understand the principles and applications of light induced beam current techniques. The fundamental equation used to describe solar cell devices was given. A brief discussion describing the effect of defects on LBIC signals was also presented. The spectral response and quantum efficiency of a solar cell device was briefly introduced. These parameters are important when investigating and characterizing defects in solar cells.

### 3.7 References


Chapter 4

Experimental details

4.1. Introduction

This chapter describes in detail the methodology carried out to investigate defects in crystalline and thin film solar cells. In this chapter, a LBIC set-up and also a current-voltage (I-V) measurement technique are described. The basic LBIC set-up used in this study adopted a similar technique used in the past [1]. However, this chapter presents a LBIC technique that uses a set-up to quantitatively study defects in solar cells. Our technique consists of a calibrated measurement of photo-current and reflection coefficient. Also, the system for performing illuminated I-V characteristics of solar cells is presented. All the LBIC measurements were performed using a monochromatic wavelength laser with a focused beam while the illuminated I-V measurements of cells were obtained by using a defocused laser beam. To complement the LBIC and illuminated I-V measurements, the method for obtaining dark I-V measurements is also described in this chapter. The dark I-V procedure does not provide information regarding short-circuit current or open-circuit voltage, but is more appropriate than illuminated I-V measurements in determining device parameters. Various studies at NMMU have shown that device parameters obtained from dark I-V characteristics of solar cells and modules are in general agreement with the light I-V measurements [2, 3, 4].

The first part of this chapter focuses on the description and operation of the LBIC system. Two set-up configurations for LBIC and I-V measurements are described. These configurations are then discussed in terms of the instruments and the methodology used. The function of each instrument is given. Also, the brief description of the dark I-V system and the experimental procedure used is given. A detailed description and discussion of each component of the dark I-V system adopted in this study has been reported [2].
The second part of the chapter provides a detailed procedure used to develop mesa diodes on solar cells. The method enables the fabrication of circular solar cell mesa diodes by using chemical etching.

4.2. **LBIC set-up description and methodology**

4.2.1 Set-up description

**Figure 4.1**: A photograph of the LBIC system

Fig. 4.1 presents a photograph of the laser X-Y stepping system. The system consists of basic sub-systems and these include the stepping equipment, optical system, data acquisition data and electronics. The stepping equipment comprises an X-Y translation stage driven by computer controlled stepper motors. The optical system consists of the laser source, beam expander, beam splitter, optical detector and objective lens. The data acquisition box is made up of drive boards for communication between the motors and a computer. Also the box has boards interfacing the current-to-voltage pre-amplifier to a computer. The electronics set-up incorporates detectors and a solar cell sample connected to the pre-amplifier.

Fig. 4.2 shows the schematic representation of Fig. 4.1. A laser source is placed horizontal as shown. A beam expander mounted in front of the laser expands the beam. An expanded beam is split into half by a beam splitter, with one half
perpendicularly incident onto the sample and the other half transmitted to a secondary solar cell. Before reaching the sample, the beam is focussed with an objective lens. The objective lens used in this study also collects part of the light reflected off the surface of the sample and direct it to a detector 2 (optical sensor) which is mounted about 30 cm above the sample. The other reflected part of the beam is collected by a detector 1 (single-crystalline silicon solar cell). Because the reflected light beam directed to detector 2 is larger than the circumference of the detector, a lens is used to focus it down for all the rays to fall onto detector 2. Detector 1 with an opening of < 2 mm diameter can be placed 2-3 mm above the sample.

\[\text{Figure 4.2: A schematic diagram of the LBIC system}\]

\[\text{4.2.2 LBIC methodology}\]

A sample is illuminated by a laser source with a monochromatic wavelength. The light reflected off the sample often scatters in different angles and is therefore collected by detectors 1 and 2. Detector 2 measures current which is proportional to the reflected intensity. The current is then amplified using pre-amplifier 2 and converted to voltage which is transferred to the data acquisition card. Detector 1 measures the reflected current which is also amplified. Also the photo-generated
current collected from the sample, is amplified and is sent to the acquisition card. LabView software control has been developed and is able to automate the motion control as well as data acquisition. A LabView programme written was used to convert voltage measurements back to the current. The induced current and relative reflection intensity is measured as a function of X-Y position on the sample. With the specified X-Y stage stepping size and measured beam diameter, the induced current and the corresponding reflection intensity maps are thus obtained. To determine the quantum efficiency of a solar device, the incident intensity according to equations 3.6 and 3.7 (in chapter 3) has to be known. Prior to the start of measurements the optical sensor is mounted onto the position where a sample is usually mounted and the apparent laser light intensity can be measured. This considers the losses that might occur through the optical system, in particular the losses at the objective lens. This approach differs from the other methods which use light intensity measured with the secondary solar cell for the determination of quantum efficiency [5].

4.3. I-V set-up description and methodology

4.3.1 Set-up description

![Diagram of illuminated I-V system](image.png)

**Figure 4.3:** A schematic diagram of the illuminated I-V system.

The configuration of the set-up for performing I-V measurements is shown in a schematic diagram in Fig 4.3. Similar to the LBIC set-up, a sample is mounted onto the X-Y stage and the laser is mounted horizontally. Some of the apparatus from the
optical system of the LBIC set-up are adopted and used in the I-V set-up configuration. These apparatus includes a laser, beam expander and beam splitter. The additional system components listed in Fig. 4.3 are an alternating current (ac) signal generator, a digital oscilloscope and pre-amplifier.

4.3.2 Methodology

Similar to the LBIC technique described above, a laser source is mounted horizontal to the sample. In this set-up an objective lens is not used thus making the beam spot reaching a sample defocused. The sample is biased from the reverse to forward bias using an alternating current (ac) voltage source. At predetermined bias voltages, an induced current is measured and converted into voltage signals using pre-amplifier. The bias voltage and the voltage (as a function of the measured current) are captured by an oscilloscope. The data is then transferred from the oscilloscope into a computer via a GBIP bus. A LabView programme then records and plot the voltage and current data.

4.4 Details of the components

This section describes in details the apparatus used in the LBIC and I-V system configurations.

4.4.1 Laser source

![Figure 4.4](image): A Coherent Cube laser source.
A monochromatic wavelength laser was used as a light source. Fig. 4.4 presents a photograph of the Coherent Cube 660 laser module which was used for LBIC and I-V measurements and is mounted on a heat sink as seen. The CUBE 660 nm laser delivers a circular beam of an intensity in the range, 1 mW - 60 mW of continuous wave, pulse and analogue output power at 660 nm. This semiconductor laser has circular prisms mounted in front of the single emitter laser diode, making the output beam circular in shape. The laser head measures 100 x 40 x 40 mm³ and dissipates heat when lasing. System integration of the laser module to a computer is facilitated by USB connection. Also, software supplied by the manufacturer enables a control of laser operation parameters such as power level and mode status.

4.4.2 Beam expander and beam splitter

![adjusting ring](image)

**Figure 4.5:** (a) 6X beam expander and (b) 50/50 beam splitter.

Fig. 4.5(a) shows a photograph of the beam expander used in this thesis. The built-in optics includes a plano-concave lens situated at the 2 mm diameter aperture entrance. In addition, an achromatic lens of about 25 mm is mounted at the exit. The entering light beam diameter first gets increased and then the beam diverges onto the achromatic lens which yields the collimated beam. An adjusting ring situated in front of the exit lens enables to control the diameter of the output beam with a 6X beam expansion power.

A 50/50 cube beam splitter mounted on a sample holder is shown in Fig. 4.5(b). This splitter is made up of two identical triangular prisms which are joined together with an interference coating. The absorption loss to the coating layer is minimal. It is capable
of transmitting 50% and reflecting 50% of light beam at 550 nm even though the output beam may be polarized.

### 4.4.3 Objective lens

![Image of objective lens](image)

**Figure 4.6**: (a) Photograph and (b) schematic diagram of the reflective objective lens.

Fig. 4.6(a) and (b), respectively, show a photograph and a schematic diagram of an objective lens used to focus the laser beam. This state of the art lens whose focal distance is 13.3 mm, was provided by Edmund Optics. It comprises a small 8.8 mm diameter mirror and three mirrors facing the small mirror. It can be seen that the collimated beam of light enters through the tube and reflected off the small mirrors onto the three mirrors. The big mirrors then focus the light on to the sample situated at the focal point below the lens. The light reflected off the sample is directed through the beam splitter to a detector.

### 4.4.4 Reflection detectors

**a) Laser intensity sensor**

The optical sensor with model 212 that was used to capture the reflection intensity (refer to section 4.2) was manufactured by Coherent and is shown in Fig. 4.7(a). The reason of using this sensor is its silicon-based technology photo detector. Therefore, its absorption coefficient will be similar to that of silicon-based solar cells. The detector converts light intensity into an analogue voltage that can be digitized. The
output voltage can be monitored using a power meter. In this study, however, the measured voltage is directly amplified by using a pre-amplifier.

![Image](image.png)

(a)  
(b)

Figure 4.7: Reflection detectors (a) Optical sensor and (b) silicon solar cell.

b) *Si solar cell reflection sensor*

Another detector used to measure the reflection intensity was a single-crystalline silicon solar cell. Fig. 4.7(b) shows the cell with a 1.5 mm diameter hole. A technique was developed to carefully drill holes through a cell. In the technique a solar cell is placed between two pieces of a glass to prevent the cell from breaking. This technique is simple and fast compared to other methods such as laser cutting [6].

4.4.5 X-Y translation stage and stepper motors

An X-Y translation stage able to move a distance greater than the size of a solar cell in both X and Y directions was used. The stage comprises an adjustable sample holder and two stepper motors supporting the X and Y axes carriages. The four-phase hybrid stepper motors provide enough stepping speed with the stepping angle of 1.8° to ensure a minimum stepping size of 5 μm. The specifications provided by the manufacture rate these motors at 12 V, 0.16 A with a holding torque of 70 Nm.
4.4.6 Drive board circuitry

The interfacing of the stepper motors to the motion controller card was achieved by using two unipolar drive boards provided by the RS components. The control logic voltage can either be 0 V low or 12 V high and also the drive boards have stepping frequency ranging between 1 to 25 kHz. A PCI 1240 4-axis stepping/pulse type motion controller card was chosen for driving the boards. This card uses 32-bit logic counter for position control and has a pulse output with amplitude of 5 V. To achieve 12 V control voltage required by the drive boards, a circuit consisting of transistors was built to employ the 5 V pulses from the motion controller.

4.4.7 Current amplifier

![SR570 current pre-amplifiers](image)

**Figure 4.8:** SR570 current pre-amplifiers.

The current from the optical system was amplified using a low-noise SR570 current pre-amplifier. Fig. 4.8 shows a photograph of the SR570 pre-amplifier. The front panel enables a user to select parameters such as filter type, bias voltage and sensitivity settings. The pre-amplifier is capable of converting an input current to an output voltage. It has a maximum gain of 1 pA/V with the sensitivity settings from 1 pA/V to 1 mA/V that can be selected in a 1-2-5 sequence to avoid overloading. An input current signal can be adjusted using offset currents in the range \(+1\) pA - \(+1\) mA in 0.1 % increments. For the LBIC measurements two pre-amplifiers were used. One measured the induced current from the solar cell sample and the other measured the voltage from the reflection detectors. The output voltage signals were transferred to the data acquisition circuit.
4.4.8 Data acquisition

The data acquisition consists of a low-noise PCI 703 input/output card provided by Eagle Technology. The card features 64 single-ended analogue inputs that allow the input voltage gain in the range between, ±50 mV and ±10 V. The 2 x 14-bit analogue output channels and the maximum sampling rate at frequency 400kHz can be used to measure voltage signals as waveforms. It also has the ability to perform multiple measurements that include measuring solar cell current and generating digital signals for the stepper motor drive boards.

4.4.9 Oscilloscope and function generator

![Function Generator](image1.png) ![Oscilloscope](image2.png)

**Figure 4.9:** (a) 33220A Agilent function generator. (b) Agilent digital Oscilloscope.

An Agilent function generator shown in Fig. 4.9(a) was used as a voltage source for biasing the solar cell. This generator is capable of generating sine waveforms with a frequency range, 1 μHz – 20 MHz and at 1 μHz resolution.

For capturing I-V measurements, a digital oscilloscope, model DSO6032A from Agilent Technologies was employed and is presented in Fig. 4.9(b). Measured data is stored and can be transferred via the USB port accessible in the front panel. This oscilloscope has input channels that can simultaneously acquire waveforms at 1Gsample/s sampling rate. In this study, bias voltage and measured cell current signals were captured through the two channels. The different display modes make it possible to view and analyse the data. For example, the measured I-V curve of a solar cell is seen on the display screen when the instrument is in X-Y mode. For every I-V
data, their corresponding sine waveforms can be displayed. The waveform data is transferred from the scope to the computer by means of a GPIB connection.

4.4.10 System software

The system software to control all the measurement hardware parameters and process the data has been developed. The LabView software used has tools that provide support for data processing and acquisition [7]. The operation of the software can be divided into two sections. Firstly, to perform LBIC measurements and also the acquisition of the I-V waveforms.

For LBIC measurements, the LabView program written featuring the PCI card drivers can drive the stepper motors and also measure both the induced current and the surface reflection intensity of the solar cell. Control of step sizes and other basic parameters are available in the program. 2D (line scans) and 3D (surface maps) formats of photo current as a function of X-Y position, can be presented and saved to data files.

A different LabView program was written to capture I-V data from the GPIB. The program is able to convert the calibrated waveforms into X-Y plane. In addition, the program uses the preamplifier sensitivity so that the X-Y data correspond to the bias voltage and measured photo current of a cell. For illustration of conversion of waveforms to I-V curve, Fig’s 4.10(a) and (b) are presented. In (a), voltage (red data) and current (blue data) sine waves with frequencies of 21 Hz are shown. The forward and reverse sweeping are defined by the positive and negative voltage, respectively. The colouration describes the forward and reverse sweeps. The teal colour represents the forward sweep whereas reverse sweep is indicated by a grey colour. The separation at about point 59 between the two regions as shown in the figure indicates the transition from forward to reverse sweeping. At the transition point, current reaches minimum and voltage reaches maximum point. Also the sweeping is indicated in the corresponding I-V curves shown in (b). In comparing (a) and (b), it can be seen that a complete I-V curve corresponds to half cycle, i.e. teal or grey colour. For example, the high and low amplitude range of the current waveform equals the positive and negative photo current range as seen in (b). Therefore, the
short-circuit current \((I_{sc})\) of the cell can be deduced from the waveform as indicated in (a).

**Figure 4.10:** (a) Sine waveforms. Teal colour indicates the forward sweep and grey illustrates the reverse sweep. Also shown is the transition point at \(I = 0mA\). (b) The I-V curves of waveforms shown in (a).
4.4.11 Peltier cell

![Peltier cell](image)

**Figure 4.11:** (a) Photograph and (b) schematic of a Peltier element.

Fig. 4.11(a) shows a photograph of a Peltier element used as a temperature controller. The heat-sink prevents the element from overheating and keeps it running efficiently. The schematic representation of (a) is shown in Fig. 4.11(b). A Peltier element is a thermoelectric device that consists of p- and n-types of semiconductors which are alternatively arranged as depicted in (b). When the electrical power is supplied to the element as shown in (b) current flow through in the direction illustrated. The majority carriers in both p- and n-type semiconductors drift from the top side to the bottom side of the element. This results in the top side cooling and heat dissipating through the bottom side into the heat-sink below the element. The amount of heat flowing out of the element is equal to the amount of heat flowing into the element. In addition, changing the direction of the current leads to the majority carriers moving from the bottom side to the top. The temperature of the top side then increases and eventually achieving heating and cooling in the top and bottom sides, respectively. When using a Peltier element, it is necessary to use a heat-sink capable of sinking all the heat produced by the element. It is also necessary to make a good thermal contact between the element and the heat-sink. This was done by using a thermal paste. A Peltier element uses a method that has a fast response and can shift quickly between heating and cooling and the temperature can be precisely controlled.
4.5 Dark I-V measurements

![Sample holder with CIS mini module](image1)

**Figure 4.12:** Dark I-V system used in this study.

A dark I-V system developed at the Nelson Mandela Metropolitan University was employed to perform the measurements. The system consists mainly of a pA meter / DC voltage source, a sample holder, and a C-V / I-V mode selector. The system can perform measurements accurately between $1.00 \times 10^{-5}$ to approximately $1.99 \times 10^{-2}$ A current range. Fig. 4.12 shows a photograph of the dark I-V system. The solar cell is placed in the dark sample holder. The pA meter / DC voltage source then forward biased the cell and measure the current through it. The measured I-V data is transferred from the system to the computer via a GPIB connection. The software program written in HPVEE was used to process the results. Further details of the dark I-V system used in this study can be found in reference [2].

4.6 Fabrication of solar cell mesa diodes

A technique for the fabrication of mesa diodes on crystalline solar cells was developed. The technique uses wet chemical etching for processing mesa diodes on a complete wafer.
4.6.1 Types of etching

Etching is a process by which a material is removed from the wafer. There are two types of etching, dry etching and wet etching. The former uses chemically active gases or plasma whereas wet etching uses chemical liquids. Also dry etching may be accomplished by physical removal of the material, i.e. ion beam milling and physical sputtering. Therefore, dry etching can not be used as an etching process for the development of mesa diodes on a complete solar cell wafer. This is because solar cell wafer can be easily broken.

The use of wet chemical etching makes it possible to etch a p-n junction solar cell wafer. The chemical reaction rate during etching process depends upon the availability of electrons for oxidation to occur and it also depends on the doping concentration. In addition the etch rate for both n- and p-type material increases with an increased doping. This implies that n-type material is etched faster than the p-type due to the greater availability of electrons in the n-type.

4.6.2 Etchants

The solution prepared using Nitric acid (HNO₃) and Hydrochloric acid (HF) was used as etchant. HNO₃ was used to oxidize the surface of the sample while HF as a complexer (weakens chemical bonds). HF makes the sample soluble in the etching solution. Table 4.1 summarises some of the chemicals that can be used to etch semiconductor materials.

Table 4.1: Chemical etchants for semiconductor materials.

<table>
<thead>
<tr>
<th>Oxidizer</th>
<th>Complexer</th>
<th>Diluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNO₃</td>
<td>HF</td>
<td>H₂O</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>HCl</td>
<td>CH₃COOH</td>
</tr>
<tr>
<td>CrO₃</td>
<td>H₂SO₄</td>
<td>CH₃O₄</td>
</tr>
</tbody>
</table>
4.6.3 Spray-gun

![Spray-gun diagram](image)

**Figure 4.13**: Spray-gun used for mesa preparations.

At the heart of the method is the spray gun for uniformly coating the sample. A photograph of a spray gun used in this study is shown in Fig. 4.13. The gun consists of an air control knob, spray-head, adjustment nut and a gas supply. Also shown is a tank containing a wax-toluene solution and is connected to the gun. The gun is connected to a compressed nitrogen gas supply via a hose. Spraying using this gun is as follows;

- Open the gas supplier.
- Press the air control knob to allow the flow of the gas.
- The interior hose inside the tank will then suck the solution up into the gun and exit through the spray-head.
- The amount of spraying can be controlled by using the adjustment nut.

4.6.4 Methodology

Prior to the mesa development, etch rates for the crystalline silicon solar cells were established. The HNO₃ and HF solution with a ratio of 5:1 was used. The samples were etched and their thicknesses were measured using the Scanning Electron Microscope (SEM). The SEM measurements as a function of etching period for single- (c-Si) and multi- (mc-Si) crystalline silicon solar cells are shown in Fig. 4.14.
It can be seen that initially the thickness of a c-Si cell is higher than that of a mc-Si cell. For both curves the thickness of cells decreases when etching for longer period.

![Graph showing etching rates of crystalline silicon solar cells]

**Figure 4.14:** Etching rates of crystalline silicon solar cells

The process of preparing mesas is as follows (refer to Fig. 4.15):

(a) Vinyl mask is pasted onto the front surface of the cell and wax melted on to the back contact to protect the area from etching;
(b) Wax is sprayed on to the surface of the masked cell and allowed to dry;
(c) Mask is removed leaving the waxed areas;
(d) The cell is etched to a depth below the p-n junction in a HNO$_3$:HF solution with a volume ratio of 5:1;
(e) Wax is removed by boiling in toluene, and then the cell is cleaned in methanol followed by rinsing in de-ionized water and dried with nitrogen.

Fig 4.16 shows the typical 2 mm diameter mesa diodes developed on a multicrystalline silicon solar cell. Also visible in the figure are the fingers that provide the top contact while the back side of the whole cell provides a common rear contact.
Figure 4.15: Schematic diagram of the processing steps during mesa preparation.
Figure 4.16: Sample holder showing 2 mm diameter mc-Si mesa diodes.

4.7 Summary and concluding remarks

This chapter presented experimental procedures that can be used for characterising defects in solar cells. An LBIC system that enables quantitative analysis of solar cells has been developed. With the LBIC system presented, photo-generated current and reflection intensity measurements can be obtained. This system makes it possible to determine the quantum measurements of solar cells i.e. external and internal quantum efficiency. In addition, the technique for performing I-V measurements of solar cells under spot-illumination conditions is described. Also described is a brief outline of the method used to obtain dark I-V characteristics of solar cells. The results obtained for solar cells of different technologies, are discussed in the following two chapters, chapters 5 and 6.

A technique for the fabrication of solar cell mesa diodes is presented in this chapter. This technique demonstrated the approach for developing isolated mesas on a complete solar cell. As will be seen in Chapter 6 the mesa diodes can be used for the analysis of defects in solar cells using techniques such as LBIC.
4.8 References


Chapter 5

Defect analysis in solar cells

5.1. Introduction

This chapter presents and discusses results of LBIC measurements and current-voltage (I-V) characteristics. The LBIC system described in section 4.2 was used to perform LBIC measurements to obtain current and surface reflection maps. Quantum efficiency (QE) mappings of solar cells were also investigated. The analysis of QE enables a quantitative description of a solar cell. The I-V characteristics of the solar cells investigated were obtained using the configuration described in section 4.3. The one- and two-diode solar cell models described in section 2.2 were used to extract device parameters from the I-V characteristics of the solar cells. The Solar Light Beam Induced Current (S-LBIC) technique described by Vorster [1] was used to obtain maps of the performance and device parameters of solar cells from their I-V characteristics. Environmental parameters such as temperature, which have an effect on the performance of solar cells and modules, are also discussed. This chapter also reports on temperature-dependent LBIC measurements performed on thin-film based solar cells.

5.2. Solar cells

The solar cells investigated include single- (c-Si) and multi-crystalline silicon (mc-Si), EFG-Silicon (EFG-Si) and Cu(In,Ga)(Se,S)\(_2\) (CIGSS) based solar cells. The LBIC measurement results of all solar cells investigated are presented, followed by quantum efficiency measurements of the cells. LBIC current map depicts current distribution through the cell while the reflection map shows reflection of incident light on the surface of the cell. The results illustrating the effect of temperature by LBIC investigation and also on the I-V characteristics of thin film CIGSS solar cells are
presented and analyzed. This chapter also reports on the Solar Light Beam Induced Current (S-LBIC) measurements performed on mc-Si solar cell.

5.3. LBIC measurements

5.3.1. Single crystalline silicon solar cells

Figure 5.1: (a) Photograph of the c-Si solar cell. (b) LBIC current map of (a). (c) Relative surface reflection map.
In this study, a piece of a solar cell cut from a complete c-Si solar cell was used. Fig. 5.1(a) shows a photograph of the complete c-Si cell and Fig. 5.1(b) illustrates a typical LBIC current map of the 7 x 7 cm² area in (a). The corresponding surface reflection LBIC map is shown in Fig. 5.1(c). Also indicated is the current level scale of the LBIC current map and the relative reflection intensity scale. LBIC measurements were performed with a laser beam of wavelength 660 nm, a power of 10 mW/cm², a beam diameter of about 150 µm and 150 µm step-sizes. The collection bus bar and contact fingers are evident in Fig. 5.1 as black lines as in (b) and white lines in (c). Also visible and marked with yellow arrows in (b) are the manufactured edges of this solar cell. From the current map shown in Fig. 5.1(b), the bus bar and the contact fingers are shading features and therefore no current is generated in these regions. Also evident is the reduced current collection along the edges of the bus bar. The decrease in current at the edges of the fingers is minimal and therefore not visible.

The spacing between the contact fingers and the width of the fingers increase current losses due to shadowing caused by the incident light [2]. It has been reported that contact finger structures shadows 3% - 12% of the incident light, however, more contact fingers increase collection of current in the emitter layer of the solar cell [3]. The lower current regions illustrated with black arrows in Fig. 5.1(b) thus indicates that there are paths at the edges of the bus bar that provide resistance to the flow of current, degrading current collection. These paths may indicate the presence of traps at the interface between the bus-bar and silicon material and would be due to the effect of diffusion of impurities from the metalization of the fingers and bus bar. Another possible reason could be due to leakage currents caused by the high electric field at the interface states [4], resulting in the creation of shunt paths. These shunt paths decrease the overall shunt resistance of the whole cell. A lower shunt resistance is known to reduce $V_{oc}$ of the cell, resulting in decreased output power [5, 6]. In most modern silicon-based solar cells, silver or aluminium metals are used as contact fingers and bus bars for the collection of current. At the metal-semiconductor interface, the flow of current carriers from the semiconductor to the metal occurs mainly via basic transport processes. These processes include electrons moving over
the metal-semiconductor barrier and some electrons tunnelling through the barrier into the metal side [3]. Tunnelling is dominant for highly doped semiconductor materials, for example silicon solar cells. Another visible feature in Fig. 5.1(b) is the lower current level indicated by yellow arrows at the edges of the cell. Shunt paths are likely to occur at the cell edges due to the insufficient separation between the emitter layer and the rear contact side of the cell [7]. It is also noticeable that there are regions of low current forming a circular shape. These features are enclosed by the double broken lines in Fig. 5.1 and for simplicity we will refer to the whole area as defect D1. From Fig. 5.1(b), these defects appear to have reduced the current. Also from the surface reflection map in Fig. 5.1(c), the amount of light reflected at D1 is higher than elsewhere on the cell. The degradation of photo-generated current and high surface reflection at D1 could be due to the degradation at the antireflective coating (ARC) layer. This is significant as it shades the bulk of the cell below, resulting in current loss. If this cell were to be used in outdoor operations for the purpose of generating power, features like D1 would partially shade the cell, leading to cell mismatch. Cell mismatch causes the cell to operate as power dissipater. The cell thus heats up and form hot spots, resulting in a reduction in cell efficiency [8].

The succeeding sections will further investigate defect such as grain boundaries (GBs) in multicrystalline (mc-Si) and EFG-Si solar cells. The electronic properties of GBs enhance recombination of carriers. Typical GBs in mc-Si solar cells are irregular in shape whereas GBs in EFG-Si are often linear and elongated.

5.3.2. Multicrystalline silicon solar cells

The effect of electrical defects on the photovoltaic properties of mc-Si was investigated using LBIC. The results obtained show the importance of LBIC as a topographical technique to detect regions of current loss in mc-Si cells.
Figure 5.2: (a) Photograph of a $6 \times 6 \text{ cm}^2$ mc-Si solar cell, (b) its LBIC map and (c) the corresponding relative reflection map.
Fig. 5.2(a) is a photograph of a $6 \times 6$ cm$^2$ area of one of the mc-Si solar cells that was investigated. Fig. 5.2 (b) shows the results of LBIC measurements and (c) the reflection measurements on the area shown in (a). LBIC measurements were obtained using a laser source of wavelength 660 nm and an incident power of 8 mW/cm$^2$. A beam diameter of $\sim 150 \, \mu$m and a step-size of $150 \, \mu$m were used. Fig. 5.2(a) provides information about the visible defects on the surface of the cell, as these are possible features that contribute to cell failure. In this figure, surface reflection features are observed on the surface of the cell and these are illustrated by black arrows. These surface defects play a role in the performance of the cell. These surface defects were further investigated using LBIC measurements. The photo-generated current map is shown in Fig. 5.2(b) and its corresponding surface reflection map is presented in Fig. 5.2(c). From (b), the non-uniform distribution of the photo-generated current is indicative of the different grain orientations in mc-Si materials. As shown in (a), the current decreases where the features indicated by the arrows occur. The lower absorption of light at these defects is shown by the high reflection seen in Fig. 5.2(c). This indicates that, in the presence of these defects, less light reaches the cell resulting in the creation fewer photogenerated carriers. The structure indicating lower current collection seen in the middle of (b) (yellow arrows) is attributed to measurement noise. This noise is related to the sensitivity of data transfer during LBIC scanning. Although it is not possible to attain noise-free signals when using multiple electrical components, a high level of signal to noise ratio is maintained in our LBIC system. This was made possible by using a pre-amplifier which has signal filters. Note that the noise observed in (b) is rarely seen in other results, and the reader is referred to LBIC results in sections 5.2, 5.4 and 5.5.

As evident from the reflection map the large variations between the different grains seen in Fig. 5.2(b) are mainly due to different light absorption by the grains. The low current collection in some grains is illustrated and these include grains G2, G3, G4, G5, G6, G7 and G8. Smaller grains, i.e. G2 and G4 as seen in (b) show the highest reduction of current as compared to larger grain like G3. The photo-generated carriers created within smaller grains are lost mainly at the electrically active grain boundaries (GBs). This is due to the shorter lateral distance between the GBs. This is evident, for example, in grain G2 where the visible boundary appears to be negatively
affecting this grain. The neighbouring grain, G1, and other larger grains including G9, G10, G10, G11 etc., depict higher photo-generated currents. However, the low collected current in some of the larger grains, viz. G3, can be due to the defects within the grains. These defects are present in the grain interior and include dislocations, sub-grain boundaries and micro-segregation. Different crystal texturisations give rise to dislocations and sub-grain boundaries [9]. It can be said that, although larger grains neighbouring smaller grains generate more current than their smaller counterparts, they are affected by inter-grain defects. Smaller grains such as G11 show a defect free region as higher photo-generated current was measured at this region.

To further investigate the photo-response of different grains in mc-Si solar cells, relative surface reflection measurements of the cell were obtained and the map is shown in Fig. 5.2(c). It is evident in this figure that some grains are more reflective than others. The grains reflecting more light include G2, G4, G5, G6, G7 and G8. It was expected from (a) that grains which showed less absorption would reflect more light. This was indeed the case as the grains listed show high reflection of light. G2, for example, shows a higher reflection indicating that the lower LBIC signal shown in (b) could also be due to crystal grain orientation. In addition, grains that appeared to generate more current as shown in (b) reflected less light. These include G1, G9, G10, G11 and G12. Grain G3 reduces LBIC signal as seen in (b) and also reflected less light as shown in the reflection map. This could be due to the presence of inter-grain defects enhancing recombination of generated carriers. Another possible reason for the lower reflectivity of this grain could be because of the surface orientation of the crystals. A surface reflection map, such as that in (c), indicates different absorption and reflectivity of the multi-crystalline grains. The variations are due to the grains different texturisations which depend on the orientation of the crystal. The more reflective grains in mc-Si solar cells have a strong influence on the photo-generated current and cannot be neglected.

From the photo-generated map shown in Fig. 5.3(b), the dark irregular lines between crystal grains correspond to grain boundaries (GBs). Also in Fig. 5.3(c), GBs appear to be reflecting more light. The current loss at GBs has been widely researched. GBs are interface states between two crystals of different orientations, and they act as traps
and recombination centres for photo-generated minority carriers. The presence of metallic impurities in GBs gives rise to interfacial states. These impurities include Fe, C, Ni and Cr [10], and due to their electrical activities majority carriers from the grain interior are trapped creating space charge regions (SCR’s) on the edges of the boundary. This results in the formation of electric fields which then control minority carrier transport in the GB [11]. In addition, the electric fields will attract all the carriers generated within the diffusion length from the GB edge, and hence these charge carriers will recombine at the GB. Therefore, the recombined carriers are lost and will not contribute towards current collection in the cell.

5.3.3. Edge-defined Film-fed Growth (EFG) silicon solar cells

Fig. 5.3(a) shows a photograph of a portion cut from an EFG-Si solar cell which was used in this work. The LBIC current map of the area indicated by solid line rectangle is shown in Fig. 5.3(b). Fig. 5.3(c) illustrates the surface reflection LBIC map corresponding to the current map shown in Fig. 5.3(b). The scanning parameters used to perform these results were similar to those described in section 5.3.2. The map in Fig. 5.3(b) depicts the photo-generated current distribution through the cell and grid contact fingers are clearly visible. The dark irregular regions indicated by the black solid arrows represent surface defects whereas the elongated and linear dark features illustrated by the blue broken arrows correspond to grain boundaries. The low current regions indicated by white arrows are clearly observable and are related to the grid regions of the rear contacts. The surface reflection map confirms this hypothesis as these regions are not visible in Fig. 5.3(c).
Figure 5.3:  
(a) Scanned photograph of 6 x 9 cm$^2$ EFG-Si solar cell  
(b) LBIC current map scanned with a 150 μm spot-size and a step-size of 150 μm.  
(c) Surface reflection map of (b).  
(d) area magnified by broken lines in (b).
The low current feature indicated by an X is due to bad soldering of the front contact. The soldering can provide shadowing to the cell, resulting in the reflection of the incident light. The high reflection in the vicinity of soldering X is visible in Fig. 5.3(c). Another interesting region situated at the edge of the cell is indicated with a Y. Although this region Y is not clearly visible in Fig.’s 5.3(a), it can be observed in (b) and (c). Fig.’s 5.3(b) and (c) illustrate the effect of this feature on photo-generated current. The severe degradation of current at Y is illustrated in Fig. 5.3(b), whereas in (c) there is high surface reflection at Y. Another feature similar to Y is indicated with the yellow arrow in Fig. 5.3(b). These features seem to originate from the edge of the cell. The growth of this type of degradation feature is detrimental and will eventually extend through the entire cell resulting in performance degradation of the cell. This degradation is common in EFG ribbon based solar cells and causes damage to a device [12].

In addition to the deterioration caused by features such as Y, the region magnified in (b) with double broken lines is shown in Fig. 5.3(d). In this figure, the solid-arrowed feature that degrades current is illustrated. This feature, and others indicated by blue broken arrows correspond to the electrically active, grain boundaries. These elongated and linear GBs appear to be parallel to the grid contacts in some regions. The EFG technique for fabricating silicon solar cells involves drawing silicon through a graphite die such that it solidifies in the form of grains above the die. This results in the formation of the GBs.
5.3.4. Cu(In,Ga)(Se,S)\textsubscript{2} solar cells

![Image](image_url)

(a) Photograph of a Cu(In,Ga)(Se,S)\textsubscript{2} solar cell;  
(b) The LBIC scan of the cell;  
(c) Its corresponding surface reflection map.

**Figure 5.4:**
(a) Photograph of a Cu(In,Ga)(Se,S)\textsubscript{2} solar cell;  
(b) The LBIC scan of the cell;  
(c) Its corresponding surface reflection map.

Fig. 5.4(a) is a photograph of a 7 \times 8 \text{mm}^2 Cu(In,Ga)(Se,S)\textsubscript{2} (CIGSS) solar cell. A visual inspection was conducted in order to determine the quality of the cell. There is a visible feature on the surface of the cell within the broken lines square. To further investigate this surface feature and other areas of the cell, LBIC measurements were carried out. Fig. 5.4(b) shows a typical photo-generated current map and Fig. 5.4(c) presents the reflection map of the cell. LBIC maps were obtained using a laser with specifications of 660 nm wavelength, 30 mW incident power of and 100 \mu m beam diameter. In Fig. 5.4(b) the non-uniformity of the current is seen and regions of different current levels are represented by contours. The surface feature indicated by the broken line square in Fig. 5.4(a) is also illustrated in (b) and (c). As mentioned previously, regions on which surface defects occur shade the cell below. This results in a decrease in the number of incident photons being available to reach the cell, leading to a reduced photo-response of the cell. Regions indicated by arrows in (b) and (c) further illustrate the effect of surface defects. The other noticeable region (blue contrast) where current distribution is lower is shown in (b). The surface reflection map in Fig. 5.4(c) showed no significant reflection in this region. Therefore, this region is indicative of an electrically active material-related defect. It is possible that with time the cell might have attracted moisture which penetrates the
front layer, accelerating the degradation of the device. We postulate that this moisture is due to the fact that the CIGSS cells used in this study have an unprotected front layer. Many thin-film based solar cells and modules, for instance, amorphous silicon and CIS-based modules have front layers covered with glass. Although thin-film PV modules in general are more vulnerable to moisture than crystalline silicon modules, the cells used in this study have an increased vulnerability to moisture because they did not have a protective glass in the front surfaces. In addition, the scribe lines separating the cells from each other may provide easy access channels for moisture to penetrate the cells. Moisture ingress accelerates degradation and contributes to the reduction of photo-generated current due to photon absorption. Parasitic absorption losses are enhanced in the degradation regions. The series resistance of the cell can increase with time in the presence of moisture. It has been reported that parasitic losses by free carrier absorption govern the photon absorption mechanisms in the Al-doped ZnO window layer and hence are detrimental to the short-circuit current [12]. This effect of increased parasitic resistances coupled with failure mechanisms such as the degradation observed in Fig 5.4(b) can, therefore, cause significant performance degradation for the whole cell.

5.4. Quantum efficiency of solar cells

The quantum efficiency of solar cells can give insight into the carrier recombination losses and also provide information about optical losses such as surface reflection. The LBIC system described in chapter 4 allows the measurements of both external (EQE) and internal (IQE) quantum efficiency of solar cells. The EQE and IQE of the solar cells used in the preceding sections were determined and the results obtained are analyzed. EQE measurements were obtained using equation 3.6 while equation 3.7 was employed to determine IQE measurements.
5.4.1. Single crystalline silicon cells

![External quantum efficiency map of a c-Si solar cell](image1)

![its surface reflection map](image2)

![Internal quantum efficiency map of (a)](image3)

**Figure 5.5:** (a) External quantum efficiency map of a c-Si solar cell; (b) its surface reflection map. The relative scale is also shown. (c) Internal quantum efficiency map of (a).

Fig. 5.5(a) shows the EQE LBIC map of the c-Si solar cell shown in 5.1. Fig. 5.5(b) indicates the corresponding reflection map, and the measured IQE map is shown in Fig. 5.5(c). These results were obtained using 660 nm laser light with intensity of 32 mW/cm². The variation of quantum efficiency is illustrated in Fig. 5.5(a), with the reduced efficiency distribution depicted by darker contrast. The effect of performance degrading features explained in section 5.1 is observed in Fig. 5.5(a). For example, LBIC map showed the reduction of photo-generated current along an area adjacent to the bus bar and also at the edge of the cell. The EQE values at these areas are low as
seen in (a). As expected IQE values are higher than the EQE measurements. It was also expected that region illustrated by the broken lines which appears degrading photo-generated current as described previously, would vanish in the IQE measurements. However, this was not the case. The IQE measurements dropped in this region. This suggests that although this region appeared to be at the surface of the cell, it is possible that it is also occurring within the cell. This confirms that the presence of degradation in the ARC negatively influences the solar cell’s photovoltaic response. The other areas with reduced IQE are illustrated by arrows in (a) and (c). It is evident from Fig. 5.5(b) that less light is reflected in these regions, indicating lower current collection. As mentioned previously, this is indicative of an increase in the effect of parasitic resistances in these regions.

5.4.2. Multi crystalline silicon solar cells

Fig. 5.6 shows the LBIC maps illustrating the quantum efficiency measurements of the mc-Si solar cell described in section 5.3. The results were obtained using the LBIC measurements in section 5.3. EQE, surface reflection and IQE maps are shown in Fig’s 5.6(a) - (c), respectively. In (a), it is evident that the EQE distribution is similar in contrast levels to the induced current measurements shown in Fig. 5.2(b). Using the data from (a) and (b), a resulting IQE map was calculated. The colour map in (c) was scaled using the contrast in (a). The relative reflection map in (b) was described in section 5.3.2. In (b) grains that show more reflection of light than others, have lower EQE values as seen in (a). These grains include G4, G5 and G8. However, it can be seen in Fig. 5.6(c) that these grains have IQE which are similar to other neighbouring grains. Thus, after the correcting the reflection losses, the variation between different grains vanish. In addition, grains such as G9, which indicated higher photo-generated current and EQE values, exhibit higher IQE. IQE measurements depicted in (c) indicate that although the reflection coefficient range (1% - 11%) is small, it has a strong influence on the photo-generated current and cannot be ignored. As expected from the LBIC maps in Fig.’s 5.2(b) and (c), regions with high photo-generated current have higher IQE values. This is due to the less inter-grain defects in these regions, leading to more photons contributing to more creation of current carriers.
Figure 5.6: (a) EQE maps of a mc-Si solar cell, (b) its reflection map and (c) represents the IQE measurement of the cell.
5.4.3. EFG silicon solar cells

![Figure 5.7](image)

**Figure 5.7:**
(a) External quantum efficiency map of the EFG-Si solar cell;
(b) The corresponding Internal quantum efficiency map of (a).

Fig. 5.7(a) shows the EQE measurements of the EFG-Si solar cell investigated in section 5.3. The corresponding IQE map is indicated in Fig. 5.7(b). The current reducing features observed in the current map shown in section 5.2.4 are indicated in both figures. These include the grain boundaries indicated by broken arrows, and degradation shown in the region labelled Y. Fig. 5.7(a) differs from (b) in that the values for the IQE efficiency have greater range than those of the EQE. For example, GB1 has a higher IQE than EQE. The possible reason for higher IQE at GB1 could be due to the denuded zones around grain boundaries. These zones correspond to a decreased impurity concentration because impurities are gettered at GB where carriers are trapped. The lower reflection of light at the GBs also contributes to their relatively higher IQE values. Feature Y, which enhances cell degradation, shows lower EQE and IQE values. The low IQE at Y indicates that very few minority carriers will be generated that can contribute to the short-circuit current.
5.4.4. Cu(In,Ga)(Se,S)₂ solar cells

Figure 5.8: (a) LBIC map of EQE measurements for CIGSS solar cell; (b) corresponding IQE map.

Quantum efficiency measurements of CIGSS solar cell are shown in Fig. 5.8. The EQE map is shown in Fig. 5.8(a) and (b) presents the IQE map of the cell. The IQE map was determined using EQE and surface reflection measurements as shown in Fig. 5.8(a) and Fig. 5.4(c), respectively. In Fig. 5.8(a), the results depict high EQE values in regions where higher current was measured. In addition, the regions of low current seen in Fig. 5.4(b) have reduced EQE values. Although EQE and IQE maps indicate similar colour contrast, the IQE values range between [0.82 – 0.98] while the EQE values range between [0.78 - 0.86]. As expected, regions with defects have lower IQE values. It was not expected that areas showing a degradation in current as observed on the EQE map in (a), would have high IQE. As seen in the reflection map Fig. 5.4(c), less light was reflected in this region. This confirms the suggestion that the degradation observed is not due to surface defects, but rather due to degradation in the cell. The small difference between the EQE and IQE values is due to low surface reflection.
5.5. Temperature-dependent LBIC measurements

CIGSS solar cells were used to investigate the effect of temperature on induced current. This study used two CIGSS cells, one cell with a 150 nm thick ZnO window layer and the other cell with no window layer. These cells have been described in Chapter 3. The LBIC system and methodology employed to obtain induced current mappings of CIGSS cells at different temperatures is described in Chapter 4. This study presents the LBIC measurements performed at room temperature (25°C) and 70°C. As mentioned in chapter 4, the cell was heated to approximately 70°C and maintained at this temperature while LBIC was performed. The measurements were performed using a laser with an intensity of 30 mW/cm², a spot-size of 50 μm and a step-size of 50 μm. The results obtained are shown in Fig.’s 5.9 and 5.10.

![Figure 5.9: Induced current line scans of CIGSS solar cell (with ZnO window layer) at 25°C and 70°C. The drastic drop of current indicates the contact fingers.](image-url)
Figure 5.10: (a) LBIC map of CIGSS solar cell at room temperature, (b) its surface reflection map. Also shown are the effective current map levels.

(c) LBIC map of CIGSS solar cell at 70°C, (d) its reflection map.

Fig. 5.9 shows the line scan measurements for the CIGSS cell with ZnO while Fig. 5.10 presents the LBIC maps of the CIGSS cell without ZnO. The line scans were obtained in order to get an indication of current distribution at room temperature and 70°C. It is clear from Fig. 5.10 that the induced current remains unchanged when the cell temperature increase to 70°C. Fig.’s 5.10(a) and (c) show the induced current maps of the cell with no ZnO at room temperature and 70°C, respectively. The surface reflection maps corresponding to (a) and (c) are presented in (b) and (d),
respectively. The features illustrated by arrows are attributed to surface reflection defects. Some of these features are caused by scratches (solid arrows) and it can be seen in Fig. 5.10(a) and (c) that these lower the current. It should be mentioned that defects such as scratches on a cell increase the effect of parasitic resistance on the cell. The area illustrated by squares in the reflection maps, Fig. 5.10(b) and (d), reflect less light. This low reflectivity could be due to the pressure exerted on the bus-bar when making contact for current collection. This does not seem to have affected the uniformity of the current as observed in the current maps, Fig. 5.10(a) and (c). With reference to the current levels in (a) and (c), it is clear that the induced current changes, with that the LBIC signal reduced at higher temperatures. To further illustrate the reduced current at elevated cell temperatures, LBIC line scan measurements were performed along the dashed lines in (a) and (c) and these are presented in Fig. 5.11. In this figure, the reduction of current at 70°C is in agreement with the current maps. This effect was not observed for the CIGSS cell with a ZnO window layer (Fig. 5.9). It is therefore, be concluded that the effect of temperature is significant for CIGSS cells with no window layer. Macabebe [14] has showed that CIGSS solar cells with no ZnO window layers have low efficiencies, whereas cells with thick ZnO layer showed improved efficiencies.

![Figure 5.11: Induced current line scans of CIGSS solar cell (with no window layer) at 25°C and 70°C. The drastic drop of current indicates the contact fingers.](image-url)
5.6. Current-Voltage parameter mapping of solar cells

In this study a scanning technique using solar spectrum radiation as the incident light source, was used. The Solar-Light Beam Induced Current (S-LBIC) system [1] enables the determination of current-voltage (I-V) characteristics of a spot-illuminated solar cell. The system was employed to obtain I-V data points for a cell which was biased using an external ac voltage source. The collimated and focused solar beam with a small diameter is scanned in the plane of the biased solar cell. I-V data are then obtained for every preset voltage bias and the results are represented in the form of maps. The performance parameters, short-circuit current $I_{sc}$, open-circuit voltage $V_{oc}$, maximum power $P_{max}$, and fill factor $FF$ of the I-V curves are determined. The S-LBIC maps at $I_{sc}$, and $V_{oc}$, are presented and analyzed. Also discussed are the S-LBIC maps of $P_{max}$ and $FF$.

![Figure 5.12](image)

(a) Portion of the surface reflection map of mc-Si solar cell.
(b) Marked area in (a) showing different grain boundaries.

**Figure 5.12**: (a) Portion of the surface reflection map of mc-Si solar cell. (b) Marked area in (a) showing different grain boundaries.

Fig. 5.12(a) shows the surface reflection of the mc-Si solar cell used in this study. The area enclosed by the square is magnified in Fig. 5.12(b). In this figure two grain boundaries are depicted, GB1 and GB2. The S-LBIC measurements were performed in the area indicated by broken lines in (b). The results of the S-LBIC are shown in Fig. 5.13. Fig. 5.13(a) shows the typical three dimension S-LBIC map at $I_{sc}$. 
Figure 5.13: Full solar spectrum LBIC maps of the area marked with broken lines in Fig. 5.12(b). Note that the direction of Fig. 5.13 is tilted through 90°.

(a) 3-D $I_{sc}$ map. (b) $V_{oc}$ map. (c) $P_{max}$ map. (d) $FF$ map.

The drastic current drop evident in this figure is due to the contact finger. Also visible is the reduction of current in the presence of GB1. Fig. 5.13(b) presents the map of $V_{oc}$. The distribution of voltage is uniform except at the GB1 and at the contact finger as expected. This indicates that GBs affect both the $I_{sc}$ and the $V_{oc}$ of the cell. However, due to the internal shunt features present in GBs (3), $V_{oc}$ is likely to be more affected. Shunt like features are more prominent under open circuit
voltage conditions when the series resistance of the cell is low. The $P_{\text{max}}$ map shown in Fig. 5.13(c) is a function of the maximum current and maximum voltage that the cell can produce. From this figure, the maximum power of the area investigated is ranging between $1.61 \times 10^{-5}$ W to $3.58 \times 10^{-5}$ W. The low power map at GB1 is clearly evident and this confirms the loss of power due to recombination of carriers at the GB. The calculated $FF$ map of the area is presented in Fig. 5.13(d). $FF$ is the measure of the cell quality and therefore the higher the $FF$, the better quality of the cell. In (d), the variation of $FF$ in the vicinity of GB1 and contact finger is shown. The decrease in $FF$ at GB1 is indicative of deleterious effect caused by the grain boundaries in mc-Si solar cells.

Although S-LBIC technique is advantageous to concentrator solar cells [15], it can also be employed to investigate performance degrading features in standard PV cells, as demonstrated here. The main advantage of the S-LBIC technique is the topographic images of the photo-generated current of a solar cell’s response can be obtained not only by using monochromatic light beam, but also using a full solar spectrum.

5.7. Current-voltage characteristics of spot-illuminated solar cells

The current-voltage (I-V) characteristics of a solar cell describe the behaviour of the cell. This section presents I-V measurements of a mc-Si solar cell performed using the LBIC system configuration described in Chapter 4. The I-V data points obtained were fitted using the Particle Swarm Optimization (PSO) extraction method to estimate the device parameters of solar cells [14]. This method provides the best fit to both dark and illuminated I-V characteristics of the solar cells and modules [16]. In addition, the PSO method employs the one- and the two-diode solar cell models to describe the I-V characteristics of the devices. In this study the one-diode model was used and the device parameters were extracted from the illuminated I-V measurements. The extracted parameters include parasitic series resistance, $R_s$, shunt resistance, $R_{sh}$, ideality factor, $n$, and reverse saturation current, $I_0$. These parameters together with the performance parameters ($I_{sc}, V_{oc}, P_{\text{max}}$ and $FF$) are presented and analysed.
The LBIC measurements of a $1 \times 1$ cm$^2$ a mc-Si solar cell were obtained. Fig. 5.14(a) shows the surface reflection map of the cell investigated. Fig. 5.14(b) shows the LBIC map of the IQE measurements of (a). From (a), it is evident that the reflected light intensity on the surface of the cell is not uniform. The non-uniformity as illustrated by regions marked A, B and C, is due to different grains having different reflectivity. As mentioned previously, the different reflectivity and absorption of the grains are due to their different texturisations which depend on the surface orientation of the crystal. Light is reflected more in region C than the neighboring regions A and
B. This increased reflection is due to the different crystallographic orientation of the grain. To further illustrate this high reflection of C, a reflection linescan was performed along the direction of the arrow in (a). The results obtained are shown in Fig. 5.14(c). This figure is in agreement with the corresponding map. Contact fingers reflect more light as shown by spikes in (c) and lighter contrast in (a). Region C also reflects more light than region A as shown. The high reflective region C indicates that fewer photons are absorbed in this region and hence this region is expected to decrease the efficiency of the cell when operational. The features indicated by arrows correspond to the GBs of which the GB marked X clearly reflects more light. In Fig. 5.14(b), region C which reflected more light intensity has an IQE value closer to that of region B. Region A on the other hand, shows higher absorption of light as in (a) and has higher IQE value compare to the other regions. Higher IQE value of A indicates that more photons contribute to the generation of current carriers.

I-V characteristics of the cell used in this study were obtained by spot illumination at selected areas in regions A, B and C shown in Fig. 5.14. Fig. 5.15 shows the I-V measurements of these regions. Also indicated are the respective curve fits based on the one-diode model of a solar cell. The maximum power points of each curve are also indicated by open-points. The results were obtained by using a 660 nm laser light with intensity, 32 mW/cm$^2$. The I-V curves were measured by biasing the cell from reverse to forward bias in the voltage range, $-0.2 \ V \leq V_{\text{bias}} \leq 0.5 \ V$ using an external ac voltage source.
Figure 5.15: The measured spot illuminated I-V curves of the mc-Si solar cell along with the curve fit based on the one-diode model and the open points on each curve indicate maximum power.

From Fig. 5.15, there are distinct variations in the I-V characteristics of regions A, B and C. Region A shows a higher maximum power than regions B and C. This confirms the surface reflection and IQE measurements for which region A shows more absorption of light and has the highest IQE value. Region C produces considerably less power than the other regions, even though it has IQE value closer to that of region B. This may be attributed to the inter-grain defects in this region that result in the low generation of current.

Table 5.1: The performance and device parameters of the spot illuminated mc-Si solar cell.

<table>
<thead>
<tr>
<th>Region</th>
<th>$I_{sc}$ (A)</th>
<th>$V_{oc}$ (V)</th>
<th>$R_{sh}$ (Ω)</th>
<th>$R_{s}$ (Ω)</th>
<th>$I_0$ ($\times 10^{-5}$A)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0571</td>
<td>0.408</td>
<td>76.30</td>
<td>0.326</td>
<td>17.4</td>
<td>2.82</td>
</tr>
<tr>
<td>B</td>
<td>0.0548</td>
<td>0.406</td>
<td>43.42</td>
<td>0.311</td>
<td>6.40</td>
<td>2.43</td>
</tr>
<tr>
<td>C</td>
<td>0.0491</td>
<td>0.403</td>
<td>39.53</td>
<td>0.215</td>
<td>6.69</td>
<td>2.49</td>
</tr>
</tbody>
</table>
The relative device parameters extracted using PSO method, are listed in Table 5.1. Also listed are the performance parameters, $I_{sc}$ and $V_{oc}$. The lower voltage region of the I-V curve is influenced by $R_{sh}$ and $R_s$ influences the curve at the higher voltage region, close to $V_{oc}$ (6). The fit in these regions make a good estimation of the true values of $R_{sh}$ and $R_s$. From Table 5.1, although all regions have similar $V_{oc}$ values, region C has the lowest value of $I_{sc}$. As mentioned above, the presence of inter-grain defects in this region reduces photo-generated current. In addition, region C has the lowest $R_{sh}$ value amongst the three regions. The low $R_{sh}$ value is indicative of an increase in the shunt paths across the cell’s p-n junction. These paths give rise to the leakage current which reduces the intended current from the load and hence the performance quality of the solar cell [17]. Based on the slopes of the curves near, $V_{oc}$ and the extracted parameters, all three regions have relatively low $R_s$ of the range $0.20 - 0.35 \ \Omega$. The ideality factor, $n$ and saturation current, $I_0$ are also listed in Table 5.1. Region A exhibits higher $n$ although all three have $n > 2$. Also $I_0$ values are of the order of $10^{-5}$ A for all regions with region A having the highest $I_0$. Although the I-V measurements of region A implies higher power or efficiency, the defects in this region affect the I-V characteristic as depicted in the ideality and saturation current.

5.8. Effect of temperature on current-voltage characteristic of solar cells.

Temperature-dependent I-V characteristics of solar cells and modules have been researched by our group, for example [18]. This section investigates the effect of temperature on I-V characteristics of CIGSS solar cells obtained under the defocused laser illumination. The same solar cell which was used to investigate the influence of temperature on LBIC measurements (section 5.5) has been used in this study. I-V characteristics were obtained by biasing the cell in the voltage range, $-0.1 \ \text{V} \leq V_{bias} \leq 0.5 \ \text{V}$ and using the external voltage source with a frequency of 119 Hz. The photo-generated current was then measured at preset voltage and at $5^\circ\text{C}$ temperature intervals as the cell temperature was varied. The results were obtained by illuminating the whole cell using the defocused laser of intensity $32 \ \text{mW/cm}^2$. The I-V measurements at different cell temperatures are presented and analysed.
**Figure 5.16**: I-V characteristics of CIGSS solar cell at 25°C and 70°C.

Fig. 5.16 show the three quadrants I-V curves of CIGSS solar cell at room temperature (25°C) and at 70°C. The maximum power points are indicated by open-points in each curve. In this figure, short-circuit current, $I_{sc}$, increases marginally while $V_{oc}$ decreases significantly with an increase of 45°C in cell temperature. The theory suggests that $I_{sc}$ increases with the elevated temperature since the band gap energy of the material decreases. A reduction of band gap energy allows more photons with enough energy to generate more current carriers [19]. The decrease from 0.46 V to 0.33 V of $V_{oc}$ indicates the negative effect caused by higher temperatures. The dominant temperature effect on $V_{oc}$ reduces the maximum power and the efficiency of the solar cell as the temperature increases.

**Table 5.2**: The device parameters extracted from the laser illuminated I-V curves of CIGSS solar cell at 25°C and 70°C.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$R_s$ (Ω)</th>
<th>$R_{sh}$ (Ω)</th>
<th>$I_{01}$ (A)</th>
<th>$n_1$</th>
<th>$I_{02}$ (A)</th>
<th>$n_2$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.153</td>
<td>46.81</td>
<td>$6.52 \times 10^{-5}$</td>
<td>2.55</td>
<td>$9.01 \times 10^{-6}$</td>
<td>3.01</td>
<td>0.998</td>
</tr>
<tr>
<td>70</td>
<td>0.105</td>
<td>23.16</td>
<td>$6.73 \times 10^{-4}$</td>
<td>3.19</td>
<td>$1.19 \times 10^{-6}$</td>
<td>4.48</td>
<td>0.996</td>
</tr>
</tbody>
</table>
The device parameters were obtained from the I-V characteristics shown in Fig. 5.16 by employing the PSO method based on the two-diode model of a solar cell. The extracted parameters at cell temperatures of 25°C and 70°C are summarised in Table 5.2, together with the corresponding $r^2$ values for each fit. The $r^2$ value gives an indication of the accuracy of the fit. The reverse saturation currents ($I_{01}$ and $I_{02}$) correspond to the dark saturation current due to recombination in the quasi-neutral regions and in the space-charge region (SCR), respectively, and are also listed in Table 5.2. In comparing $I_{01}$ and $I_{02}$ at 25°C and 70°C temperatures, $I_{01}$ increases while $I_{02}$ decreases with a rise in cell temperature. The increase in $I_{01}$ suggests that the recombination in quasi-neutral regions increases at higher temperatures. The reduction of recombination current, $I_{02}$ however, indicates that recombination in the SCR is decreasing at higher temperatures. It has been reported in the literature that increase in the recombination current due to the SCR recombination reduces the band gap energy in Cu(In,Ga)Se$_2$ based solar cells [20]. In addition, Turcu et al [21] have reported that sulphur in CIGSS solar devices widens the band gap of the alloy. Although $I_{sc}$ increases slightly as mentioned it could be said that the inclusion of sulphur in CIGSS cells reduces carrier recombination process in the SCR. The ideality factors ($n_1$ and $n_2$) at cell temperatures of (25 °C and 70 °C), respectively, are also shown in Table 5.2. Both $n_1$ and $n_2$ are greater than 2, and continue to increase at higher temperatures, indicating a decrease in the quality of the diodes. It has been argued that in polycrystalline thin-film solar cells based on CIGSS films, the Shockley-Read-Hall recombination rate controls the diode with ideality factors in the range between 1 and 2 [22]. When $n > 2$ the presence of trap-assisted tunneling and field-assisted recombination is dominant for devices with $S/S + Se$ ratio greater than 0.45 [23]. In addition, Cu-poor solar cells can lead to bulk recombination which increases ideality factors [24]. The increasing $n_2$ at high temperature indicates that the recombination in the SCR is increasing which is contrary to the assessment of $I_{02}$. A possible explanation is that there could be areas on the cell that exhibit shunting at higher temperatures. Fig. 5.17 shows the effect of temperature on parasitic resistances $R_{sh}$ and $R_s$. $R_{sh}$ decreases significantly from 15°C to 30°C and remains relatively constant from 30°C to 70°C. $R_s$ remains constant throughout the measured
temperature range. The decreasing $R_{sh}$ indicates an increase in the shunts paths across the solar cell junction.

![Graph showing parasitic shunt and series resistance ($R_{sh}$ and $R_s$) as a function of temperature.]

**Figure 5.17:** Parasitic shunt and series resistance ($R_{sh}$ and $R_s$) as a function of temperature.

### 5.9 Summary and concluding remarks

A calibrated LBIC system developed was utilized to investigate lifetime limiting regions in solar cells. In the first part of the chapter, typical LBIC measurements were obtained indicating the topographical mapping of solar cells. The results revealed that surface and material defects are detrimental to the performance of a solar cell. In multicrystalline solar cells, it was observed that different grains reflect light differently depending on the texturisation of the crystal. The LBIC results of the thin film solar cell tested, showed that device degradation can be accelerated especially when the cell are not covered with glass.

In the second part, IQE measurements were investigated on solar cells of different technologies. The results showed that IQE is relatively high in some areas of the cell.
In mc-Si solar, the IQE indicated that the large variations between the different grains vanish. This exercise showed that reflection intensity has a strong influence on the photo-generated current and cannot be neglected.

The study also investigated the effect of temperature on thin film solar cell. The results revealed that for the material used, photo response is reduced at higher temperatures. The results were confirmed by I-V measurements of the cell. The LBIC reduction at higher temperature can be mainly due to the introduction of shunt paths.

The device parameters derived from the I-V characteristics obtained under spot-illumination conditions, showed that the spot-illumination can contribute to defects characterisation in solar cells.

Finally, regions with low minority carrier lifetime are made visible by LBIC mapping technique. The results indicated that LBIC is in agreement with other known characterization techniques such as I-V characterization of solar devices.

5.10 References


Chapter 6

Characterisation of solar cell mesa diodes

6.1. Introduction

As mentioned previously, crystalline silicon materials have great potential for terrestrial solar applications. The efficiency of multi-crystalline silicon (mc-Si) solar cells, however, is limited by the presence of electrically active defects in the material, in particular grain boundaries (GBs), which cause a degradation of electrical properties in the material. Various theoretical models show that GB interface states determine the electrical and photovoltaic properties of mc-Si by acting as carrier traps and recombination centres [1-3]. This study investigates GBs and other related defects by analysing the photovoltaic characteristics of solar cell mesa diodes. The aim was to prepare mesa diodes on areas containing defects in order to investigate the impact of the defects, and to analyze the variation of material and device characteristics across the region investigated. In addition, the mesa diodes were used to investigate photo-generated current with a minimum of interference from undesired loss mechanisms, such as leakage along the edges of a solar cell.

In this chapter, mesa diodes prepared on multi-crystalline silicon (mc-Si) and EFG-Si solar cells are characterized. The procedure for the fabrication of the solar cell mesa diodes is described in Chapter 4. The mesa diodes were characterized using Laser Beam Induced Current (LBIC) measurements and also by evaluating current-voltage (I-V) characteristics. The LBIC measurements describe the photo-generated current profile and the relative surface reflection intensity of the mesa diodes, while the I-V characteristics represent their electrical photovoltaic ability. The results of the LBIC measurements, followed by the evaluation of the I-V characteristics are presented and analyzed in this chapter.
6.2. EFG-Si mesa diodes

Fig. 6.1(a) shows a photograph of a 65 mm x 30 mm EFG-Si solar cell. The features illustrated by X are due to process damage and their influence on the performance of the solar cell is discussed in Chapter 5. Fig. 6.1(b) illustrates the 2 mm diameter mesa diodes fabricated on the same EFG-Si cell shown in (a) with contact fingers visible.

(b)  
Figure: 6.1: (a) A photograph of a 65 x 30 mm$^2$ EFG-Si solar cell. (b) A scanned image showing 2 mm diameter mesa diodes fabricated on the cell in (a).

6.2.1 LBIC measurements

The LBIC technique described in Chapter 4 was employed to perform LBIC measurements on the mesa diodes seen in Fig. 6.1(b). The LBIC measurements were carried out using a 660 nm wavelength laser light with an intensity of 8 mW/cm$^2$. 

The LBIC maps were generated using a laser spot-size of 100 μm and a step-size of 50 μm. The mesa diodes, B1, B2 and G5, marked with the circles in Fig. 6.1(a), were selected and are analyzed. The reason for selecting these mesas was to investigate carrier transport within different areas of the solar cell. For example, damaged areas, grain boundary areas, finger areas, etc. The laser light incident on the mesa diode produces an induced current, and by scanning the surface of the mesa an LBIC map of the mesa diode was obtained.

Figure: 6.2: An LBIC photo-current map of mesa B1 obtained using a 50 μm step size and a 100 μm spot size. Also shown is the current scale.

Fig 6.2 shows a typical LBIC map of the mesa B1. The scale for the photo-generated current is also shown. In this figure, the induced current distribution of the mesa is presented and the region of lower current is labelled X. It can be seen in Fig. 6.1(a) that the mesa B1 has been created on the partially damaged area. It is, therefore, clear that damage at X is detrimental to the photo-generated current. Fig. 6.3 presents an LBIC map of the mesa G5. The contact finger, which drastically reduced the photocurrent, is clearly seen. This mesa was also formed on a damaged region of the cell, as seen in Fig. 6.1(a). In comparing the LBIC maps of B1 and G5, it can be seen that the photocurrent is in the range 10.31 μA and 27.28 μA for B1, while the current ranges between 10.45 μA and 21.76 μA for G5. Although the difference between the current ranges is small the reduced current levels in G5 indicate the effect of the damage region occurred. The damaged region in an EFG-Si solar device degrades the performance of the device. This is due to the decrease in number of photons from the...
incident light being available to reach the cell below the affected area. It has been shown in Chapter 5 that damaged regions in the EFG-Si cell reflect more incident irradiance and therefore less light is absorbed by the cell. Photo-generated current is almost proportional to the incident photons that are not reflected at the surface.

**Figure: 6.3:** LBIC photo-current map of mesa G5 with 50 μm step size and 100 μm spot size.

The other noticeable feature in Fig. 6.3 is the irregular edge of the mesa and these irregularities are indicated by arrows. This irregular shape is common when preparing mesas on a processed solar cell wafer using wax, as it is difficult to control the flow of the wax. During the etching process, areas under the wax-defined regions are often etched, resulting in the irregular shape around the edges. In some mesas preferential etching along the defect can reduce the junction locally. This then reduces photo-generated current in that region.
Figure: 6.4: (a) An LBIC map of mesa B2 and (b) the LBIC line scan across the line indicated by the black arrow in (a).

Fig. 6.4(a) presents the LBIC map of mesa B2 with the contact finger clearly shown. The corresponding LBIC line scan measured along the black arrow in (a) is presented in Fig. 6.4(b). The striations of reduced contrast indicated by the solid blue arrows in (a) correspond to the grain boundaries (GBs). The decrease in current at the GBs is confirmed by the line scan presented in (b). This is typical for a device fabricated using the EFG ribbon growth technique. GBs are known to be recombination centres for current carriers in solar cells, and twin boundaries are likely to be found in EFG
solar cells. Although individual GBs are detrimental to photo-generated current carriers, studies have shown that twin boundaries have less influence on the photo-response of a PV cell [4]. Twin boundaries are regions with a significant concentration of micro-twins.

6.2.2 Current-voltage (I-V) characterization

I-V measurements of the mesa diodes were performed using the method described in section 4.3 in Chapter 4. The I-V data were obtained by illuminating the whole mesa using a defocused 660 nm laser with a beam power of 30 mW.cm\(^{-2}\). The I-V curves were then measured by biasing the mesa from reverse to forward bias in the range, \(-0.2 \leq V \leq 0.8\) using an external ac voltage source with a frequency of 19 Hz. The photo-generated current was measured at preset voltages. The open-circuit voltage, \(V_{oc}\), and short-circuit current, \(I_{sc}\), were obtained directly from the I-V curves. The slopes of the I-V curves at \(I_{sc}\) and \(V_{oc}\) give an indication of shunt resistance, \(R_{sh}\), and series resistance, \(R_s\), respectively [5]. This method was used to investigate \(R_{sh}\) and \(R_s\) of the mesa diodes in this study. However, this method is qualitative, and there are more accurate methods available for determining the parasitic resistances of the PV devices. The known methods include determining \(R_{sh}\) using low irradiance and by neglecting the effect of \(R_s\), whereas \(R_s\) can be determined from the slopes of the cells’ I-V curves [6]. These methods, however, are independent of the diode parameters (ideality factor and saturation current). A more accurate method for determining the device parameters is by fitting the illuminated or dark I-V curve to the one- or two-diode model using Particle Swarm Optimization [7].

In this study, 18 mesa diodes were investigated. They include B2 and G5, discussed in the preceding section. Fig. 6.5 shows the \(V_{oc}\) (red symbols) and \(I_{sc}\) (black symbols) values of the mesas. The values of \(V_{oc}\) vary only slightly and all are in the 0.5 V – 0.55 V range, whereas there is significant variation in the \(I_{sc}\) values amongst the mesas. Mesas A4 and C10 have the highest \(V_{oc}\) and \(I_{sc}\) of all the mesas.
Although B2 and G5 have the lowest $I_{sc}$ values, they exhibit higher values of $V_{oc}$. The lower $I_{sc}$ value of B2 is attributed to the current loss at the GBs that are present in this mesa. The presence of impurities such as copper enhances the recombination activity at the GBs. In addition, the high levels of impurity concentration not only reduce the photo-generated current at the GBs but can also drop the current in the vicinity. The reduced $I_{sc}$ for G5 is due to the deterioration of the material occurring in this region. The possible explanation could be that the damage and the associated discolouration results in lower photons from the incident irradiance being available to reach the cell below. This is in agreement with the LBIC measurements which depicted the degradation of generated current in this area. Also the lower $I_{sc}$ could indicate an increase in series resistance [8]. Although $R_s$ influence the slope of the I-V characteristics near the $V_{oc}$, it does not affect $V_{oc}$ itself. B2 and G5 are therefore
expected to show higher $R_s$, even though this mesa has the highest $V_{oc}$ value. This low $I_{sc}$ and high $V_{oc}$ can result in a decrease in the fill factor ($FF$) of the cell. $FF$ describes the maximum area under the I-V characteristic and is useful in indicating the quality of the cell. The value of $FF$ may vary from 0.52 to 0.82 depending on the technology of the solar cell [9]. The lower $FF$ values indicate poor cell quality and therefore the higher the $FF$, the better the quality of the cell. $FF$ influences the efficiency of a solar cell. Mesas such as D8, E14 and F8 having lower values of $I_{sc}$ and $V_{oc}$ can have high $FF$ values but lower efficiency compare to other mesas with high $V_{oc}$ and $I_{sc}$, e.g. C10 and D12. The device parameters that affect the $FF$ of a cell include the effect of parasitic resistance; an increased $R_s$ decreases $FF$, while low $R_{sh}$ reduces $FF$ of the solar cell [5].

![Figure 6.6](image)

**Figure 6.6:** $R_s$ measurements obtained for the EFG-Si mesa diodes.

Fig. 6.6 shows the calculated $R_s$ values of the mesa diodes investigated. Also shown is the average $R_s$ value obtained from the measured $R_s$ values of the mesas. This value does not represent the true $R_s$ value of the whole solar cell, but for a qualitative
discussion the average $R_s$ value will be assumed to be close to the true value. It can be seen from the figure that few mesas have $R_s$ values higher than the average. B13 has the highest $R_s$. This was not expected since B13 has low $V_{oc}$ and high $I_{sc}$ values. It has been mentioned that large $R_s$ is detrimental to the $I_{sc}$. The increased $R_s$ for this mesa could be due to the contact resistance between the contact finger and the semiconductor. Mesas with high values of $R_s$ will degrade the fill factor, resulting in performance degradation of the cell. The increase in $R_s$ can be detrimental to the efficiency of a mesa which already show lower values of $V_{oc}$ and $I_{sc}$, for instance, E14. On the other hand mesas such as A4, B2, B5, D5 and F8 having low $R_s$ will have higher cell efficiencies. B2 has a low $R_s$, even though it showed reduced $I_{sc}$. As mentioned, the low $I_{sc}$ of this mesa is due to the GBs. GBs are most likely to introduce shunt paths, resulting in the decrease in shunt resistance. When these paths are present, current is diverted from the intended load, thus degrading the performance of the cell. Although mesa G5 does not have $R_s$ values as high as the six mesas with increased $R_s$ (above the average), the damage in the region is significant as seen in the reduction of $I_{sc}$. Therefore, mesas with defects are likely to have increased $R_s$, suggesting that even though more generated carriers are lost to defects due to recombination, the remaining few may experience series resistance between the metal contacts and semiconductor material. Also in areas with less electrical or surface defects, more carriers are created. For example, G1 has relatively high $I_{sc}$ and $V_{oc}$, but exhibits high $R_s$. It could be due to the series resistance in the quasi-neutral regions.
Fig. 6.7: \( R_{sh} \) measurements obtained for the EFG-Si mesa diodes.

Fig. 6.7 presents the individual shunt resistance, \( R_{sh} \), values of the 18 mesa diodes investigated in this study. The average value of \( R_{sh} \) for the mesas was obtained (similar to average \( R_s \) and is shown in Fig. 6.7 by the dotted line. It is evident that the mesas have different \( R_{sh} \) values. In comparing \( R_{sh} \) values, C10 has the highest followed by G1, E14 and G14. Mesas D12 and G5 with \( R_{sh} = 220 \, \Omega \) and \( 200 \, \Omega \), respectively, have the lowest \( R_{sh} \) values. As reported by Green [8], high shunt paths in a device can reduce the open-circuit voltage, but this is not seen for G5. G5 has the highest \( V_{oc} \) value. It is possible that the shunted current is not high enough to affect the \( V_{oc} \) of this mesa. If the mesas investigated were to be connected in series, mesas having low \( R_{sh} \) will detract from the cell output. The low \( R_{sh} \) indicates the presence of parallel paths that allow leakage of current from the intended load. Mesas will be severely affected by the shunting regions particularly under low irradiance conditions. Therefore, regions where mesas were formed indicating a decrease in \( R_{sh} \) will not contribute to the cell output under reduced irradiance levels. Other mesas with higher
$R_{sh}$ values will perform adequately and mesas with $R_{sh}$ values close to the average will be marginal performers under reduced irradiance.

### 6.3 Mc-Si solar cell mesa diodes

The mc-Si solar cell investigated in this study was used in the LBIC investigation discussed in the previous chapter. Fig. 6.8 (a) shows a photograph of the $6 \times 6$ cm$^2$ cell. The corresponding LBIC map is presented in Fig. 6.8 (b). As discussed previously, electrical defects such as grain boundaries (GBs) and also surface defects reduce the quantum efficiency of the solar cell and hence degrade its performance. 1 mm diameter mesa diodes were manufactured on the cell investigated. The areas where mesa diodes were created were chosen to coincide with areas of interest as revealed by LBIC map which indicate variations in the photo response of the mc-Si solar cell. The GBs which reduced photo-generated current have lower IQE values as discussed in Chapter 5. Mesa diodes were intentionally created around, for instance, GBs in order to investigate local defects.

![Image](image_url)

**Figure 6.8:** (a) Photograph of a $6 \times 6$ cm$^2$ mc-Si solar cell.
(b) LBIC map of (a) using beam diameter of 150 μm and step size of 150 μm. The relative photocurrent scale is also shown.
6.3.1 LBIC measurements

Laser light of wavelength 660 nm was used in the LBIC system to analyze defects within the mc-Si solar cell mesa diodes. At this wavelength silicon solar cells reflect 20% of the 660 nm wavelength light [10] and the remaining light penetrates to a depth of about 3.5 µm. This makes it possible to detect and analyse defects on the surface and within the penetration depth. The results of the LBIC measurements were obtained using focused laser light with a diameter ranging between 100 µm and 150 µm and scanning step size between 50 µm and 150 µm.

**Figure 6.9:** Photograph of the mesa diode developed on mc-Si solar cell in Fig. 6.8.

Fig. 6.9 shows 1 mm diameter mesa diodes created on the mc-Si solar cell sample shown in Fig. 6.8. From Fig. 6.9, contact fingers are evident on some of the mesa diodes. During current collection, the fingers provide front contacts while the back side of the whole mc-Si solar cell sample provides a common rear contact. This study presents and analyzes results of LBIC and I-V (preceding section) measurements on
the mc-Si solar cell mesa diodes selected from the areas marked in the squares in Fig.’s 6.8(a) and (b). In the selected areas, mesas F7, A19, V9 and U20 were analyzed.

Figure 6.10: LBIC measurements of the mesa A19 using beam diameter of 100 μm and step size of 50 μm. (a) LBIC map, (b) LBIC line scan, (c) Reflection map, (d) Reflection line scan.

The effect of a surface reflection feature and a grain boundary (GB) that are visible in mesas A19 and V9, respectively, was investigated using LBIC. Fig. 6.10(a) shows the LBIC current map obtained for A19 mesa diode. Fig. 6.10(c) is the relative surface reflection map of (a). LBIC line scans were performed across the surface as
indicated by the arrows in (a) and (c). These line scans are shown in Fig’s. 6.10(b) and (d), respectively. A surface defect, indicated by an X, is observed. The effect of region X is characterized by a reduction of photo-generated current at X as shown in Fig 6.10(a). The magnitude of the current reduction at X is illustrated in (b) and is indicative of the effect of this defect. It can also be seen that the magnitude of the current drop at X is comparable to that of the contact finger. Defect X and similar defects such as those marked by arrows in Fig.’s 6.8(a) and (b) shade the cell below resulting in less light reaching the cell, leading to a reduced photo-generated current. A solar cell with a significant number of surface defects such as these will produce less current than the others in a module with series-connected solar cells. Such a cell will be reversed biased with respect to other cells and the power produced by other cells with less surface defects will be dissipated by this cell [11]. Dissipation of power in the mismatched cell can increase cell temperature and then give rise to the formation of hot spots, yielding the reduction of cell efficiency [12]. As mentioned above, less light reaches the cell below X indicating that more light is reflected at this defect. To investigate this, the surface reflection measurements shown in Figs 6.10(c) and (d) are analyzed. In Fig. 6.10(c) the low reflection is evident in almost the entire areas of the mesa except at the defect X and contact finger which reflect more incident light. The high reflection at X and contact finger is confirmed in the line scan shown in (d). The areas marked by arrows in (c) and (d) show that more light is reflected at the edge of defect X. This suggests that defect X may be caused by a scratch deep into the cell, creating conducting paths that may increase the presence of parasitic resistance. As mentioned previously, the high $R_s$ and low $R_{sh}$ negatively affect solar cell fill factor. The presence of surface defects contributes to degradation of photo-generated current.
Figure 6.11: LBIC measurements of the mesa V9 using beam diameter of 100 µm and step size of 50 µm. (a) LBIC map, (b) LBIC line scan.

Fig. 6.11(a) shows the three dimension LBIC current map of mesa V9. The corresponding line scan taken in the direction indicated by the arrow in (a), is shown in Fig. 6.11(b). The current distribution in mesa V9 is depicted in (a) and as expected for multicrystalline material, is not uniform, with the uniformity of current compromised by features such as Y. The effect of feature Y on the current distribution in the entire mesa V9 is analyzed. The low induced current at Y is confirmed by the line scan shown in Fig 6.11(b). This feature is clearly visible in Fig. 6.9 and is attributed to a performance degrading, grain boundary (GB). The presence of GBs is typical in multicrystalline based solar cells. Current loss at GBs is due to the formation of space charge layers on the edges of the GB [4, 13]. These layers give rise to electric fields which then control carrier transport. All the minority carriers created within the diffusion length of the GB edge will be attracted and recombine. These recombined carriers will, therefore, not contribute to the collected current.
6.3.2 Current-voltage characterization

Both illuminated and dark I-V measurements allow the determination of device parameters. I-V measurements were obtained for the four mesa diodes investigated, viz F7, A19, V9 and U20.

6.3.2.1 Illuminated I-V measurements

The light I-V measurements were obtained using defocused 660 nm laser with a beam intensity of 30 mW/cm$^2$ to illuminate the whole mesa. The I-V characteristic curves were then measured by biasing the mesa from reverse to forward bias in the range, $-2V \leq V_{bias} \leq 0.8V$ using an external ac voltage source with a frequency of 22 Hz and measuring the photogenerated current at preset voltages. The $V_{oc}$, $I_{sc}$ were obtained directly from the I-V curves and the device parameters were extracted by employing a Particle Swarm Optimization (PSO) iteration method based on the one-diode model of a solar cell. These parameters include $R_s$, $R_{sh}$ and diode parameters, reverse saturation current $I_0$, and ideality factor $n$.

![Illuminated I-V curves of the mesa diodes along with the curve fit based on one-diode model.](image)

**Figure 6.12:** Illuminated I-V curves of the mesa diodes along with the curve fit based on one-diode model.
Fig. 6.12 illustrates the 3rd-quadrant illuminated I-V characteristics for the mesas. The slope at $I_{sc}$ and also in the reverse bias region for all of the I-V characteristic remains constant. Similarly, the slope at $V_{oc}$ follows into the negative current region. The $V_{oc}$ of mesa A19 is low compared to others. The mesa U20 has the highest $I_{sc}$ and compared to other three which have similar $I_{sc}$ values. The fitting of the I-V curves was done in the photovoltaic operating region (1st quadrant) using the one-diode model described earlier and the device parameters were extracted. The extracted parameters are summarised in Table 1, with the $r^2$ values for each fit. Although the fitting for mesa U20 at $V_{oc}$ was not very good, in the regions of interest, i.e. near $I_{sc}$ and $V_{oc}$, the fits of the other mesas were very good. The I-V characteristic near $I_{sc}$ is influenced by $R_{sh}$ and close to the $V_{oc}$ the I-V curve is affected by $R_s$ [5]. Therefore, the fit in these regions yields a good estimation of the true values of $R_{sh}$ and $R_s$. It can be seen that $R_{sh}$ is high for all mesas, but much lower for U20. It has been reported that within multicrystalline solar cells, transport of current in areas in the vicinity of a grain boundary is influenced by the internal shunt resistance at the grain boundary. From the LBIC measurements, mesa V9 with grain boundary Y, was expected to exhibit high shunting behaviour. However, this was not the case. This could be due to the fact that some grain boundaries act as carrier recombination centres and are weakly charged [10]. It is thus difficult to detect shunt paths in grain boundaries by electrical measurement techniques such as I-V characterization. The extracted $R_s$ values for all the mesas (Table 6.1) are high. $R_s$ of A19, 0.79 $\Omega$, is higher compared to other mesa diodes and can be attributed to defect X, in agreement with the abovementioned LBIC measurements in Fig. 6.10. This supports our hypothesis that surface defect X could be damage deep into the top layer of the mesa, contributing to an increase in the effect of parasitic resistances, degrading the performance of the cell. The saturation current, $I_0$, and ideality factor, $n$, are also listed in Table 6.1. All the mesa diodes have $n > 2$, and mesas V9 and A19 have the highest ideality factors. The ideality factor reflects the quality of the solar cell junction. As $n$ increases the quality of the junction deteriorates. In contrast to the high $R_{sh}$, the high $n$ of V9 indicates the influence of defect Y in this mesa. Since the mesa V9 exhibits some shunting, the GB (defect Y) could extend through to the p-n
junction, reducing the quality of the junction. In addition, the saturation current, $I_0$, $2.54 \times 10^{-5}$ A, of mesa A19 is greater than that of the other three mesas. This high $I_0$ result for the mesa A19 corresponds to the LBIC measurements is expected.

Table 6.1: The device parameters of the mesa diodes.

<table>
<thead>
<tr>
<th>Mesa</th>
<th>$R_s$ ($\Omega$)</th>
<th>$R_{sh}$ ($\Omega$)</th>
<th>$I_o$ (A)</th>
<th>$n$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7</td>
<td>0.286</td>
<td>621</td>
<td>$1.52 \times 10^{-5}$</td>
<td>3.11</td>
<td>0.996</td>
</tr>
<tr>
<td>A19</td>
<td>0.790</td>
<td>715</td>
<td>$2.45 \times 10^{-5}$</td>
<td>3.43</td>
<td>0.997</td>
</tr>
<tr>
<td>V9</td>
<td>0.295</td>
<td>513</td>
<td>$7.80 \times 10^{-6}$</td>
<td>3.08</td>
<td>0.993</td>
</tr>
<tr>
<td>U20</td>
<td>0.233</td>
<td>286</td>
<td>$3.38 \times 10^{-6}$</td>
<td>2.79</td>
<td>0.980</td>
</tr>
</tbody>
</table>

6.3.2.2 Dark I-V measurements

Dark I-V measurements were performed by biasing the mesa diode with a dc voltage source under dark conditions. The biasing voltage was in the range, $-3 \leq V_{bias} \leq 0.5$ V. Dark I-V curves were obtained for the mesa diodes investigated. The results obtained are presented in Fig. 6.13. The slope of the forward bias I-V characteristic in the lower voltage range is influenced by $R_{sh}$ while $R_s$ influences the curve at higher voltages [14]. In the lower voltage region the recombination of carrier in the SCR is predominant. Only the lower voltage range region of the I-V curve is depicted in Fig. 6.13. The reverse bias region of the I-V curve gives a good indication of the reverse saturation current $I_o$ of the cell. In the forward region of the I-V characteristics all the mesas show good rectification except mesa A19, which shows a poor rectifying quality. The slope of the curve at low voltage suggests that A19 exhibits high shunting. This disagrees with the illuminated I-V characteristic and LBIC investigation of this mesa. In the reverse bias of the I-V curves, it can be seen that mesa A19 shows the highest $I_o$ compared to other mesas. The other three mesas have similar slopes and show relatively similar saturation current. The high $I_o$ of A19 can be associated with the abovementioned defect X present in this mesa. The
high saturation current degrades the open-circuit voltage of the cell [15]. Therefore, surface defects such as X decrease of the cell, resulting in the reduction of the fill factor of the I-V curve.

![Figure 6.13: Dark I-V curves of the mesa diodes.](image)

**Figure 6.13:** Dark I-V curves of the mesa diodes.

### 6.4 Summary and concluding remarks

The aim of the study was to develop a method of investigating the effect of current limiting defects in photovoltaic (PV) solar cells by electrically isolating and characterizing defect containing regions. The value of using mesa diodes to determine the spatial distribution of PV device parameters and defects has been shown. The mesas developed on areas of interest within crystalline silicon solar cells were investigated. The results of LBIC and I-V measurements were obtained.

The LBIC results showed the current distribution within the mesa diodes. In addition, LBIC revealed that different defects influence the photo-generated current in a device. This work also analyzed effect of defects such as grain boundaries and surface...
reflection feature in solar cells, without the interference of other current reducing factors.

The device and performance parameters describing the shape of the solar cell mesa diode I-V characteristic were obtained. The I-V results revealed the effect of defects on the parasitic resistance and diode parameters of a solar cell mesa diode. The study showed that mesa diodes can be used to characterize spatial non-uniformity across a cell and directly determine the PV parameters of the cell as a function of position across the cell.

6.5 References


Chapter 7

Conclusions

The main objectives of this study were to identify areas in solar cells which limit minority carrier lifetime and efficiency of a cell and also to investigate localised I-V characteristics of solar cells.

The LBIC system capable of mapping photo-generated current of solar cells was employed to investigate distribution of defects in the cells. In addition to the current maps the LBIC line scan measurements can be performed with this system. Other capabilities of the system include:

- The effective lifetime measurements of solar cells based on the optical open-circuit voltage decay method [1];
- Mapping of the surface reflection intensity of solar cells;
- External (EQE) and Internal (IQE) quantum efficiency measurements of solar cells.

The single-crystalline silicon solar cell that was analysed using the LBIC investigation showed the various current reducing features including current reduction in the vicinity of the bus-bar. Both LBIC and reflection maps of this sample showed a feature occurring at the antireflective coating (ARC). In addition, the IQE measurements revealed that this feature has an effect on the performance of the cell. Although LBIC line scan measurements confirmed the influence of the degradation of ARC on LBIC signal, further investigations will be performed to study the type of degradation occurring at the ARC.

The multi-crystalline silicon (mc-Si) solar cells that were investigated in this study showed typical electrical defects such as grain boundaries (GBs). The LBIC maps
showed current distribution of the cell indicating the variation of defects and GBs. The surface reflection features observed in this sample were detrimental to the photo-generated current. The IQE investigation on other mc-Si solar cell indicated that the differences in crystal grain orientations and sizes influence the performance of a cell. The I-V characteristics of this cell under spot-illuminated conditions agreed with the related IQE measurements.

The typical LBIC maps of EFG-Si solar cell used in this study, revealed the material damage occurring within the cell. Also observed were linear grain boundaries which are typical in EFG-Si solar cells.

LBIC results of solar cell based on Cu(In,Ga)(Se,S)2 thin film material were obtained and they showed the current reducing some areas with the cell. The reduction was due to the degradation of the device.

The results of LBIC measurements and I-V characteristics of mesa diodes developed on mc-Si and EFG-Si solar cells were obtained. The results have shown that mesa diodes can be used to characterise spatial non-uniformities in crystalline solar cells and directly determine the photovoltaic parameters of cells.

Finally, this study highlighted the importance of using an LBIC technique as a diagnostic tool for investigating photo response of solar cell devices. The study also showed that I-V characteristics of a solar cell can be regarded as a useful method to better understand the device performance parameters. In addition, it has been shown that LBIC measurements are in agreement with I-V characterisation of solar cells.

Reference

APPENDIX

Research output associated with this study

Publications:  Thantsha N.M., Macabebe E.Q.B., Vorster F.J. and van Dyk E.E.

Thantsha N.M., Vorster F.J. and van Dyk E.E.
On the fabrication of mesa diodes for the characterization of multicrystalline silicon solar cells. Submitted for publication in Journal of Solar Engineering.

Thantsha N.M., Vorster F.J. Sheppard C.J. and van Dyk E.E.

International Conferences:  Thantsha N.M., Vorster F.J. Sheppard C.J. and van Dyk E.E.

Thantsha N.M., Macabebe E.Q.B., Vorster F.J. and van Dyk E.E.
National
Conferences: Thantsha N.M., Vorster F.J. and van Dyk E.E.
Characterization of silicon solar cell mesa diodes. 52nd SAIP conference, 3-6 July 2007, University of Witwatersrand.

Thantsha N.M., Vorster F.J. and van Dyk E.E.
Analysis of silicon solar cell mesa diodes. 1st ALC student symposium, 8-9 May 2008, Port Alfred.