CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1 Introduction

The fabrication of thin film solar cell devices (see Fig. 2.6) is complex and involves several independent processing steps. The various processing steps as well as the specific experimental details followed during the deposition of the respective thin films (i.e. Mo, Cu(In,Ga)Se_{2}, CdS, and ZnO), are described in detail in this chapter. An important aspect of this study was the accurate characterization of these semiconductor thin films and completed solar cell devices. Relevant aspects of these characterization techniques are also highlighted in this chapter.

4.2 Substrate Preparation

All films in this work were deposited on soda-lime glass substrates with dimensions of approximately 76x15x1mm³. The chemical cleanliness of the glass substrate, prior to growth, directly influences the material properties of the deposited films. Scratches on the glass have an adverse effect on the structural properties of the thin films, while the presence of contaminants normally results in films with poor adhesion properties. In order to prevent these problems, all substrates were ultrasonically cleaned in a commercially available soap solution for 10 minutes, followed by a rinse under cold running deionized water for at least 5 minutes to ensure the removal of excess soap from the substrates. The substrates were then ultrasonically cleaned in acetone, methanol and deionized water. Finally, the
substrates were dried under flowing nitrogen and loaded into the deposition chamber.

### 4.3 Molybdenum Deposition

Molybdenum was used as the back contact for solar cells due to its low contact resistance to the chalcopyrite absorber films, negligible diffusion of Mo atoms into the absorber layer and its good thermal stability. In this study, electron-beam evaporation and direct current (DC) magnetron sputtering were used to deposit high quality Mo thin films (approximately 1 µm) on the glass substrates.

In the former case, Mo pellets of 99,999% purity were used during the deposition process. Depositions were carried out at a pressure of about $10^{-6}$ mbar and a quartz crystal thickness monitor measured the thicknesses of the Mo layers. The most crucial factor controlling the final quality of the Mo films was the temperature of the glass substrates during growth. Films with superior structural properties (i.e. smooth, uniform films with good adhesion properties) could only be obtained at substrate temperatures above 200°C. In addition, it was found necessary to preheat the samples at elevated temperatures for at least 3 hours in order to obtain high quality material. Several glass substrates were loaded during each run and the samples were rotated during growth to ensure a high degree of thickness uniformity.

The DC sputtered Mo films consisted of two layers. The first layer was deposited under conditions of low pressure ($1.2 \times 10^{-3}$ mbar). The second layer was deposited under conditions of high pressure ($7.6 \times 10^{-3}$ mbar), and had a low sheet resistivity. The first layer was less than half of the thickness of the whole layer and usually had a high sheet resistivity. This growth procedure produced Mo films with superior adhesion properties and low resistivity, which are important considerations during the fabrication of solar cell devices.
4.4 Absorber Formation

4.4.1 Introduction

CuInSe$_2$ and related compounds were deposited by the thermal evaporation of elemental copper and binary selenide compounds. The respective binary selenides (In$_2$Se$_3$ and Ga$_2$Se$_3$) replaced the pure In and Ga metals generally used in thermal evaporation processes. The selenide compounds exhibited improved reproducible and stable evaporation rates near their melting points, compared to the pure metals. In addition, analysis of the remaining materials in the crucibles revealed no detectable change in composition of the selenides even after several depositions.

In this study, a relatively simple, easily scalable two-stage processing approach was used to produce the absorber films. In this approach, various selenium-containing precursor stacks were thermally evaporated from specially designed graphite heaters. The second step involved the reaction of these precursors to elemental Se vapor under low vacuum conditions. In the following section, the experimental details followed during the different stages of absorber formation are outlined.

4.4.2 Three-source evaporation system

The homogeneous deposition of the precursor elements (i.e. Cu, In, Ga and Se) onto large-area substrates is complicated and therefore requires innovative system designs. Fig. 4.1 depicts the interior design of the thermal evaporation system used during this study. This concentric arrangement of the cylindrical-shaped evaporation sources (indicated as H1, H2 and H3 in Fig. 4.1 (a)) closely resembles the typical design of co-evaporation systems. These graphite heaters were positioned directly below (about 40 cm) the substrate holder (indicated by S in Fig. 4.1 (b)). It is also important to note that the graphite heaters were tilted in order to ensure a direct line
of sight to the centre of the substrate holder. They were normally shielded by molybdenum heat shields in order to reach and maintain temperatures above 1500°C, if required. The temperatures of the respective graphite crucibles were accurately monitored by S-type thermocouples (indicated as T1 in Fig. 4.1 (a)), positioned in small cavities at the bottom of each crucible. In order to ensure uniform heating of the glass substrates, a plate-like graphite heater was employed. The substrate heater (indicated as H in Fig. 4.1 (b)) was positioned directly above (about 3cm) the substrate holder (indicated as S in Fig. 4.1 (b)), and a J-type thermocouple (indicated as T2 in Fig. 4.1 (b)) made direct contact with the glass substrates. A molybdenum heat shield (indicated as M in Fig. 4.1 (b)) was placed directly above the graphite heater to ensure maximum heat transfer towards the glass substrates. A shutter (indicated as P in Fig. 4.1 (b)) mounted just below the substrate holder was manually opened or closed to expose the substrates to the material fluxes. The evaporation rates and thicknesses of the respective layers were measured with a quartz crystal monitor. The quartz crystal (indicated as Q in Fig. 4.1 (b)) was mounted in close vicinity of the substrate holder.

An elemental Se vapour flux was continuously supplied from an effusion cell (indicated as E in Fig. 4.1(a)). The effusion cell was mounted at an angle of about 45° with respect to the substrates and the distance from the substrate holder to the effusion cell was around 20cm. In essence, the effusion cell consisted of a stainless steel tube (length = 12 cm and diameter = 2.5 cm) with an evenly spaced heating coil. Selenium pellets of high purity (99.99%) were used and the temperature was accurately monitored by a J-type thermocouple mounted in the bottom part of the effusion cell (indicated by T3 in Fig. 4.1 (a)). The top part of the effusion cell was shielded with a molybdenum plate in order to create a temperature gradient across the cell. The higher temperature region at the top was required to prevent the
condensation of Se at the cell walls during evaporation. A small bolt with a 1 mm hole near the top of the effusion cell controlled the elemental Se flux during the selenization processes. This bolt could also be removed in order to replenish the effusion cell with Se pellets when required. The amount of Se evaporated was calculated by weighing the effusion cell before and after each selenization processes.

In order to ensure uniform and reproducible deposition processes, it was essential to accurately control the power supply to the evaporation sources, substrate heater and effusion cell. Accurate temperature control was ensured by the use of programmable REX P96 and P200 temperature controllers, allowing up to 10 heating stages. The controllers were connected to silicon-controlled-rectifiers (SCR’s), which supplied the electrical power to the evaporation sources, substrate heater and effusion cell. This configuration was extremely reliable and provided stable and controlled power supply to the respective heaters and hence uniform heating profiles.

The system was pumped down to pressures below $10^{-6}$ mbar with a mechanical pump supported by a diffusion pump. The pressure in the deposition chamber was continuously monitored with a Penning gauge.
Fig. 4.1 In-side view of the thermal evaporator used during this study, clearly revealing (a) the cylindrical-shaped graphite evaporation sources (H1, H2 and H3) and effusion cell (E), and (b) the orientation of the substrate heater (H) with respect to the substrate holder (S) and quartz crystal monitor (Q).
4.4.3. Growth procedure

4.4.3.1 Preparation of selenium-containing precursors

Selenium-containing precursors (Cu-In-Se and Cu-In-Ga-Se) were prepared with a relatively simple thermal evaporation process in which the constituent elements and compounds (Cu, In$_2$Se$_3$ and Ga$_2$Se$_3$) were sequentially evaporated from the three graphite heaters, indicated in Fig. 4.1 (a). In this growth process, the stoichiometry of the precursor films was fixed by the relative thickness of material evaporated. In the case of CuInSe$_2$ deposition, the Ga$_2$Se$_3$ layer was omitted. Typically, the Cu and InSe layer thicknesses were kept constant at 200 nm and 1500 nm respectively in order to produce slightly In-rich CuInSe$_2$ absorber films. In the case of Cu(In,Ga)Se$_2$ thin films, the Cu and InSe were kept constant at 200 nm and 1500 nm, while the GaSe layer thicknesses were varied between 10 nm and 200 nm to adjust the Cu/(In+Ga)- and Ga/(Ga+In) atomic ratios. The substrate temperature during Cu and InSe deposition was always maintained around 200ºC, while it was varied between 200ºC and 400ºC during GaSe deposition. Schematic representations of typical structures investigated during this study are depicted in Fig. 4.2.

Figure 4.2: Schematic representation of typical (a) Cu-In-Se and (b) Cu-In-Ga-Se precursor structures deposited during this study.
It is important to mention that the **order of deposition and/or the number of individual layers in the precursor stack** were varied in order to optimise the structural quality of the precursor layers. These results are discussed in detail in Sections 5.2.2 and 5.4.2. In order to obtain stable evaporation rates around 1 nm/s, the crucible temperatures were maintained at 1350°C during copper evaporation, 720°C during GaSe evaporation and at 650°C during the deposition of InSe. It is important to mention that the shutter was opened only once the final temperature set points were reached and stable growth rates were established.

### 4.4.3.2 Selenization process

The term selenization refers to the process of incorporation of selenium into the precursor films, resulting in the formation of ternary and quaternary CuInSe$_2$ or Cu(In,Ga)Se$_2$ thin films. The reaction of the precursor elements with Se species at high temperatures results in the rapid conversion of metallic to semiconductor phases, according to diffusion process outlined in Section 2.4.

In this study, the precursors were exposed to elemental Se vapour in vacuum, as described in Section 4.4.2. In order to ensure the rapid incorporation of Se into the precursor structures, the substrate temperature was typically maintained at 550°C during selenization. For complete reaction of the precursor films, a reaction period of at least 60 minutes was required, which corresponded to about 2g of Se being evaporated. In addition, the quartz crystal monitor was utilized to estimate the selenium delivery rates to the substrates. The effusion cell was heated from ambient temperature to about 330°C in 10 minutes, which resulted in a stable elemental Se flux.
4.4.3.3 Post-sulfurization of CuInSe$_2$

CuInSe$_2$ samples were sulfurized by the solid-state thermal diffusion of sulfur into the CuInSe$_2$ thin films. During this process the fully selenized samples were removed from the vacuum system depicted in Fig. 4.1 and inserted together with chalcogen elements (Se and S) into a commercially available quartz tube at atmospheric pressure [Alberts and Dejene, 2002]. The masses of the Se and S elements were maintained at about 1.0 g and 0.3 g, respectively. The additional Se during the sulfurization process was required to compensate for the anticipated selenium losses during the high temperature annealing step. The tube was heated to temperatures between 400°C and 500°C in 5 minutes, followed by a temperature plateau at these temperatures for approximately 15 minutes. These sulfurization experiments were conducted under constant Ar-flow rates.

4.5 Device Fabrication

A schematic representation of the completed solar cell structure is given in Fig. 2.6. After the absorber formation process, the films were immediately covered with a thin CdS buffer layer. The solar cell structure was completed by the deposition of a ZnO window layer and Ni/Al front contacts. In this section, the experimental procedures followed during the respective stages of devices fabrication, are briefly outlined.

4.5.1 CdS buffer layer deposition

In this study, 50nm thick CdS buffer layers were deposited onto the glass/Mo/absorber structures by means of a chemical bath deposition (CBD) process [Urner et al., 1994]. Depositions were carried out in a tube-like reactor (100cm$^3$), which was positioned vertically in a temperature controlled water bath. The temperature was maintained at 60°C. The bath was made up of three separate
solutions including cadmium acetate \([\text{Cd}(\text{AcO})_3]\), thiourea (\(\text{NH}_2\text{CSNH}_2\)) and ammonia (\(\text{NH}_3\)). The bath was continuously stirred and high purity chemicals and deionized water were used. The typical concentrations of the solutions are given in Table 4.1.

<table>
<thead>
<tr>
<th>Chemicals</th>
<th>Mixture</th>
<th>Volume (ml)</th>
<th>Concentration [mol/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Cd}(\text{AcO})_3)</td>
<td>1.039g/1000ml of H(_2)O</td>
<td>20</td>
<td>(3.9 \times 10^{-3})</td>
</tr>
<tr>
<td>(\text{NH}_3)</td>
<td>247ml/1000ml of H(_2)O</td>
<td>20</td>
<td>3.3</td>
</tr>
<tr>
<td>(\text{NH}_2\text{CSNH}_2)</td>
<td>1.37g/100ml of H(_2)O</td>
<td>20</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 4.1: Experimental details regarding the chemicals and concentration of solutions used in the CBD process.

The three solutions were prepared at least 8 hours before being used. The reaction process was initiated by adding 20ml of each solution to the reactor in the same sequence: first \(\text{Cd}(\text{AcO})_3\), followed by the thiourea and finally \(\text{NH}_3\). The samples were subsequently dipped into the heated chemical bath and rotated to ensure homogeneous bath conditions. The samples were removed from the heated bath after about five minutes and immediately rinsed in deionized water and dried under flowing nitrogen gas. The CdS thin films are formed from the reaction between dissolved cadmium ions and thiourea molecules in the ammonia solution according to the global reactions:

\[\text{Cd}(\text{NH}_3)_4^{2+} + \text{SC(NH}_2)_2 + 2\text{OH}^- \rightarrow \text{CdS} + \text{CH}_2\text{N}_2 + 4\text{NH}_3 + 2\text{H}_2\text{O}\]
4.5.2 ZnO window layer deposition

In this study, the ZnO films were deposited by DC magnetron sputtering. The system is equipped with a circular planar magnetron, which has a 55 mm erosion zone. A 99.999% pure ZnO ceramic target was used to deposit intrinsic films. For the deposition of conductive films, a 2% Al$_2$O$_3$-doped ZnO target was used. In the sputtering system, the targets were bonded to a water-cooled backing plate. After pumping the system down (about 10$^{-7}$ mbar), the substrates were heated to the desired temperature around 200°C. The working pressure was maintained around 7x10$^{-3}$ mbar, while 99.999% purity Ar was used as sputtering gas. The DC power was kept constant around 450 W, and the distance between the target and substrates was maintained at 7 cm. A summary of the sputtering conditions is given in Table 4.2.

<table>
<thead>
<tr>
<th>Control Parameters</th>
<th>ZnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base pressure (mbar)</td>
<td>$3 \times 10^{-7}$</td>
</tr>
<tr>
<td>Sputtering pressure (mbar)</td>
<td>$7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sputtering current (A)</td>
<td>1.0</td>
</tr>
<tr>
<td>Sputtering Voltage (V)</td>
<td>450</td>
</tr>
<tr>
<td>DC power (W)</td>
<td>450</td>
</tr>
<tr>
<td>Ar flow (sccm)</td>
<td>173</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of the experimental parameters used during the sputtering of intrinsic and doped ZnO window layers.
4.5.3 Ni/Al front contact deposition

Electron-beam evaporation was used to deposit 50nm of Ni and 1µm of Al through a metal mask onto the ZnO window layers. The mask was designed to cover only 5% of the total active cell area. Evaporations were carried out at about $10^{-6}$ mbar at a rate of 2 nm/sec. The Ni/Al grids were deposited without any intentional heating and the respective layer thicknesses were monitored by an oscillating quartz crystal monitor. A rotatable four-pocket crucible permitted the sequential deposition of Ni and Al without breaking vacuum. Cell areas were delineated by mechanical scribing to produce individual cells with 0.5 cm$^2$ areas.

4.6.1 Film Characterization Techniques

4.6.1 Introduction

In this study, a wide variety of characterization techniques were used to evaluate the material quality of the semiconductor thin films. The structural properties of the polycrystalline films were studied by scanning electron microscopy (SEM) and the presence of crystalline phases by x-ray diffraction (XRD). The stoichiometric ratios and the CuInSe$_2$, CuIn(Se,S)$_2$ and Cu(In,Ga)Se$_2$ absorber layers were determined by energy dispersive x-ray spectroscopy (EDS) and x-ray fluorescence (XRF). The optical properties of the films were evaluated by infrared spectroscopy. Completed devices were evaluated in the dark and under illumination by standard I-V characterization equipment. The most important features of these characterization techniques are outlined in the following sections.
4.6.2 Structural Analysis

4.6.2.1 Introduction

Several levels of structural information were of interest in this particular study. The first level broadly deals with the issues of film surface topography and morphology including grain size and shape, evidence of film voids and the lack of adhesion between the glass substrates and the thin films. Somewhat more difficult to obtain, but crucial to successful device fabrication, is information about the compositional uniformity of the films as function of depth. Another important aspect of structural analysis was x-ray diffraction and the information it conveys especially regarding the presence of secondary phases in the compound films.

4.6.2.2 Determination of thickness

Film thicknesses were controlled by how long the shutter remained open. As discussed in Section 4.4.2, the film thicknesses during thermal evaporation of layers were measured in situ with a quartz crystal monitor. In order to confirm the thickness values of the films, the thicknesses were also determined gravimetrically by using the simple relation:

$$d = \frac{\Delta m}{A \times \rho}$$  \hspace{1cm} (4.1)

where $A$ is the area covered by the film, and $\rho$ is the density of the thin film. In these calculations, the densities of the thin films were assumed to be the same as for the bulk material.
4.6.2.3 Scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS)

The morphology of the films was characterized using a JEOL JSM-840 scanning electron microscope (SEM). The composition of the films was determined using the same instrument equipped with energy dispersive x-ray spectroscopy (EDS) capability. The EDS operates with a LINK AN10000 detection system with an ultra-thin window for light element analysis. EDS analysis utilizes characteristic x-rays when the high energy electrons strike the sample. Normal operating acceleration voltages to generate the high energy electrons range between 20 and 30kV. The penetration depth of the electrons into the sample depends on the acceleration voltage. The generated x-ray photons enter a lithium drifted silicon detector, Si(Li), in which electron-hole pairs are created. An applied bias voltage enables the separation of these electron-hole pairs. The collected electrons are sent to a field-effect-transistor (FET) preamplifier, which converts this current into a voltage output pulse. These pulses undergo subsequent signal processing in the multi-channel-analyser (MCA).

4.6.2.4. X-Ray fluorescence (XRF)

XRF and the widely used EDS techniques are similar analytical techniques. However, in the case of XRF, the characteristic x-rays are generated by incident x-ray beams. Usually the polychromatic radiation from a x-ray tube is the excitation source of the XRF. The primary beam of the x-ray source penetrates the sample atoms. When electrons from outer shells fill the resulting gaps, the characteristic radiation is emitted. In most cases Kα1,2 or Lα1− lines are used for chemical analysis, because they are generally the most intense lines of the spectra. The Kα1,2− lines provide information about the total amount of each of the elements and thicknesses
of films, while the L_{\alpha1^{-}} lines are more surface sensitive. It has recently been indicated [Klenk et al., 1999] that the large penetration depth of x-rays leads to proportional relations between the K_{\alpha1,2^{-}} lines intensities and the mass per analyzed area of the sample. As the information depth (approximately 100 \, \mu m) is much larger than a typical thin film layer thickness (1-2 \, \mu m), not only the absorber material but also other layers of a thin film solar cell can be analyzed. In the case of a typical chalcopyrite solar cell this means, for example, that the thicknesses of the very thin CdS layers as well as that of the molybdenum and ZnO layers can be determined. Due to the high 2\theta resolution of XRF, there is also no line overlap of the different elements present in the chalcopyrite absorber material, which could influence the measurement. There is also no line overlap caused by other commonly used solar cell materials such as Mo, ZnO or CdS. The large penetration depth of x-rays also minimizes the matrix effects and allows for a relatively easy calibration process. Besides the concentration in atomic percent, the in-depth compositional uniformity of the samples can be determined by XRF intensity measurements of K_{\alpha1,2} lines as a function of sample depth. For this purpose the absorber films were repeatedly etched in bromine methanol (Br_{2}/MeOH), followed by XRF K_{\alpha1,2} measurements of the remaining material after each etching step. Chemical etching was conducted at room temperature and the samples were rinsed in water and blown dry with nitrogen before XRF measurements. The K_{\alpha1,2} scans were recorded with a sequential XRF wavelength dispersive spectrometer (SRS 3000, Bruker-AXS, Rh-anode, 60 kV).

4.6.2.5 X-Ray Diffraction (XRD)

The identification of any crystalline phases present and the determination of lattice parameters constitute an important use of XRD [Cullity et al., 2001]. In this study,
two systems were used for symmetric XRD measurements, (i) a computer controlled Philips model PW 1729 x-ray diffractometer and Co Kα (1.7890 Å) radiation and (ii) a SIEMENS D5000 x-ray diffractometer and Cu Kα (1.5418 Å). Typical wide angle scans from 10 - 90° at 0.02° steps were taken at 35 kV and 20 mA for most samples in order to carry out phase analysis. To resolve closely spaced peaks, high resolution scans were carried out at a step size of 0.01° integrated for 5 seconds per step. Identification of the phases from XRD was done using Bragg’s law:

\[ n\lambda = 2d \sin \theta \] (4.2)

where \( d \) is the interplanar spacing, \( \theta \) the Bragg angle and \( \lambda \) the wavelength of x-rays. In the case of the tetragonal systems, to which most of the samples encountered in this work belong,

\[ d = \frac{ac}{\sqrt{c^2(h^2+k^2)+a^2l^2}} \] (4.3)

where \( h, k, l \) are the Miller indices of the diffracting planes, and \( a \) and \( c \) are lattice parameters. The crystalline phases were identified by matching the experimentally measured XRD peak positions with those given in the Joint Council for Powder Diffraction Studies (JCPDS) files.

### 4.6.3 Optical Properties

One of the important aspects of this study was the optical characterisation of the semiconductor thin films. Standard transmission and reflectance measurements
were used to determine the absorption coefficients and optical band gaps of films. In addition, low temperature photoluminescence was employed to investigate the presence of intrinsic defect levels in the chalcopyrite absorber films.

4.6.3.1 UV-VIS-NIR Spectroscopy

Optical measurements were conducted using a Cary UV-VIS-NIR spectrophotometer. Transmission and reflection measurements were taken of relevant samples at room temperature with a scan range typically between 300-2000 nm. Following the analysis of Pankove, the optical transmission coefficient (T) of a transmitting medium is defined as the ratio of the intensity of transmitted radiation to that of the incident radiation, $I/I_0$ [Pankove, 1971]. These two intensities are related to the absorption coefficient ($\alpha$), and the optical path length (t) by the following expression:

$$I = I_0 e^{-\alpha t} \quad (4.4)$$

Taking reflection effects into account, for an incident intensity of $I_0$ at a front surface of a transmitting medium, the transmitted radiation is given by $(1 - R)I_0$, where $R$ is the reflection coefficient. Using the above relation in equation 4.4, the portion of the radiation reaching the back surface of the medium is $(1 - R)I_0 e^{-\alpha t}$. Only a fraction of this radiation given by $(1 - R)(1 - R)I_0 e^{-\alpha t}$ emerges from the medium. Taking into account all the multiple internal reflections, the total transmitted radiation can be expressed as [Pankove, 1971]:

$$T = \frac{I}{I_0} = \frac{(1 - R)^2 \exp(-\alpha t)}{1 - R^2 \exp(-2\alpha t)} \quad (4.5)$$
where $I$ and $I_0$ are again the transmitted and incident light intensity respectively, $t$ (or optical path length) is the film thickness, and $\alpha$ is the absorption coefficient. For high values of $\alpha$, the term $R^2 \exp(-2\alpha t)$ in the denominator can be neglected since $R$ is also neglected for high absorption, and $\exp(-2\alpha t)$ is approximately zero. This leads to the simplified relation between $\alpha$ and the measured $R$ and $T$,

$$\alpha = \frac{2 \ln(1-R) - \ln(T)}{t} \quad (4.6)$$

The optical absorption coefficient $\alpha$ varies with photon energy $h\nu$ according to the relation

$$\alpha h\nu = A(h\nu - E_g)^n \quad (4.7)$$

where $n$ is characterized by the specific transition process, and $E_g$ is the band gap. For direct band gap semiconductors, such as those discussed in this work, $n = 1/2$.

### 4.6.3.2 Photoluminescence

Photoluminescence (PL) provides a non-destructive technique for the determination of certain impurities in semiconductors [Bedd and Williams, 1972]. It is particularly suited for detection of shallow-level impurities. PL spectra were acquired at the University of Port Elizabeth (UPE) using an Ar$^+$ laser (514nm) laser for excitation at temperatures between 4.2 K and 45 K. The luminescence was dispersed by a 0.5m monochromator (calibrated with the 632.8 nm line of a HeNe laser) and detected using a Ge-detector.
4.6.4 Device characterization

Completed devices were characterized by dark and illuminated current-voltage (I-V) measurements and quantum efficiency (QE) measurements. From the illuminated I-V characteristics measured under standard test conditions (AM 1.5, 1000 W/m², 25°C) the most important cell parameters, the cell efficiency $\eta$, the short circuit current density $J_{sc}$, the open circuit voltage $V_{oc}$ and the fill factor were extracted. A correlation between the dark and illuminated characteristics can be made under the assumption of the super principle for solar cells, which states that the current density of an illuminated solar cell equals the short circuit density subtracted by the dark current density. This theory was discussed in detail in Section 3.3.6. Quantum efficiency measurements were conducted at the Institute of Energy Conversion (IEC) in the USA. In these studies the short circuit current densities of completed devices were measured as function of the wavelength of monochromatic light impinging on the cells. From this data the cell’s spectral response was obtained.
References


