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Building-Integrated Concentrated Photovoltaics

effects of inhomogeneous illumination

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Chapter 1

General Introduction

1.1 The need for photovoltaics

The increasing importance of renewable energy sources is underlined when considering three phenomena. Firstly, the increasing life expectancy of the Earth’s human population, which is expected to reach an average mortality age of 75 in 2100 leading to a population expansion of over 11 billion ($11 \times 10^9$) people in that year \[1\,2\]. Secondly, the increasing yearly energy consumption per inhabitant, which has increased from 2800 kWh/person to 8300 kWh/person between 1950 and 2013 and is expected to increase further due to increasing prosperity \[3\]. Combined this means that the annual global energy demand is expected to increase nearly three-fold from its current level of approximately 160 PWh to around 450 PWh in the year 2100\[1\]. Finally, there is the matter of fossil fuels, the burning of which at the moment still accounts for the majority of energy generation. One problem here is that these resources are finite and will eventually be depleted \[4\,5\]. Another problem is the pollution of the Earth that the burning of fossil fuels entails. The Intergovernmental Panel on Climate Change (IPCC), which is a scientific body for the assessment of climate change, regards it extremely likely that ‘human influence has been the dominant cause of the observed global warming since the mid-20th century’ and that ‘continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system’ \[6\]. It is thus important to substantially reduce the amount of greenhouse gas emissions and pollution caused by the burning of the fossil fuels, while still meeting the vastly expanding energy need \[7\]. To achieve this, a transition to another energy source is an absolute necessity.

1 Note that the definitions generated energy or primary energy differs from the world final energy consumption or demand because much of the energy that is acquired is lost during the process of its refinement into usable forms of energy and its transport to the final consumer. For example, in 2012 the world primary energy use or supply was 156 TWh while the final energy consumption was 104 TWh.
1.1. THE NEED FOR PHOTOVOLTAICS

Figure 1.1: Global primary energy use, projected until 2050 and 2100 according to the German advisory council on global change, showing the increasing amount of total energy use, and the large proportion of the total energy use that solar energy is expected to provide [7].

regarding the operation of nuclear power plants, the long term disposal of radioactive waste and weaponization. Most importantly however, like fossil fuel reserves, the nuclear fuel reserves are finite. Therefore nuclear power will eventually not be a sustainable energy source. A safer and more sustainable option, therefore, is a transition to renewable energy sources for our power supply. Solar energy generation, also known as photovoltaics (PV), is expected to be a large contributor to the 'renewable energy mix', according to technical feasibility estimates by the World Energy Assessment [8], and as shown in figure 1.1. The figure shows a projection of energy use by source type according to the German advisory council on global change which takes into account the mentioned increases and the expected fossil fuel reserves [7]. The growing total energy consumption is clearly identified in this scenario, as well as the expectancy for a large proportion of the energy to be produced from solar power. The challenge in achieving photovoltaic power generation on such a large scale should not be underestimated. Because even though there has been a massive installation rate of PV in recent years, resulting in the 100 GWp\(^2\) milestone of total installed nominal PV capacity worldwide being reached at the end of 2012 [9], this only amounted to 0.08% of the total energy demand. In order

\(^2\)Wp stands for Watt-peak, the power a solar panel provides under standard test conditions.
to currently meet the global demand of electrical energy, 8.7 TW of installed production power is required \(^3\). In order to obtain all this electrical energy from PV however, an installed power of 19.1 TWp would be required, since PV typically has a lower capacity factor compared to conventional electrical energy generation, mainly because the sun will not irradiate the system 24 hours per day, but also the location on Earth and the orientation of the panel are factors \(^5\). This would amount to installing an area of 885 000 km\(^2\) of solar panels\(^4\), an area roughly the size of France\(^4\).

Still, although there are challenges, it is clear that solar energy will have a major role to play in the renewable energy transition that shall have to take place in the foreseeable future. Therefore a wide research interest for PV is increasing.

### 1.2 A brief history of photovoltaics

The first photovoltaic device was created in 1839 by Alexandre Edmond Becquerel\(^5\) by combining an acidic silver chloride solution with platinum electrodes \(^12\). He found that this device produced current when illuminated, thereby identifying the photovoltaic effect. In the following century the photovoltaic effect was studied on a small scale, but it was not until the mid 1950s that the first semiconductor photovoltaic devices - which make up the majority of modern solar cells today - were reported \(^13\)\(^14\). The devices had low light-to-electricity conversion efficiencies (\(\eta\)) in the order of 6% and were quite expensive to produce. Therefore there was no immediate interest to apply them as a means of generating consumer electricity. However, a niche application was found in the first satellites, where reliable and durable energy sources were required. Hence the first application of solar cells was on the Vanguard I satellite in 1958 \(^15\). Around this time, development of the theoretical framework for solar cell operation started, predicting maximum efficiencies that might be obtained and theoretical concepts aimed at enhancing solar cell efficiency \(^16\)\(^19\).

During the 1960s and early 1970s the space industry remained the main driving force for research in photovoltaics. The early space missions proved to add new challenges to device design, as space turned out to be a much harsher environment than our own atmosphere, featuring a.o. radiation belts, floating debris, and large temperature fluctuations. Solar cell research was directed towards producing more efficient cells, improving radiation hardness and improving physical stability. Crystalline Silicon (c-Si) solar cells received most of the attention, although thin-film technologies such as CdTe \(^20\) were also investigated. Thin-film cells offer a potentially higher power to weight ratio, which is a very enticing prospect when

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\(^3\)Considering a 20% efficient silicon solar panel \(^11\) and 1000 W m\(^{-2}\) illumination which accumulates to 200 Wp m\(^{-2}\).

\(^4\)Note that the increasing population and energy consumption per capita are left out of account in this example.

\(^5\)Not to be confused with his son Henri Becquerel who in 1903 received the Nobel Prize in Physics for his discovery of spontaneous radioactivity.
Figure 1.2: The theoretical maximum convertible power of the AM1.5 standard solar spectrum, with a Si cell (left), and an InGaP/GaAs/Ge cell (right). The AM1.5 spectrum is marked in yellow, while absorptions by the four considered semiconductors are coloured as shown in the respective legends.

The device is to be launched into space, in which case every added gram means an increased launching cost.

The interest in using photovoltaics on Earth was sparked by the 1973 oil crisis, which put a strain on the energy supply. As a result, solar cell and other renewables research received more funding. For terrestrial applications, the primary issues to be addressed at the time were large scale manufacturability, and cost reduction. Although c-Si remained the primarily used solar cell material\textsuperscript{6}, different technologies, such as amorphous silicon (a-Si), Cu(In, Ga)Se\textsubscript{2} (CIGS) and CdTe cells were also reported.

Also in the mid 1970s the idea of using different solar cell materials simultaneously by stacking them on top of one another was first pursued. Such multiple junction (MJ, where a ‘junction’ refers to a single semiconductor type within the stack\textsuperscript{7}) solar cells are often primarily based on III-V semiconductors such as e.g. gallium arsenide (GaAs) and indium gallium phosphide (InGaP). Here, III and V refer to an element categorized in the third and fifth column of the Periodic Table of the Elements, respectively. The initial MJ devices were GaAs grown on a germanium (Ge) substrate; they were followed by InGaP on GaAs ‘tandem’ cells, and InGaP/GaAs/Ge triple junction (TJ) cells. As a MJ cell consists of a stack of multiple subcells, it is important that the crystal lattices of the subcells fit onto

\textsuperscript{6}Note that even today, Si based solar cells make up the vast majority of all photovoltaic systems for two main reasons. Firstly, Si is quite an abundant element on Earth, especially compared to the other materials used for semiconductor manufacturing. Secondly, since the commercialization of Si based mesa transistors in 1958 by IBM and the subsequent development of among others the chip and computer industries, large scale production, processing, and test equipment for Si semiconductors are readily available.

\textsuperscript{7}The junction is actually the interface of the p-doped and n-doped material layers of the semiconductor. This will be briefly elaborated in section 2.1.
one another (lattice matching) in order to avoid defects and it is good to note that the entire cell stack often features two contact terminals, rather than two contacts per subcell. The main benefits of these solar cells are the high material quality and the option to use the full spectrum of sunlight in a more efficient way than with a single junction cell, as shown in figure 1.2. Here, the maximum theoretical power generation of a Si cell is compared to that of a InGaP/GaAs/Ge cell when illuminated by the AM1.5 standard solar spectrum as defined in [21]. This is the spectrum used by solar cell researchers to simulate incident sunlight in test setups. Aside from the displayed wavelength distribution, the total illumination density of this spectrum equals 100 mW cm$^{-2}$, to simulate ‘one sun’ illumination.

Additionally, interest arose in using these solar cells in conjunction with Concentrating Solar Power (CSP) technology that was until then used to generate heat from sunlight. By using the focusing optics of CSP to concentrate large areas of insolation onto a small, highly efficient solar cell, the higher solar cell cost is alleviated, allowing an economically more attractive way to use these MJ cells on Earth. This field is known as Concentrator PhotoVoltaics (CPV), and is the main research area of this thesis. An overview of the historical development of CPV is provided in section 1.3.
1.2. A BRIEF HISTORY OF PHOTOVOLTAICS

Figure 1.3: The National Renewable Energy Laboratory’s best research-cell efficiency chart, displaying the highest solar cell efficiencies measured for various solar cell technologies [22].
In the past two decades research labs worldwide have investigated several promising new PV technologies, as shown in the lower right corner of figure 1.3, where the champion efficiency solar cells for several PV technologies are recorded by the US National Renewable Energy Laboratory (NREL). Organic solar cells ($\eta_{\text{max}} = 11.5\%$) hold the promise of cheaper manufacturing costs and a higher degree of aesthetic freedom than conventional Si based panels [23]. Thin-film dye-sensitized solar cells ($\eta_{\text{max}} = 11.9\%$) hold the promise of simpler large scale manufacturability, and are semi-flexible and semi-transparent. Therefore they allow applications that are not possible for conventional PV [24]. Quantum dot solar cells ($\eta_{\text{max}} = 13.4\%$) replace bulk semiconductor material by quantum dot absorbers that are tuneable over a wide range of energy levels [25]. Therefore they can be used to improve cell efficiency by harvesting multiple parts of the solar spectrum. However, the maximum reported efficiencies for these technologies are still far removed from conventional c-Si panels ($\eta_{\text{max}} = 25.3\%$, typical installed panel 16$\%$ to 18$\%$). Recently perovskite based solar cells have been increasingly gaining interest. The first report of perovskite solar cells appeared in 2009 [26] and since then a record efficiency of 22.1$\%$ has been achieved, which is very close to those of CIGS ($\eta_{\text{max}} = 22.6\%$), CdTe ($\eta_{\text{max}} = 22.1\%$) and even c-Si. Perovskites may well become the dominant PV technology in the future, provided that the current problems with the lifetime of the cells, and large area production will be solved. The highest solar cell efficiencies, shown at the top of figure 1.3, are achieved by III-V technologies, which are mainly applied in space solar arrays and terrestrial CPV systems, examples of which are shown in figure 1.4. Lattice matched InGaP/(In)GaAs/Ge triple junction cells ($\eta_{\text{max}} = 37.9\%$).
1.2. A BRIEF HISTORY OF PHOTOVOLTAICS

for regular one sun illumination, and 44.4% under concentration) are the current benchmark for commercially available (at typically 32-34% conversion efficiency) MJ solar cells. The need for more efficient, light-weight and cheaper cells drives III-V solar cell research ever further. In order to reach higher efficiencies the band gap combination of the solar cell can be optimized \[29\] and/or additional junctions can be added to the device. Currently 4, 5 and even 6 junction solar cells are being investigated \[30\] \[32\]. When this many junctions are desired, conventional lattice matched growth on a growth substrate (typical GaAs or Ge) as used for InGaP/Ga(In)As/Ge cells is no longer possible. Two main strategies are employed to circumvent this difficulty. Firstly by wafer bonding two separate devices together to form one functional four-junction two-terminal device \[33\] \[35\]. The surfaces of both devices are polished to a very high smoothness and chemically cleaned, after which the surfaces are brought together to be bonded by a slight pressure and annealed. Secondly, an inverted metamorphic (IMM) approach is used \[29\] \[36\] \[37\]. Here, a compositionally graded buffer is used to gradually change the lattice constant during cell growth. These IMM structures are grown in inverse order so the lattice matched InGaP and Ga(In)As junctions are grown first, after which the lattice constant is changed and additional junctions are grown on top. Both wafer bonding and IMM growth methods require substrate removal before the cell can be processed into a functional device, as in both cases a substrate is attached to the top cell, effectively blocking light from entering the semiconductor. Substrate removal is currently mainly achieved by wet chemical etching or mechanical grinding and polishing. These methods result in the loss of the expensive growth substrate, therefore substrate removal techniques that allow for substrate re-use \[38\] \[39\] are of interest. The two main techniques that are currently available are epitaxial lift-off (ELO) \[40\] \[43\] and controlled spalling \[44\] \[47\]. Reusing the substrate can significantly reduce the solar cell production cost. Substrate removal has some additional benefits. The substrate typically makes up a large part of the solar cell weight, hence substrate removal allows for the creation of high-efficiency, thin-film, light-weight, flexible solar cells. Also, the accessibility of the back surface of the solar cell device allows for implementation of a back reflector to enhance solar cell efficiency \[48\] \[50\].

Besides the development of cells with increasingly higher efficiencies research efforts have recently been directed towards lowering the costs of III-V devices. This includes lowering the production costs of III-V epi-structures by increasing the MOCVD growth rate and by developing Hydride Vapour-Phase Epitaxy (HVPE) growth methods for III-V solar cells \[51\] \[53\], either growing, bonding or stacking III-V devices on silicon \[54\] \[55\] and the investigation of cheaper Cu-based metallization schemes \[56\] \[58\].
1.3 Concentrated solar energy

1.3.1 Historical development

The idea of concentrating sunlight is by no means new. For instance the statement that Archimedes used so-called ‘burning mirrors’ to focus sunlight to such intensity that it set fire to Marcellus’ fleet that was besieging Syracuse in 212 B.C.\footnote{There are many written documents describing, discussing or falsifying this matter that the reader could be referred to. In the opinion of the author, the exposition provided by D.L. Simms in 1977 \cite{59} is very nice.} is quite well known. Also, scores of children have used this principle to set fire to a piece of material (or sometimes, more maliciously, small insects) using a magnifying glass. Nowadays the same concept is employed as a means to harvest energy from sunlight, ideally (and unexcitingly) without setting anything ablaze. In this way a large area of insolation is concentrated onto a small receiver designed to extract energy from the light. This provides benefits when it is difficult to build a receiver on a large scale, when the concentrator is much cheaper per unit area than the receiver, or when concentration achieves a property that non-concentrating technologies cannot easily reach, such as high temperatures (read: 600-1000°C).

The first solar concentrators aimed at producing energy from the light were used for heat collection. There are four main technologies that use this principle which is referred to as Concentrating Solar Power (CSP), as shown in figure \ref{fig:1.5}. Firstly, a parabolic through collector utilizes a large number of parabolic shaped mirrors to focus the light in a line shape along its focal axis as shown in figure \ref{fig:1.5a} \cite{64}. The receiver contains a thermal oil, molten salt or pressurized water to deliver reach temperatures of 400-550°C. This technology was pioneered in Meadi Egypt, in 1913 \cite{65}. The second is linear Fresnel collector technology which is based on several flat, ground mounted mirrors which individually rotate to follow the sun position and are arrayed in a Fresnel pattern, as shown in figure \ref{fig:1.5b} \cite{66}. The light is concentrated on a linear, fluid filled absorber tube. The first prototype was demonstrated in Genoa, Italy in 1964 \cite{67}. The first solar power tower was also demonstrated in Italy, in Adrano in 1965 \cite{67}. A power tower (see figure \ref{fig:1.5c}) consists of many circular arrays of mirrors that follow the sun through the sky (sun tracking), and reflect the sunlight to a central receiver atop a power tower. The high temperature heat generated here is used to produce superheated steam to drive a conventional generator \cite{68}. Finally, the Stirling, or parabolic dish system as shown in figure \ref{fig:1.5d} utilises a parabolic dish shaped concentrator with a receiver mounted at its focal point to generate high heat that in turn drives a Sterling engine \cite{69}. The first system was demonstrated in Southern California in 1982 \cite{70}. There are several other CSP technologies and for more details the reader is referred to reviews found in \cite{65,71,72,73}. The optics used in CSP are also applied in ConcentratorPhotoVoltaics (CPV) where instead of heat, electrical energy is generated by direct conversion of the concentrated light by a photovoltaic cell.

Research into producing electrical energy rather than heat from concentrated sun-
1.3. CONCENTRATED SOLAR ENERGY

Figure 1.5: The four main CSP technologies: a) Parabolic through system by 3M and Gossamer Space Frames, installed in Daggett, California [60], b) Linear Fresnel reflector concentrator by Reliance Power and Areva Solar installed in Rajasthan, India [61], c) Crescent Dunes Solar Power Tower plant, installed in Nevada [62], d) Stirling dish in Phoenix, Arizona [63].

light began in earnest in the mid 1970s, spurred on by the oil crisis. Initially, the main interest for CPV was situated in the US, where the budget for concentrators increased from $1.25 M to $6.2 M between 1976 and 1978. At that time already a variety of approaches were used, including reflective, refractive, and luminescent concentrators [74]. Over time, many large scale companies conducted research into CPV, notably Motorola [75], GE [76], Martin Marietta [77], E-Systems/Entech [78], Boeing, Acurex [79], and Spectrolab [80]. The most prominent universities in the CPV field were Stanford [81], Arizona State [74, 82], and Purdue. In Europe and Japan CPV research was less prominent at the time, as the direct normal incidence (DNI) was percieved to be low there. However, the

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9Please note that the references provided in the following refer merely to examples of the work done by several parties, and by no means provide a complete list.

10As it turns out, the DNI in for instance Spain and Italy is actually quite high.
Catholic University of Leuven, the Polytechnical University of Madrid, and the Ioffe Physical-Technical Institute in St. Petersburg developed CPV programs, leading to several successful large-scale demonstration projects.

During the 1980s the oil prices plummeted and CPV research programmes were scaled back as the energy crisis passed. During this time, many parties dropped their CPV research as funding became less abundant. Nevertheless, several parties (a.o. ASEC, Spectrolab, SunPower, Solarex, Solar Kinetics, En-tech, Alpha Solarco, SEA Corp) kept performing dedicated CPV research into the 1990s. In spite of the reduced interest, near the end of the 1990s new participants in the CPV research field emerged. At this time, Point focus Fresnel lens based systems were being investigated by Alpha Solarco, Amonix, SunPower, and the University of Reading. Line focus systems were being investigated by the Australian National University (trough based), BP Solar (trough based) and Entech (lens based). Reflective dish systems were developed by Ben-Gurion University, Solar Research Corporation, and SunPower. Furthermore research into single axis tracked and static CPV technology was being conducted at Fraunhofer ISE, Photovoltaics International, The University of New South Wales, The Polytechnical University of Madrid, and Tokyo A&T University. The leaders in the field of CPV cell development were NREL, Fraunhofer ISE, and the Ioffe Physical-Technical Institute. At the turning of the millennium, the state and promise of CPV technology was reviewed extensively by Richard M. Swanson.

The interest in CPV was resparked in the mid 2000s when the ramping up of global Si solar cell production and the related silicon shortage of 2005 caused the prices of polycrystalline and multicrystalline silicon, which are the raw materials for conventional solar panels, to increase over 15-fold in three years time. In this period the constraints on silicon became so severe that the industry had to idle roughly one quarter of the available PV production capacity. This was one important reason for the increase in industrial activities in high concentration PV, and other reasons include the progress in MJ solar cell efficiency and industrial availability, progress in concentrating optics and optimised CPV systems. Accordingly, the market potential for CPV systems increased. The industrial capacity for large-scale high-concentration PV at the time was limited to two companies: Amonix in the US, and Solar Systems in Australia. Their systems used Fresnel lenses and mirrors as optical concentrators, and Si back contact cells. However, the use of much higher efficiency (above 35%, see also figure 1.3) III-V based cells for CPV appeared to be much more promising. Therefore, aside from the established firms, also several new players tried to commercialise III-V based CPV systems. In the US demonstrators were set up i.e. by Pyron and Concentrator Technonogies LLC. In Japan Daido Steel had already been active in CPV development for some years, and showed a conversion efficiency of 30% using a PMMA Fresnel dome combined with a kaleidoscope and a III-V cell. In Australia Green and Gold Energy developed several novel approaches to CPV.

\[11\] The small area cells employed in the setups reduced the Si dependence of the systems to an extent to be viable, in spite of the Si shortage.
1.3. CONCENTRATED SOLAR ENERGY

systems. In addition Solar Systems achieved 30% conversion efficiency using III-V cells in their established dish system instead of Si \cite{106}. In Europe the company SolG3 developed a system to be used on rooftops \cite{107}. Additionally Isofoton developed a concentrating optic for 1000x in collaboration with the University of Madrid Instituto de Energia Solar. Also Concentrix was founded to commercialize Fraunhofer ISE’s FLATCON system \cite{102,108}, which would become the standard for terrestrial CPV technology. When several new silicon plants opened production in 2008 the Si shortage ended and as the production potential for the benchmark Si based panels soared, research interest for - and the spur in development of - CPV systems again waned somewhat over time.

1.3.2 Concentrator photovoltaics today

Currently there are several main concentrator technologies, that differ wildly in optical properties and applied principles. They will be briefly summarized here and examples of each are shown in figure 1.6. Firstly, Compound Parabolic Concentrators (CPC), as shown in figure 1.6a, use a truncated parabolic optic that relies on internal reflection to allow the incident light to reach the solar cell (placed at the truncated tip) \cite{109-112}. Due to this design very high concentration ratios are difficult to achieve, but a large acceptance angle (26°) is achieved - meaning that incident light with unparallel components, can still be harvested by the system. Secondly, a hyperboloid concentrator, illustrated in figure 1.6b, again relies on reflections to guide the light toward the solar cell placed in the aperture \cite{113}. The main advantage of this setup is its compactness \cite{114}. The Dielectric Totally Internally Reflecting Concentrator (DTIRC) first introduced by Ning et. al. \cite{115}, and illustrated in figure 1.6c, relies on a similar principle, although the design of the optic is very different. It consists of a curved front surface, totally internally reflecting body, and an exit aperture where the solar cell is placed. Compared to CPC, the DTIRC achieves higher efficiency and concentration ratio, however cannot easily pass all the harvested solar energy into a lower index medium, as it is solid whereas CPC and DTIRC are hollow \cite{116}. Furthermore, the parabolic through system as discussed above is a much recognised technology due to its low unit cost and high dispatchability. It is now used for generation of electric as well as thermal energy (known as PhotoVoltaic-Thermal, PVT) in some cases \cite{117,118}, as shown in figure 1.6d. Fresnel lenses as shown in figure 1.6e, are a prime choice for use in CPV because of their low weight, small volume, and low production cost. Current Fresnel lenses can be cut from glass, made by silicon on glass techniques, or cast in PMMA, which has very similar optical properties to glass \cite{119}. An additional benefit of a Fresnel lens is its excellent optical efficiency \cite{120} which allows for high concentration ratios in CPV, and therefore offer the greatest reduction in semiconductor area. Drawbacks include the need for two-axis sun tracking because of a typically low acceptance angle (0.2°), the need for cooling because of local heating of the solar cell, and inhomogeneity in the flux and heat profile on the solar cell surface introduced by the lens. Finally, several novel optical systems exist with wide-ranging applications. An example is given in figure 1.6f. Specific
CHAPTER 1. GENERAL INTRODUCTION

Figure 1.6: Examples of the current main types of CPV setups. a) A CPC optic as sold by Edmund Optics [121] where the aperture for incident light is shown at the bottom of the picture; b) hyperboloid concentrator as described by Ali et al. [113]; c) DTIRC module for building façade integration developed at the University of Exeter [122]; d) CHAPS parabolic trough PVT collector at the Australian National University [123]; e) Concentrix FLATCON system as described by Gombert et al. [124]; and f) CPV tracking setup featuring novel flat optics by Morgan Solar (further details in chapter 7 and morgansolar.com), as well as a pyrometer and pyrheliometer for measuring insolation and sun position, installed at Radboud University.
CPV setups within these main types of concentrators may vary on many design points, depending on which parameters are optimized or the specific application. For instance, Mallick et al. [111] developed an asymmetric CPC for building-façade integration, Entech’s fourth generation module uses a curved rather than a flat Fresnel lens [125], and Akisawa et al. [126] investigated domed Fresnel lenses. The various systems have been reviewed extensively in recent years [127–130]. Note-worthy are so-called two-stage concentrators [131], that use a Secondary Optic Element (SOE) [132,133], also called secondary concentrator, in conjunction with a larger, primary concentrator. SOEs provide homogenization of the illumination profile on the cell surface usually by multiple reflections of the light, as well as secondary concentration. SOEs come in many shapes and sizes and range from kaleidoscopic light pipes to glass domes covering the solar cell, and even CPC, DTIRC, and hyperboloid concentrators are used as secondaries.

A complete overview of all parties engaged in CPV research or development has been included by Sarah Kurtz of NREL in her report on the opportunities and challenges for the CPV industry, which she first published in 2009 [134], and revised in 2012 [135].

1.3.3 Building-integrated concentrator photovoltaics

Forty per cent of the European energy consumption is attributed to buildings [136]. The European Union actively adopts energy efficiency policies to reduce this amount, as is evidenced by the “20-20-20” objectives: 20% decrease in greenhouse gas emissions, 20% share of renewable energy and 20% improvement in energy efficiency by 2020. As a consequence of these objectives, in the past decade there has been a movement for integrating PV into buildings, as this connects to the abovementioned aspirations excellently. Building-integrated photovoltaics (BIPV) systems offer the benefits of local energy generation, as well as being more aesthetically pleasing than typical rooftop applied solar panels. In recent years, as the energy performance regulations have become the dominant driving factor in the BIPV market, the focus of the technology has shifted from mainly aesthetic, to mainly functional benefits. That is to say, rather than being applied on a building in order to convey a sense of innovation and sustainability, novel systems more often replace and fulfill the function of structural parts of the building skin, as well as generate renewable energy [12]. These systems contribute to the move towards energy neutral buildings by combining PV in the building design in a variety of ways, depending on the structural component(s) being replaced. Examples include, but are not limited to, full roof systems [137–140], solar skylights [141,142], solar roof tiles [143,144], rain-screen solar façade [145], solar curtain wall [146].

In this thesis, with regard to being installed in or on a building, photovoltaics systems are categorized based on the nature of the installation: they can be i) applied onto an existing building, ii) incorporated into a building structure, or iii) integrated in the building, replacing a structural component. The terms used here for these installation methods will be respectively, building applied, building-incorporated, and building-integrated. The studies described in later chapters have been performed in the framework of systems in the latter two categories.
and an energy producing greenhouse \[147\]. A good overview of the current status of BIPV has recently been published by the Solar Energy Application Centre (The Netherlands) and the University of Applied Sciences and Arts of Southern Switzerland \[148\].

These BIPV systems have an opportunity for multiple energy efficiency functionality, as the energy demand in a building is not limited to electricity. For example, heating of the building interior often accounts for the majority of the energy consumption. In this regard building-integrated concentrator photovoltaics (BICPV) can offer further opportunities. Because of the focusing nature of such systems, aside from electrical energy generated by the solar cell, an elevated heat level is also obtained at the focal point. Therefore, BICPV offers an excellent possibility to combine the generation of electrical power and directly usable heat \[149\]. Another major source of energy use comes from artificial illumination of the building interior, even during the daylight hours. Often, blinds will be closed in office buildings to shut out the natural light when it is too bright to be able to comfortably work on a computer, only to turn on a lamp. In this case also, BICPV can offer a solution through multiple functionality. In concentrator systems, only the \textit{direct} fraction of light is focused on the solar cell, while the \textit{diffuse} fraction is not, but is typically distributed in the plane around the cell. If the cell is mounted in a transparent medium, this characteristic can be employed as a way to regulate daylight entering into the interior of buildings \[150\]. In this fashion, electrical energy is produced by the PV cells, while simultaneously the energy demand of the building is reduced because the need for artificial lighting is alleviated. Clearly, BICPV is a very promising technology to address the increasing, and many-faceted energy demand. Recent developments in this field include luminescent solar cell windows \[151, 152\], façade integrated dielectric concentrators \[122, 153\], linear Fresnel lens systems for illumination and temperature control of the building interior \[154, 156\], a CPVT system for roof incorporation that uses a Fresnel prism in conjunction with a multi-lobed parabolic mirror to reduce the bulk of the tracking system in a major way \[157\], and a semi-transparent, profiled plate, light-guide system for façade integration that combines daylight regulation and electricity generation \[158\]. The latter two systems are studied in more detail in this thesis.

1.4 Subjects and outline of this thesis

The recently adopted energy efficiency policies in the EU induce a movement towards energy neutral buildings. This in turn drives the growth of building-integrated photovoltaics, as this technological field connects to this aspiration very well. As mentioned in the previous section, it offers multiple functionality by combination of the local generation of electricity with directly usable heat, or daylight or temperature regulation.

Building integration and multiple functionality give rise to specific challenges as it e.g. puts size, weight, and geometrical constraints on system design. To meet
these challenges, the applied optics generally have a more complex geometry than those applied for field-based CPV systems. By its very nature CPV deals with inhomogeneities in the illumination of the solar cell. In BICPV applications, these can be much more severe than in ‘traditional’, field-based concentrators because of the increased complexity of the optics. In the studies presented in this thesis, the main focus will be on these inhomogeneities in illumination distributions, and their implications for BICPV applications. More specifically, the focus is on the ways in which cell illumination in BICPV application differs from typical lab conditions. The general route taken to study these phenomena, is to produce the inhomogeneous illumination conditions, as found in the applications, in a controlled fashion in the lab, and then compare to ‘benchmark’ lab tests. First in chapter 2 is presented, an introduction to the experimental techniques used to i) produce some of the solar cells investigated in this study, and ii) characterize these cells electrically and optically. Next, in chapter 3 the in-house developed ray tracing software that is used to simulate and study illumination patterns is introduced.

The subsequent three chapters consider inhomogeneities in illumination on the solar cell level. This is an omnipresent phenomenon in CPV, as light that is focussed through an external medium will inherently feature a gradient in illumination intensity [159]. Moreover, light refraction usually occurs in a wavelength dependent fashion, causing spectral inhomogeneity on the cell surface.

The effects that inhomogeneous illumination intensity has on the electrical output of the solar cell is discussed in chapter 4. Not only the electrical performance of CPV cells is studied, but also the individual GaAs subcell is investigated, because GaAs is often the limiting subcell, and is known to suffer from perimeter recombination effects. This is compared to the performance of in-house produced deep junction GaAs solar cells, that aim to improve the solar cell performance.

In chapter 5 spectral inhomogeneity [160,161] and its effect on cell performance is studied using methods that specifically illuminate different parts of the solar cell with a partial spectrum. Chromatic aberrations cause a spatially non-uniform subcell current mismatch in the solar cell [162], which is in this way studied in a controlled fashion.

Other points of attention of in particular complex concentrator systems are the guidance of light to the solar cell, and the cell illumination angle. To assist in the first regard, a secondary optical element [163] can be used to capture light that would otherwise not reach the cell. Additionally the secondary optic can provide extra concentration, and homogenize the light. However, secondary optics also elevate the average cell illumination angle, therefore adding to the second issue. The solar cell performance as a function of the illumination angle is studied in chapter 6. Using ray tracing simulations, the tradeoff that a secondary optic imposes, between increasing the optical performance and increasing the average cell illumination angle is discussed.

Finally, building-integrated concentrator systems face challenges from the building itself. Whereas traditional concentrator systems are normally deployed in open
space to ensure a complete illumination of the system at all times, a building incorporated system may encounter shading by i.e. the building it is incorporated in, external objects (trees, other buildings), or even itself. In chapter 7 this is investigated in the context of a BICPV solar window system that aims to also be a daylight regulation device. Partial shading is applied on a benchmark Fresnel lens CPV system, as well as a novel flat optic CPV receiver aimed to be used in the daylight regulation window, and also on a 4x4 panel of these optics. The electrical properties of the systems are discussed under these conditions.
1.4. SUBJECTS AND OUTLINE OF THIS THESIS
Chapter 2

Experimental Techniques

2.1 Device description

Solar cells are fundamentally simple devices. They are semiconductor diodes \(^1\) with the capacity to absorb light and deliver a portion of the absorbed energy as electrical current \(^2\). A real solar cell features several additional material layers aimed at collecting the maximum amount of light, and creating an ohmic contact for electricity extraction, as shown schematically in figure 2.1a. Which photons can or cannot be absorbed by the solar cell depends on the used semiconductor material and is largely determined by the energy bandgap \(E_{gap}\), as illustrated in figure 1.2. The occurrence of the bandgap arises from discrete energy states, or bands, in which charge carriers can exist within the material. The highest energy state in which electrons are 'bound' to the material is called the valence band, while the lowest energy state in which electrons can be considered 'freely moving' is called the conduction band. The energy difference between valence - and conduction band determines the bandgap energy and a solar cell can only absorb photons of an energy equal to or greater than its bandgap energy:

\[
E_{ph} \geq E_{gap}
\]  

and excite electrons from the valence to the conduction band. Only carriers in the conduction band can be extracted to generate electricity. Additionally, excess energy present in the photon is lost during carrier excitation, in the form of heat or phonons. Therefore, optimal conversion of photon energy to electrical energy occurs close to the bandgap \(^2\). Because of this, the solar cells currently capable of the best light-to-electricity conversion efficiencies utilize multiple subcells of different semiconductor materials, as shown in figures 1.2, 1.3, and 2.1b that are each

\(^1\)There are notable exceptions such as organic \(^{164,165}\), or perovskite \(^{166}\) based solar cells, but they will not be discussed in this thesis.

\(^2\)This also explains why a very low bandgap material is not the ideal solar cell, even though it would have the capacity to absorb the entire solar spectrum.
Figure 2.1: Schematic representation of typical solar cells; a) a single junction solar cell with a p-n junction for charge splitting, a window for repelling positively charged holes, a back surface field for repelling negatively charged electrons, an ARC to entrap the maximum amount of light, and metal contacts; and b) a similar monolithic triple junction structure featuring three different semiconductor materials in which case each junction acts as an optical band pass filter to the junctions beneath it, absorbing short wavelength (high energy) photons while transmitting longer wavelength (lower energy) photons.

Tuned to absorb a certain part of the sunlight, while transmitting the remainder to the lower subcells so that:

$$E_{gap}^{top} \geq E_{gap}^{top-1} \geq ... \geq E_{gap}^{bottom+1} \geq E_{gap}^{bottom}$$  \hspace{1cm} (2.2)$$

This results in the entire spectrum being used, while all conversions occur relatively close to the bandgap energy, thus reducing thermalization and transmission losses.

2.2 Solar cell growth and processing

Some of the single junction solar cell structures described in this thesis were in-house produced with the Metal Organic Chemical Vapour Deposition (MOCVD) method \[168]\]. This technique was first described in 1968 by Manasevit and Simpson \[169]\]. Using this technique, metal-organic compounds and hydrides in a carrier gas are flown over a growth substrate at a high temperature. Chemical reactions take place, resulting in the deposition (or growth) of a crystalline structure on the substrate. At the AMS department an Aixtron 200 low pressure MOVPE reactor depicted in figure 2.2 is used to grow III-V semiconductor structures. The MOCVD process employed uses hydrogen as a carrier gas. Metal-organic compounds like trimethyl-gallium (Ga(CH$_3$)$_3$), trimethyl-aluminium (Al(CH$_3$)$_3$) and
trimethyl-indium (In(CH$_3$)$_3$) are used to introduce the group III elements, and hydrides like arsine (AsH$_3$) and phosphine (PH$_3$) to introduce the group V elements. Disilane (Si$_2$H$_6$), telluride (Te), carbon (C), or diethyl-zinc (Zn(C$_2$H$_5$)$_2$) are added to the gas mixture in order to obtain $n$-type or $p$-type doping, respectively. Chemical reactions occur as a result of the high temperature in the reactor, for example:

$$\text{Ga(CH}_3\text{)}_3 + \text{AsH}_3 \rightarrow \text{GaAs} + 3 \text{CH}_4$$

for the formation of solid GaAs, or

$$x \text{In(CH}_3\text{)}_3 + (1 - x) \text{Ga(CH}_3\text{)}_3 + \text{PH}_3 \rightarrow \text{In}_x\text{Ga}_{1-x}\text{P} + 3 \text{CH}_4$$

with $0 \leq x \leq 1$ for the formation of solid InGaP. Typical growth rates are in the order of 1 to 2 $\mu$m per hour. The required substrate temperatures are in the 600 to 750 °C range and are achieved by using infrared light to heat the graphite susceptor that holds the substrate. Layers grown with MOCVD can be grown lattice matched to the specific substrate used (typically GaAs, Ge or InP), depending on the applied gas composition. As long as the compound material has a lattice constant that does not differ too much from that of the substrate, an excellent single crystal structure can be obtained.

After growth, the semiconductor structures are processed into functioning solar cells. Following extensive cleaning, the structures are subjected to standard photolithography processes to define a metal contact grid on the front faces of
2.2. SOLAR CELL GROWTH AND PROCESSING

Figure 2.3: Examples of finished solar cells; a) typical collection of GaAs solar cells as grown on a 2” substrate; and b) small GaAs CPV cell with the outer perimeter fully covered with metal contact and ribbon bonded to a pcb carrier. The coloured sheen of the cell is caused by the large number of thin, laterally close front contact metal grid lines.

cells. This contact grid, as well as a fully covering back contact, is deposited using e-beam evaporation in vacuum. For the cells used in this work, the thickness of the 0.3µm evaporated contacts is increased by several µm using electroplating, in order to decrease resistances in the metal lines. This is done because resistance becomes an important factor for cell performance under concentrated light. Next, photolithography is again used to define the exact area and shape of individual solar cells, after which the surrounding material is etched away. Then the heavily doped top contact layer of the structure is etched away, in between the metal grid lines, while keeping it intact underneath the grid metal. The contact layer is vital to ensure a good ohmic contact between the semiconductor layer and the metal grid. However if left to remain in between the grid lines it would undesirably absorb part of the incident light during cell operation. Rapidly after this etching step, as to avoid oxidation of the bare semiconductor layer, an anti-reflective coating (ARC) is thermally evaporated onto the front face of the cells to facilitate maximum light trapping, as well as protect the semiconductor surface. Finally, the cells are mounted on a printed circuit board (pcb) for convenient handling and contacting. The front and back contacts are separately connected to electrically isolated parts of the pcb, by ribbon bonding and electrically conducting glue respectively. Examples of finished solar cells are shown in figure 2.3.
2.3 Solar cell characterization

2.3.1 Current-Voltage characteristic

Being a semiconductor diode, the electrical characteristics of an ideal solar cell follow the two diode model:

\[ I = I_{01} \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right] + I_{02} \left[ \exp \left( \frac{qV}{2kT} \right) - 1 \right] \] (2.3)

with \( I_{01} \) and \( I_{02} \) the dark saturation currents of the diodes.\(^3\) When illuminated, the light-generated current adds to the dark currents to shift the diode characteristic into the fourth quadrant indicating that power can be extracted from the device,\(^4\) thus the diode law becomes:

\[ I = I_{01} \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right] + I_{02} \left[ \exp \left( \frac{qV}{2kT} \right) - 1 \right] - I_L \] (2.4)

Usually the exponential terms \( \gg 1 \), and under illumination \( I_L \) dominates \( I_{01} \) and \( I_{02} \), so the -1 terms can be neglected. Additionally the two diode terms are often combined for the sake of simplicity:

\[ I = I_L - I_{0n} \left[ \exp \left( \frac{qV}{nkT} \right) \right] \] (2.5)

where \( n \) is the so-called ideality factor ranging from 1 to 2 - which holds information about recombination processes of carriers in the cell - and \( I_{0n} \) represents the total dark current.

The electrical characteristics of solar cells are evaluated experimentally by measurement of this diode characteristic. This is performed by contacting the solar cell to a variable external load that is swept from 'zero resistance' (short circuit) to 'infinite resistance' (open circuit) while measuring current-voltage (IV) pairs. When no illumination is applied to the cell, \( I_0 \) as well as \( n \) can be determined, while under illumination the characteristic is dominated by \( I_L \). Proper illumination by convention approximates the AM1.5G solar spectrum\(^2\) and has an intensity of \( E_e = 100 mW cm^{-2} \). Additionally the cell temperature should equal 25°C. An example of such a 'one-sun' illuminated IV curve is shown in figure 2.4. The main solar cell parameters distilled from the curve are highlighted in the figure and include:

- the short-circuit current \( (I_{SC}) \): the maximum current generated by a solar cell, which occurs when the voltage across the device is zero. From equation 2.4 follows that \( I_{SC} \) is proportional to \( I_L \), and is offset by \( I_{01} \) and \( I_{02} \).

---

\(^3\)Often, current density \( J \) is evaluated instead of the current \( I \), as this allows for easy comparisons between solar cells of different sizes by eliminating the cell area \( A \).

\(^4\)For convenience, the I-V characteristic is often depicted inverted, in the first quadrant rather than the fourth, so that generated currents acquire a positive sign.
2.3. SOLAR CELL CHARACTERIZATION

Figure 2.4: I-V curve of an InGaP single junction solar cell with cell parameters pointed out. The efficiency is the ratio between the generated electrical power at MPP and the power of illumination.

- the open circuit voltage \((V_{OC})\): the maximum voltage available from a solar cell, which occurs at zero current. Substitution of \(I = 0\) in equation 2.4 gives an expression for \(V_{OC}\):

\[
V_{OC} = \frac{n k T}{q} \ln \left( \frac{I_L}{I_{0n}} \right)
\]  
(2.6)

- the maximum output power \((P_{mp})\), determined by the maximum power current and voltage \((I_{mp} \text{ and } V_{mp})\):

\[
P_{mp} = V_{mp} \times I_{mp}
\]  
(2.7)

which occur at the maximum power point \((MPP)\) where:

\[
\frac{dP}{dV} = \frac{d(V \times I)}{dV} \equiv 0
\]  
(2.8)

- the fill factor \((FF)\) which is a measure for the squareness of the I-V curve, and is defined as the ratio between the \(P_{mp}\) to the product of \(V_{OC}\) and \(I_{SC}\):

\[
FF = \frac{V_{mp}I_{mp}}{V_{OC}I_{SC}}
\]  
(2.9)
CHAPTER 2. EXPERIMENTAL TECHNIQUES

Figure 2.5: The effects of parasitic resistances on a InGaP solar cell IV curve showing a) shunt resistance; and b) series resistance (Curves generated using the tool available at pveducation [171]).

- and the light-to-electricity conversion efficiency ($\eta$):

$$\eta = \frac{P_{mp}}{P_{in}} = \frac{V_{OC}I_{SC}FF}{P_{in}}$$  \hspace{1cm} (2.10)

where $P_{in} = 100mWcm^{-2}$, and the spectrum is the AM1.5G spectrum.

The shape of the I-V curve is affected by parasitic resistive effects in the solar cell. The performance and efficiency of a cell are reduced as power is dissipated in the resistances. In most cases the key impact of parasitic resistance is the reduction of the $FF$. The parasitic resistances are the shunt resistance $R_{SH}$ and the series resistance $R_S$, that affect the I-V characteristic as shown in figure 2.5. Low shunt resistance offers an alternate current path in the cell that reduces the amount of current extracted from the solar cell, and is typically caused by manufacturing defects. On the other hand series resistance is largely dependent on cell design and has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, contact resistances between the semiconductor and the metal contact; and finally the resistance of the metal contacts themselves. The diode equation accounting for parasitic resistances becomes:

$$I = I_L - I_{0n} \left[ exp \left( \frac{qV + IR_S}{nkT} \right) \right] - \frac{V}{R_{SH}}$$  \hspace{1cm} (2.11)

In multi-junction solar cells each subcell has its own I-V characteristic. Depending on the cell design, these curves are superimposed on one another in the overall I-V curve according to Kirchoff’s laws. The multi-junction cells considered in this thesis are mostly two-terminal, monolithic InGaP/GaInAs/Ge cells, in which the three junctions are interconnected in series. As a consequence, the total cell current is limited by the least current producing subcell, while the total
2.3. SOLAR CELL CHARACTERIZATION

Figure 2.6: I-V characteristics of InGap (blue), GaAs (green), and Ge (red) subcells, and the constituent overall multi junction IV curve (black). In this particular case, the cell is current limited by the InGaP top cell, while the Ge bottom cell produces a comparative excess of current.

Cell voltage is a sum of the subcell voltages. Figure 2.6 illustrates how the subcell curves determine the overall I-V characteristic of such a cell.

In the studies described in this thesis, one-sun I-V characterization of the solar cells is performed using an ABET Technologies Sun 2000 Class A solar simulator, which provides homogeneous, parallel illumination over a 100 x 100 mm$^2$ area. An Ushio 550W Xenon short arc lamp is used in combination with an AM1.5G spectral filter to approximate the AM1.5G spectrum. A calibration measurement using an appropriate reference cell is used to correct for any deviations in spectrum and illumination intensity. A mechanical shutter is used to avoid any unnessecary illumination and heating of cells in between measurements. The setup is equipped with a Keithley 2401 sourcemeter and data acquisition is performed using ReRa Tracer3 software. During measurement, the solar cells are kept at 25 °C by water cooling.

Xenon arc lamps are currently available light sources that resemble the desired AM1.5d spectrum reasonably. The biggest mismatches in this case concern the prominent emission lines between 850 nm and 1000 nm that are present in the Xe light but absent in the solar spectrum.
2.3.2 Concentrated Current-Voltage characteristic

In the context of CPV, a solar cell’s diode characteristic at higher than standard irradiance level is also of interest, as CPV systems operate in concentrated irradiance conditions. The strength of irradiance applied to the solar cell during measurement is expressed as concentration factor \( C \) which is also referenced to as a number of ‘suns’. Both definitions refer to the applied irradiance divided by the standard 100 \( mW/cm^2 \), so that for example 100 suns (or \( C = 100X \)) equals an irradiance of 10000 \( mW/cm^2 \). Considering the solar cell electrical performance, the produced current density scales linearly with concentration:

\[
J_L(C) = CJ_L(C = 1)
\]

(2.12)

Additionally from equation [2.6] follows that the \( V_{OC} \) of the cell also increases with concentration via:

\[
V_{OC}(C) \approx V_{OC}(C = 1) + \sum_{i=1}^{m} n_i \frac{kT}{q} \ln(C)
\]

(2.13)

for a cell containing \( m \) subsells. Therefore an increase in \( V_{OC} \) of nearly 60 mV per subcell per decade of concentration is obtained at constant temperature. Counteracting these advantages in electrical parameters for higher concentrations are an increasing power losses \( P = R \cdot I^2 \) due to series and sheet resistance; elevated temperature of the solar cell which lowers \( V_{OC} \); and inhomogeneities in the illumination of the cell surface that may be caused by the optical system, which are studied in more detail in chapters 4, 5, 6, and 7.

One approach for the experimental determination of I-V curves under concentration is to perform outdoor measurements, utilizing a concentrating optical system to realize higher concentrations, such as described in chapter 7. The main benefit of this approach is that the actual working conditions of a CPV system are most closely approximated. Therefore the method is very suitable to evaluate full scale systems, prototypes, novel concentrating approaches etc. Drawbacks however include a changing solar spectrum throughout the year [172], weather effects such as clouds that prevent testing, humidity [173][174], wind speed [173][175][176] and ambient temperature [176][181] that have major impacts on the measurements, and often the need for accurate sun tracking [182][184].

When more control in these matters is desired, utilization of a high irradiance solar simulator offers a suitable approach. In this case, a high power Xe arc lamp is used, usually combined with concentrating optics, to supply homogeneous, high intensity illumination. This approach is suitable for measurement of single solar cells, such as performed in chapters 4 and 5. Illumination of the cell can be continuous, like in one sun I-V setups, which offers the benefit of a constant concentration factor. However prolonged high intensity illumination of the cell will cause heating, so a cooling system is needed to control the temperature. To eliminate this necessity, a flash setup can be employed, which is the approach taken
In the research described in this thesis. Such a setup generates a short (in the order of several milliseconds) and intense light pulse during which rapid measurement of I-V pairs is performed. Because of the limited illumination time, cell heating is not a factor in this case. However, the illumination intensity varies strongly during the flash, thus a dedicated strategy is required to obtain I-V curves at a constant concentration factor.

In this work, to achieve this, multiple flashes are applied to the cell, and a different bias voltage is applied across the cell during each flash. A broncolor pulso G Xe arc lamp equipped with a parabolic reflector, with a maximum energy of 3200 J is used (with UV protection dome removed) to apply uniform illumination resembling the AM1.5D spectrum across the solar cell. The lamp is driven by a broncolor topas A4 source to produce a 6 ms flash. A KEPCO BOP 20-50MG
source is used to bias the cell at a specified voltage during measurement, as well as readout data points at 4MHz sample rate during a flash. Irradiance intensity is monitored using a reference cell with a linear current response as a function of illumination. I-V pairs for many concentrations are obtained for the specified bias voltage during a flash. Then, the system moves to the next bias voltage and triggers a new flash, again measuring I-V pairs for many concentrations. This is repeated until all relevant voltages for the measured cell have been applied. I-V curves at any particular concentration are subsequently constructed from datasets at all the bias voltages. The entire process is illustrated in figure 2.7. The major benefit of this multiple flash setup over measuring an I-V curve quickly during one flash, is that during a flash, the illuminated spectrum may change slightly. As a consequence, using the latter method, the limiting subcell in the MJ stack may change mid-measurement, causing artifacts in the I-V characteristic. Using the multiple flash procedure however, I-V pairs for a given concentration are measured at the same moment during a flash, thus at the same spectrum. Therefore artificial discontinuities in the I-V curve are not present using multiple flashes. No more than one flash is applied in every 30 seconds to prevent heating of the solar cell, as well as the lamp, which would alter the spectrum.

### 2.3.3 Quantum Efficiency

The External Quantum Efficiency (EQE) of a solar cell is the wavelength dependent ratio between the number of carriers collected from the cell and the number of photons incident on the cell for a given wavelength:

\[
EQE(\lambda) = \frac{\text{collected carriers per second}}{\text{incident photons per second}} = \frac{I_L/q}{E_e/\frac{hc}{\lambda}}
\]  

(2.14)

where \(E_e\) is the power density of the incident monochromatic light. The External QE (EQE) includes optical losses such as absorption (A) and reflection (R). Alternatively, the Internal QE (IQE) is corrected for these losses:

\[
IQE = \frac{\text{collected carriers per second}}{\text{absorbed photons per second}} = \frac{EQE}{1 - R - A}
\]

(2.15)

By these definitions, the EQE depends on both the absorption of light and the collection of charges, while the IQE purely shows the wavelength dependent photon to charge conversion and collection. If all photons of a certain wavelength are absorbed by the cell and all the resulting minority carriers are collected, QE for that wavelength equals one. Conversely, if no photons of a certain wavelength are absorbed, or no generated carriers are collected, the QE for that wavelength equals zero. The shape of the QE holds a great deal of information on the solar cell material properties, as is further detailed in figure 2.8. For instance front surface recombination mainly affects the short wavelength range of the QE, as those photons do not penetrate deeply. Back surface recombination mainly affects the long wavelength range of the QE as those photons are absorbed near the back
2.3. SOLAR CELL CHARACTERIZATION

The figure shows the quantum efficiency (QE) of a single-junction GaAs solar cell. The graph indicates that the quantum efficiency is limited by diffusion length and reduced by reflection and absorption. The QE is highest near the bandgap, where the light is absorbed above the bandgap, and it decreases as the wavelength increases, indicating a decrease in absorption.

**Figure 2.8:** Quantum Efficiency of a single junction GaAs solar cell, with characteristics marked in the graph.

Quantitative information on diffusion lengths is difficult to determine as contributions of the emitter, depletion zone and base are very difficult to decouple, as has been described in [185]. In certain fringe cases, such as for example a deep junction solar cell [186] in which the QE is nearly completely dominated by the emitter, the diffusion length can be determined quantitatively. Finally, $E_{\text{gap}}$ can be determined from the longest converted wavelength. By integration of the EQE over the AM1.5G spectrum [21], the maximum produced current of the solar cell for standard illumination can be accurately determined.

For multi-junction solar cells, the main challenge to measure the EQE lies in the fact that the individual subcells cannot be directly contacted separately. Additionally, due to the series connected nature of two terminal MJ devices, the lower subcells cannot be directly measured by the method described above. Therefore, QE analysis of MJ cells additionally requires [187]:

- tuning of the continuous bias light in such a way that the junction to be...
Figure 2.9: EQE measurements a) of an InGaP junction in a MJ cell with optimized resp. non-optimized bias lighting conditions; and b) of the individual InGaP (blue), GaAs (green), and Ge (red) subcells in a typical TJ CPV cell.

measured limits the generated current;

- application of a bias voltage to force the current limiting cell to operate at short circuit current conditions.

The first condition is met by applying strong broadband illumination in the wavelength ranges of the subcells to be biased, while excluding the subcell of interest when it is probed by a low intensity test light. This is achieved by choosing the correct wavelength ranges for the bias light. The effect of using an optimized versus a non-optimized bias light to measure the EQE of an InGaP subcell in a TJ cell is shown in figure 2.9a. Here a diminished EQE of the measured InGaP subcell, and an artifact EQE in the GaAs subcell are observed when the bias conditions are not met (orange line) compared to a good InGaP EQE and no artifact in optimized conditions (blue line). Such artifacts may be caused by a low parallel resistance of the measured subcell, or an early reverse breakdown of the measured cell. Also, strong luminescent coupling of an above lying subcell may cause such artifacts, although this is not applicable in this example as the measured InGaP subcell is the top cell here. The necessity for the second condition arises from the fact that all subcells except the subcell to be measured operate at an excess current due to the series connection. The overall current however is limited by the subcell to be measured. Consequently all other subcells operate at a point on their I-V curve between $V_{MP}$ and $V_{OC}$. Considering Kirchhoff’s laws, forcing zero voltage will cause the measured subcell to operate at negative voltage. This is compensated by applying a positive bias voltage, the magnitude of which should be slightly lower than the sum of the expected $V_{OC}$ of the other subcells to ensure

\[\text{For a detailed exposition on I-V curves see section 2.3.1}\]
that they operate at a point on their I-V curve between 0V and $V_{MP}$. In this work 0.8V is applied when measuring InGaP, 1.4V when measuring GaAs, and 1.8V when measuring Ge. The positive bias voltage cancels the negative voltage in the subcell to be measured to allow it to operate in short circuit conditions. EQE characteristics typical of InGaP/GaAs/Ge triple junction cells such as those used in this thesis are shown in figure 2.9.

Measurement of the EQE is performed here using the spectral responsivity method as introduced by Metzdorf [188]. The ReRa Solutions SpeQuest QE measurement system used here is controlled by ReRa Photor 3.1 data acquisition software and uses both a Xenon and halogen light source to access all wavelengths present in the solar spectrum. A monochromator is used to generate quasi-monochromatic light and a chopper and lock-in amplifier for intensity modulation. This generates a test light of variable wavelength while a continuous bias light is used to put the cell under test in operating conditions. The wavelength dependent photocurrent is measured, and the EQE is determined via equation 2.14.

2.4 Ray tracing

Ray tracing is essentially the determination of the optical path of waves or particles through a given volume. The approach of ray tracing assumes that a wave or particle can be modeled by a large number of idealized, very narrow beams, called 'rays' and moreover that there is a distance over which such a ray is straight. A ray tracer advances the ray over this distance and then recalculate the ray's direction, intensity and other optical properties, based on the medium that has been passed. Then, from this location a new ray with the newly determined properties is sent out. This is repeated until a complete optical path is generated. The volume in which the ray propagates may include objects of varying propagation velocity, absorption characteristics, and reflecting surfaces. Therefore when travelling through such a volume the rays may for instance bend, change directions, reflect, change wavelength or polarization which complicates analysis of the optical path.

In the context of CPV, ray tracing is mostly applied as a tool to design or study optical systems, as a powerful statistical approach for the prediction of the optical performance of a given optical system. For example, ray tracing can be used to determine the optical path of light through a CPV system, or a detailed analysis of the local solar cell illumination can be performed. Ray tracing simulations described in this thesis are performed using the in-house developed "Scientrace" ray tracer, described in chapter 3. Scientrace is applied in chapter 6 to study the angular distribution of light at the cell surface of a solar cell, reflections off the cell surface and front contact, as well as to evaluate the optical efficiency of several secondary optic elements.
Chapter 3

The ”Scientrace” ray tracer

Abstract

Currently available ray tracers for optical studies are very limited in terms of platform independence and source availability. To meet those and additional demands, Scientrace has been developed. In order to study multiple parameters of light at once, it is desired to program large batches wherein several properties may be varied independently. Using constants, complex formulae and loop constructions, simulation environments are designed and setup to be easily maintained. The output offers both insightful images of many kinds and powerful quantitative data. By applying operators to basic functionality, vectors can be modified and the properties of light can be tuned to the user’s desires in great detail. In addition to the scientific demand for source verifiability and the freedom to use dito operating systems, these functions make Scientrace a very powerful scientific tool.

1The study presented in this chapter is based on
3.1 Introduction

As mentioned in section 2.4, ray tracing is the simulation of the path of light through matter in a 2D or 3D environment. There are two main applications for ray tracing: i) the real-time creation of visual 3D frames by 3D engines, or 3D media processors such as Blender\textsuperscript{2} and POV-Ray \textsuperscript{189}; and ii) the quantitative analysis of optics, such as lenses and reflectors, in optical systems like headlights, microscopes and solar concentrators. Common applications to study optical systems quantitatively are ASAP, LightTools, TracePro and ZEMAX \textsuperscript{190}.

The Scientrace ray tracer is designed for the second purpose and is freely available via \url{www.scientrace.org}. In contrast to most available quantitative ray tracers, Scientrace is open source and platform independent. This allows for the inspection and modification of the source code, as well as availability to a large variety of operating systems. Scientrace is developed in C# using Monodevelop\textsuperscript{3} and the Open Toolkit\textsuperscript{4} library.

As will be shown, Scientrace is a versatile and powerful tool in the design, development, and research of photovoltaic applications. The Scientrace core library (scientrace-lib) is supplemented with two complementary, easily programmable XML interpreters in the whole package called the Scientrace Suite. The structure of the Scientrace Suite is illustrated in figure 3.1. The programming of Scientrace simulation batches does not demand significant software engineering experience. Photon interaction with the surface occurs mainly based on the Fresnel equations and the photon polarization properties. Effects of scattering and absorption can be added manually by altering surface properties of objects. The interaction with dielectrics is handled by a material class that can be set by the user\textsuperscript{5}. The Scientrace XML interpreter (scientrace-xml) can read Scientrace XML source files (named .scx files), containing all the information for a simulation, e.g. light sources, optics such as lenses, reflectors, dielectric volumes, screens, etc, but also instructions concerning data output. The Scientrace Batch Creator (scientrace-batch-creator) is a separate interpreter, that parses Batch Creator source files (named .bcx files). .bcx files describe how to modify .scx files, and can create large batches of .scx files. The Batch Creator reads both a batch instruction file (.bcx, Batch Creator XML) and a Scientrace XML template file (.scx) to produce large series of modified .scx files. These created files are to be submitted to the Scientrace XML interpreter that performs the actual simulations. By combining both command line inter-

\textsuperscript{2} \url{www.blender.org}
\textsuperscript{3} Monodevelop is a cross platform development environment. More information can be found on \url{http://www.mono-project.com/docs/about-mono/languages/csharp/} http://www.mono-project.com/
\textsuperscript{4} Open Toolkit is an external library for math operations. More information can be found on \url{www.opentk.com}
\textsuperscript{5} \url{https://github.com/JoepBC/scientrace/blob/master/source/scientrace-lib/DielectricSurfaceInteraction.cs} contains a detailed description of all used variables and external references for used formulae.
Figure 3.1: The Scientrace Suite processes schematically. The Scientrace core library is illustrated by the factory: this is where the actual simulations routines are stored. The library is addressed by the Scientrace XML interpreter, the symbolic pair of glasses, reading the Scientrace XML source files (.scx). Additionally, the Scientrace Batch Creator is depicted as the printer/copier. The Batch Creator reads both a batch instruction file (.bcx, Batch Creator XML) and a Scientrace XML template file (.scx) to produce large series of modified .scx files. These created files are submitted to the Scientrace XML interpreter that performs the actual simulations. (The images of the printer and the file icons are modified versions of images published under the LGPL licence by resp. David Vignoni and Nuno Pinheiro et al. [192] [193]).

3.2 Scientrace data structure

The layout structure of the .scx and .bcx files is XML, and to keep things simple, some basic programming language features (like variables, loops, basic math including vector operations) are integrated using solely XML.

The recommended structure of the Scientrace XML .scx file is illustrated in figure 3.2. The use of a single root element (here, <ScientraceConfig>) is
3.2. SCIENTRACE DATA STRUCTURE

mandatory in the XML specifications. The contents of the elements <PreProcess>, <Output> and <ObjectEnvironment> are explained in the following paragraphs.

Figure 3.2: The main structure of a Scientrace XML .scx file. The order is not mandatory, neither is the use of the PreProcess and the Output elements - default values are used in their absence. Descriptions within square brackets are explained below and in sections 3.5 and 3.3.

Since the virtual environment is described by XML, it is relatively easy to modify, multiply or reuse parts of the environment. Any part of the description can be replaced using variables (e.g. using <Replace> elements), much like the use of constants in any traditional programming environment. In addition, the contents of other files can be assigned to variables, to be inserted at any point in the XML code. This may improve readability and structure to the sources. Furthermore, using <Solve> elements, the result of a calculation can be assigned to a variable. Mariusz Gromada’s mXparser library⁶ offers a large set of math operations available to the <Solve> element.

Preprocessing can be described as ”modifying the code before actually using it”. Preprocessing is used to replace variables and unfold loops in the source. To verify the behaviour of preprocessor operations (<PreProcess>), the preprocessed .scx files can be exported using the <XML> element in the <Output> settings. For example:

```
<ScientraceConfig>
  <PreProcess>
    <Replace Key="VALUE_X" Value="4"/>
    <Solve Key="VALUE_Y" Formula="sqrt(9+@VALUE_X@ˆ2)"/>
  </PreProcess>
</ScientraceConfig>
```

⁶The mXparser library is available at http://mathparser.org/
In the first listed source, variables are assigned at the \texttt{\textless Replace \textgreater} and \texttt{\textless Solve \textgreater} elements and inserted where the key string is enclosed by \texttt{@ signs (@)}. In the second part of the example, the preprocessed source is exported, which shows that the inserted variables are replaced by the assigned values. This way, an intuitive analysis of the simulations is possible.

### 3.3 Object generation

The \texttt{\textless ObjectEnvironment \textgreater} part of the \texttt{ScientraceConfig} file contains all the items with physical relevance. Light sources, lenses, mirrors, projection screens, \textit{etc.} The most commonly used ones are highlighted hereafter\(^7\).

#### 3.3.1 Light Sources

Traces are generated by light sources. In a nutshell, a light source is simply a point or surface in space, emitting a certain amount of traces in a defined spatial distribution, towards a set direction or range of directions.

In addition, spectra (section 3.4.3) can be assigned to light sources, defining the wavelengths and their respective intensities/occurrences as radiated from the light source. The divergence/angular aperture of a light source is regulated using \texttt{\textless TraceModifier \textgreater} elements (section 3.4.4).

It is possible to use multiple light sources in a single simulation, all having their individual properties. The optical performance data (section 3.5.4) provides statistics per light source together with the total. For example, when studying multi-junction solar cells in an optical system, it is useful to break down the used benchmark spectrum (e.g. the AM1.5 spectrum) into multiple light sources with spectra that correlate with the wavelength ranges of the individual subcells of the solar cell (e.g. 300-680nm, 680-900nm, 900-1800nm respectively, for an

\(^7\)A list of most XML elements including examples can be found at the wiki: [https://github.com/JoepBC/scientrace/wiki/Scientrace-XML-Elements](https://github.com/JoepBC/scientrace/wiki/Scientrace-XML-Elements)
3.3. OBJECT GENERATION

Figure 3.3: Wulff construction examples for cubic crystals. a) a crystal with equal surface tensions for the (100), the (110) and the (111) directions; b) the surface tension for the (100) direction is 1.2 times that of the (110) and (111) directions; c) the surface tension for the (110) direction is 1.2 times that of the (100) and (111) directions; d) the surface tension for the (111) direction is 1.2 times that of the (100) and (110) directions.

InGaP/Ga(In)As/Ge triple junction cell. Disregarding the External Quantum Efficiency of the cell for simplicity reasons, the solar cell performance is related to that of the least performing light source. By splitting the overall light source into several with partial spectra, this can be investigated more easily.

3.3.2 Lenses

Currently, Scientrace offers support for spherical convex (both plano-convex and bi-convex) lenses and Fresnel lenses, based on spherical rings. However, in order to approach the detail of aspherical lenses, an aspherical ring composition Fresnel lens has been included. This Fresnel lens consists of a given amount of rings, but optimises the spherical base for each individual ring to approach perfect/aspheric concentration. When dispersive materials are used, the concentration wavelength should be assigned as well (the default setting is 600nm), since the lens geometry is optimised for this wavelength.

3.3.3 Bordered Volumes

Any volume enclosed by flat surfaces can be described using a <BorderedVolume> element. The <BorderedVolume> contains one or more <SubVolume> elements. The <SubVolume> element in turn contains a set of <Plane> elements, describing the boundaries of the SubVolume. For example, a cube is easily generated by describing its 6 planes.\footnote{A plane is described as the plane connecting three independent points (<Loc1>), <Loc2> and <Loc3>) in space together with an allowed location (<IncludeLoc>) in space (to separate inside from outside of the border), or alternatively, a location (<Location>) in space combined with the surface normal pointing to the volume inside (<AllowedNormal>).} A bit more complex, but in essence equal to the
cube polyhedron, are the polyhedrons \textit{dodecahedron} and \textit{icosahedron}. When the relative sizes of the dodecahedron and the icosahedron are adjusted correctly, and all planes are combined within a single \texttt{<SubVolume>}, the \textit{truncated icosahedron}\(^9\) is created. Alternatively, if the dodecahedron planes define one \texttt{<SubVolume>}, and the icosahedron planes fill a second \texttt{<SubVolume>}, a \textit{compound of dodecahedron and icosahedron} shape is constructed. Here, two subvolumes are created separately and merged afterwards. In contrast, in the truncated icosahedron example, a single volume is limited by all planes.

The bordered volumes construction method can for instance also be used to create 3D crystal drawings based on the Wulff Construction method. Some examples of arbitrary cubic crystals can be found in the example simulations\(^{10}\). The 3D shape of the crystal results directly from the surface tensions of the 100, 110 and 111 planes as shown in figure 3.3. The same method can be used to predict the shape of a crystal based on the growth rates of the different faces (the kinetic Wulff plot).

Using this method, virtually any physical object can be generated for use in a simulation. For example, in chapter 6 bordered volumes are used to define solar cell material, metal contacts, and glass optical elements.

### 3.4 Object properties

#### 3.4.1 3D Vector operations

The simulation environment is built on user supplied 3D vectors. In addition to static vectors, Scientrace XML allows the addition of operations\(^{11}\) on vector elements. This enables the user to base dynamic vectors on logical parameters (lengths, rotation angles, rotation bases, translation vectors, or even base transformation matrices) instead of collections of plain numerical vectors of which the physical relevance is difficult to discern.

The Wulff construction example explained in section 3.3.3 shows an example of a vector \texttt{<Location>} modified by a Length attribute, two \texttt{<Rotate>} elements and a \texttt{<Formula>} element, in order to describe the cubic symmetric properties with minimal redundancy. Below is an example of these modifications. To shorten the example, some of the variable names used in the original simulations have been abbreviated or replaced by direct values.

```xml
<Location xyz="1;1;0" NewLength="1">
  <Rotate> <Angle Degrees="@Y_ROT@"/>
    <AboutAxis xyz="0;1;0"/>
  </Rotate>
  <Rotate> <Angle Degrees="@X_ROT@"/>
</Location>
```

\(^9\)Chemists might recognise this as the shape of a Buckminsterfullerene or \textit{C}\textsubscript{60} molecule. Sport fans might recognise a football instead.

\(^{10}\)\url{https://github.com/JoepBC/scientrace/tree/master/example_simulations/3d_wulff-construction}

\(^{11}\)An overview of available vector operations is available at \url{https://github.com/JoepBC/scientrace/wiki/Vector-Operations}
3.4. OBJECT PROPERTIES

<AboutAxis xyz="1;0;0"/> <Rotate>
<Formula x="@HX@*x+@KX@*y+@LX@*z"
y="@HY@*x+@KY@*y+@LY@*z"
z="@HZ@*x+@KZ@*y+@LZ@*z"/>
</Location>

Operations are always performed attributes before elements and then in order of appearance. First the <Location> vector with original length $\sqrt{2}$ is normalised using the NewLength attribute. Subsequently, two rotations are performed. Finally, after all these operations, the resulting vector is subjected to a matrix multiplication using the somewhat more complex yet very versatile <Formula> operation.

By using the vector operations in this example, a resulting vector is based on two rotation angles given by two nested for-loops defined earlier in the source, and a base-transformation using three base vectors (H, K and L) defined in the <PreProcess>-section for maintainability.

3.4.2 Materials

A <Material> is assigned to each optical component. In most cases, the most important parameter of a material is the refractive index, influencing both the angle of refraction and the partial reflection fraction. In some cases, reflection is defined as a constant fraction (e.g. 100% for a perfect mirror, Material="mirror"). It is also possible to set the absorbed fraction for a material. The black absorber (Material="black") for example will absorb all incident light at its surface, making it an ideal material for analytical surfaces. In addition to some predefined materials as those mentioned above, it is also possible define material properties dynamically, by supplying manual fractions or even complex formulae.

3.4.3 Spectra

As a part of a <LightSource> element, but as an independently defined entity, a <Spectrum> is defined. A spectrum describes the output of a light source in terms of wavelengths and the respective intensity distribution. A spectrum can be described as a single wavelength, a range of wavelengths, or as a set of discrete user defined entries - for readability and reusability purposes often supplied using external spectrum files.

3.4.4 Trace Modifiers

Without modification, all surfaces of optical components are simulated to be geometrically perfect, and all light sources emit light in a single direction. In many

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13 A list of available <Spectrum> classes with examples is available at [https://github.com/JoepBC/scientrace/wiki/SCX-Element-Spectrum](https://github.com/JoepBC/scientrace/wiki/SCX-Element-Spectrum)
cases though, e.g. to simulate a divergent light source, or reflective scattering upon reflection at a surface, this default behaviour should be modified. In order to do so, `<TraceModifiers>` are applied to light source elements or optical component elements.

In a nutshell, a `<TraceModifier>` tells Scientrace how to modify a vector given some parameters, e.g. a `<MaxAngle>` element describes up to what angle modifications occur. For light sources, this behaviour is rather straightforward: it describes a range of outgoing trace directions. Upon interaction at the surface of an optical component, this may be less intuitive: the `<TraceModifier>` describes modifications to the normal at the surface of interaction, as used in chapter 6.

There are several ways to modify a beam (or surface normal) direction within a range of angles. The beam can be split up into several new traces, or the original direction can be altered, or replaced. The distribution of the new directions can be random, or organised like a square matrix or along a spiral grid covering a surface uniformly. But there are also two types of uniform distributions available: uniform angles, and uniform projections. The easiest way to describe the differences is by example. A point source radiates equally in all directions. On average, all angles are represented equally → uniform angles. Alternatively, imagine a spherical body, with radiating point sources distributed uniformly at the surface (e.g., the sun). When this body radiates through an aperture, it projects the round image behind the aperture including a blur from the size of the aperture - this is the concept of the pinhole camera. The intensity of the projected image, outside the region of the blurry edges, is uniform (and therefore the distribution of the angles is not) → uniform projections. Both uniform distributions are visualised for a point source in figure 3.4.

### 3.4.5 Beam splitting

By default, refractions at dielectric surfaces occur together with partial reflections when examining the whole beam. But at the single photon level, there is a probability distribution for reflection and refraction at the dielectrical surface as described by the Fresnel equations. When designing a ray tracer, a choice has to be made: will a single trace, after partial reflection/refraction, still consist of a single trace based on probability, or is the trace split up into two separate traces with decreased intensities. Scientrace employs the latter, in order to increase the resolution of simulations with small numbers of traces. This describes the smallest trace unit as a beam, instead of a photon. Beam splitting reduces the amount of randomness in the Scientrace output. In order to make simulations as reproducible as possible, in general optical components and `<TraceModifier>` elements that use random distribution can be seeded optionally. The downside of this approach is that the simulation processing time for a trace doubles after each partial reflection - at least until a defined minimal intensity for a trace has been exceeded.

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14 TraceModifiers are explained in more detail, including examples, at [https://github.com/JoepBC/scientrace/wiki/SCX-Element-TraceModifier](https://github.com/JoepBC/scientrace/wiki/SCX-Element-TraceModifier)
3.5. OUTPUT FEATURES

\[ \alpha \]

(a)

(b)

Figure 3.4: A 2D representation of uniform trace distributions. a) At uniform angles, the angles are distributed equally (the distance in between the traces at the orange arc are equal since \( \alpha \) is constant), but the projections of the traces at a surface orthogonal to the light source direction are not; and b) at uniform projections, the projections of the traces at an orthogonal surface, in this case the green bar, are distributed equally at a distance \( x \) instead.

3.5 Output features

3.5.1 3D exports

Since all simulation setups are designed as an XML source, method to visualise the environments is in place. The easiest way to do so is to view exported 3D visuals (.x3d files\(^{15}\)). When performing simulations with hundreds of rays (or more; quantitative simulations may take up to millions of rays), it is strongly recommended to disable 3D exporting via the <X3D> element in the <Output> settings to save processing time and disk storage. X3D is a popular open standard for 3D files, with many available viewers \(^{16}\). The output has been tested to work with the application view3dscene. Examples of stills from X3D files are included in chapter 6.

3.5.2 Histograms, 1D and 2D

To gain information about the incident angles upon a surface, incident angle histograms can be exported. Besides the 1-dimensional angle of a trace with the surface normal (<Histogram>), it is also possible to decompose incident angles into angles on two independent planes which is referred to as 2D histograms (<Hist2>). Usage of these (and other) elements is explained at the Scientrace

\(^{15}\)X3D is an ISO standard for 3D computer graphics, [http://www.web3d.org/standards](http://www.web3d.org/standards)

\(^{16}\)view3dscene is an open source VRML / X3D browser, and a viewer for other 3D model formats. It can be downloaded for Linux, Windows and Mac OS-X at [http://castle-engine.sourceforge.net/view3dscene.php](http://castle-engine.sourceforge.net/view3dscene.php)
wiki. This method is employed in chapter 6 to study the effects of oblique irradiation at concentrator solar cells, with a focus on metal grid interactions.

### 3.5.3 Photon Distribution Plots

To visualise the irradiance at a given surface, photon distribution plots (PDP’s) are a helpful tool. These vector based (.svg files) images plot the traces at a surface. When polarisation support\(^{18}\) is on (default setting), the direction of the polarisation vectors can be plotted too. In addition, both the photon wavelength and the incident trace direction can be expressed by the colour of the spots as shown in figure 3.5.

![Figure 3.5: The photon distribution plots (PDPs) for a simple lens concentrator system separated in wavelength ranges; a) 400 → 660 nm; b) 660 → 880 nm; c) 880 → 1800 nm; and d) all combined. In e) an X3D export still is shown; and f) is a PDP wavelength legend.](image)

An illustrative example of a PDP displaying polarisation is the classic polarising plates example in figure 3.6 which shows a simulation of the pile-of-plates polariser invented by Dominique F. J. Arago in 1812, as described by Hecht and Zajac\(^{19}\).

### 3.5.4 Optical performance data

Quantitative irradiation reports can be produced by exporting spreadsheet files (Comma Separated Values, .csv) containing optical efficiency data. When Scientrace XML is used together with the Scientrace Batch Creator, the Batch Creator

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\(^{17}\)Scalable Vector Graphics are a W3C open standard, [https://www.w3.org/Graphics/SVG/](https://www.w3.org/Graphics/SVG/)

\(^{18}\)Polarisation support uses an approach disregarding photon phase, which has some limitations. More details on this topic can be found at [https://github.com/JoepBC/scientrace/wiki/Scientrace-Polarisation-Support](https://github.com/JoepBC/scientrace/wiki/Scientrace-Polarisation-Support)
3.5. OUTPUT FEATURES

Figure 3.6: The pile-of-plates-polariser using a stack of 8 plates with a refractive index of 1.5 and an incident (polarisation) angle of 56.31°. The 3D export in a) illustrates the setup. Since the light enters the plate at the dielectrums Brewster angle, in b) the p-polarised light is refracted to the transmission screen; c) shows partial s-polarised reflections that are collected at the reflection screen; and d) a zoom of the reflections. The polarisation vector components are marked by the white lines inside the absorption spots in the PDP’s. The size of a spot indicates its trace intensity.

3.5.5 Detailed photon data

In addition to the Optical Performance data, detailed information about every individual trace on a surface can be exported using the <PhotonDump> element in the <Output> settings. It will produce a table (CSV) with data per trace, such as the wavelength, location, direction, intensity, polarization, supplemented with information about this trace at creation at the light source. For large simulations this table will grow to immense proportions, but it does allow for deeper investigation of the simulation data and isolate single trace information from it.

In order to verify the correct implementation of equations and physics in the Scientrace package, an example comparing Scientrace output to experiments will

\footnote{See \url{https://github.com/JoepBC/scientrace/wiki/SCX-Element-Rectangle} for more information on registering surfaces}
CHAPTER 3. THE "SCIENTRACE" RAY TRACER

Figure 3.7: 3D exported side view of the simulated CPV system with two simulated rays visible.

Figure 3.8: Simulated photon distribution plots (top) that show the illuminated pattern at the 1cm x 1cm solar cell surface for reflections from different mirror areas, and their experimentally determined counterparts (bottom).

be briefly discussed below.

3.5.6 Qualitative analysis example

An application example of Scientrace concerns the illumination pattern on a solar cell surface in a CPV system that is described in [157] and [196]. The system features a refractive prism and a parabolic mirror that rotate uni-axially to provide sun tracking, as well as concentration of the sunlight on a stationary solar cell.\(^{20}\)

Scientrace simulations are performed to predict the wavelength dependent il-

\(^{20}\)The concentrator geometry can be found on the website of the manufacturer: http://www.suncycle.nl/about-2/.
lumination pattern on the solar cell surface, after the light has refracted through
the prism, and reflected off three distinctly different areas of the parabolic mirror.
A 3D export of one of the simulated optical system and rays, showing (for clarity)
only two beams is shown in figure 3.7.

In the simulations the AM1.5D spectrum is used because this is the standard,
universally applied reference spectrum in the field of concentrator photovoltaics,
and an angular aperture of 0.5° is applied to mimic illumination by the sun.
To experimentally determine the illumination pattern, a Xe lamp was used to
approximate the correct spectrum. The illumination was attenuated to parallel
beams of 5mm diameter, and was used to specifically illuminate different areas
of the parabolic mirror while the illumination pattern on the cell surface was
recorded. A comparison between the Scientrace simulations and corresponding
experiments, shown in figure 3.8 shows excellent overlap in illumination pattern,
and wavelength dependent light dispersion.

3.6 Conclusions

Scientrace is an open source, platform independent, ray tracer, designed for the
Linux-minded scientist. The 3D vector based XML-file input creates 3D simula-
tion environments comparable to how HTML is used to create documents. The
modification of vectors, materials and other properties is easily varied in these
source files. Using the Scientrace Batch Creator, large series of configurations
can be programmed with minimal effort. Since optical properties can be defined
in great detail and the output allows inspection of a large variety of properties -
using open standards only - the software provides a very powerful tool for scien-
tific solar concentrator research. Examples and additional information on how to
compile/install/use Scientrace can be found at [http://scientrace.org](http://scientrace.org).

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Chapter 4

Inhomogeneous Illumination Intensity

Abstract

Currently, an important concern in CPV is inhomogeneity of the light distribution on the cell introduced by the applied optical systems, which may affect system performance. In BICPV applications, the inhomogeneities can be much more severe because of design constraints introduced by the building incorporation. Additionally, one of the predominant loss mechanisms in CPV solar cells is perimeter recombination. In this study, the electrical parameters of CPV cells are investigated under inhomogeneous illumination intensity profiles. Partial shading is used as a model for extremely inhomogeneous illumination, while several shadow patterns are used to study the effect of perimeter recombination on the cell performance. As the latter occurs most strongly in GaAs subcells, shallow and deep junction GaAs CPV cells have been developed and subjected to these experiments, as well as commercial triple junction CPV cells. Deep junction GaAs cells are shown to perform significantly better under concentrated light than their shallow junction counterparts. A large degree of shading exceeding 70% has been found to cause only minor losses in the cell performance of 4%. Also, the cell performance is found to be independent of the location of illumination, in spite of perimeter recombination effects, because the current density spreads out. Clearly, increased illumination inhomogeneities caused by elaborate BICPV optical systems, do not inhibit the electrical performance strongly. As a consequence, a large degree of design freedom exists for the optical systems, which offers good opportunities to develop BICPV that meet all the design challenges of the built environment.

The study presented in this chapter is based on
Paper accepted in Solar Energy Materials and Solar cells; available online.
4.1 Introduction

In the last decades the interest in multi-junction (MJ) solar cells for use in concentrator photovoltaic (CPV) setups has dramatically increased because of their higher conversion efficiency compared to other PV technologies [22]. Still, the demand for higher efficiency cells continues to rise and drive the need for research in MJ solar cell technology. CPV systems aim to deliver electrical power at a lower cost than will be possible with traditional photovoltaics such as flat Si panels [73,100]. To achieve this goal, maximum performance from the MJ solar cells optimized for concentrators should be obtained, while minimizing the cost of optics, temperature control and other balance-of-system [198]. As demonstrated efficiencies for 3-, 4- and more junction III-V CPV cells continue to rise the chances for economically viable CPV systems are increasing, but this also puts more demands on the concentrating systems. In recent years a noteworthy rise in building integrated photovoltaics has occurred in Europe. These systems contribute to the move towards energy neutral buildings by combining PV in the building design, applying several different integration methods. Examples include full roof systems [137–140], solar skylights [141,142], solar roof tiles [143,144], rain-screen solar façade [145], and solar curtain wall [146]. A good overview of the current status of BIPV has recently been published by the Solar Energy Application Centre (The Netherlands) and the University of Applied Sciences and Arts of Southern Switzerland [148]. Added functionality in building integrated photovoltaics can be realized through concentrator photovoltaics, in the form of heat generation [149,157] or daylight regulation [150,158].

At present, an important concern in CPV remains the inhomogeneity of the light distribution on the cell introduced by these optical systems [199–207]. This may cause loss of performance due to an increased series resistance, as well as current mismatch between junctions [208]. In BICPV applications in particular, the inhomogeneities can be much more severe than in ‘traditional’, field-based concentrators because of design constraints introduced by the building incorporation that often lead to the use of optics with a complex geometry [157,158]. Many concentrator system designs aim to minimize this inhomogeneity by means of a homogenizing Secondary Optical Element (SOE) [132,133]. SOEs can reduce spatial and spectral inhomogeneity via (multiple) internal reflections of the incident light. In addition, a SOE usually adds secondary concentration to a CPV system. In previous work we showed the benefit of using a SOE in symmetrical CPV systems [209]. However it is also noted that for asymmetric systems the use of a SOE might be detrimental to the overall device performance. As many CPV systems do not apply a SOE it remains important to gain a better understanding of the solar cell performance when the high intensity illumination is not uniform.

Previous works [159,203,205,210,220] have studied the solar cell electrical performance with non-uniform illumination intensity. Some authors have explored this issue through developing and validating models, finding generally a disproportionate loss of cell performance of several per cent [203,205,210,213]. Others use experimental methods [159,214,220], describing a loss in cell performance [215], an
internal current and voltage drop [216], a loss in fill factor [159] and a mitigating effect in the spread of current density [219]. Several authors note that in point-focus CPV the irradiation profile resembles a gaussian distribution and therefore use such distributions in their works [159, 207, 214, 219]. Others, like Githas and Sabry [217, 218], focus on the location of shadows on the cell surface, specifically the edge as that is usually the area that receives the least amount of illumination.

In the current study the electrical parameters of III-V CPV solar cells under an extreme form of non-uniform illumination intensity are investigated experimentally by use of a homogeneous illumination source, with partially shaded cells using the shading factor S as introduced by Quashing and Hanitsch [211]. Experiments under concentrated illumination are performed using a multiple-flash setup. The I-V characteristics of commonly applied InGaP/Ga(In)As/Ge triple shallow junction (TSJ) cells are investigated, as well as GaAs single junction cells, in-house grown to resemble the individual junction in a TSJ stack. In performance optimized TSJ solar cells for CPV the InGaP and Ga(In)As subcells are designed to be lattice matched for a certain spectral distribution of the incident light. However, as in practice the spectral distribution changes during the day, also the limiting subcell in power output optimized cells changes during the day [221]. In the red-shifted morning and evening spectrum the InGaP cell will be limiting while in the midday blue shifted spectrum the GaAs cell will be limiting. Also it is known that carrier recombination in the outer cell perimeter especially, is one of the major causes of performance losses in GaAs solar cells [222, 223]. It may therefore be expected to also affect the electrical performance of CPV multijunction cells that contain a GaAs subcell, in particular because small CPV cells have a relatively larger perimeter to surface area ratio. On the other hand the relative contribution of this effect on output power diminishes when cells are operated at high light concentrations [224]. Therefore in the investigation of inhomogeneous cell illumination intensity carried out here, special attention is devoted to the outer cell perimeter. These recombination effects are usually determined by comparison of the dark diode characteristics of cells of varying surface area. However, the dark diode characteristic might not be representative for a solar cell under non-uniform illumination intensity. Especially in BICPV setups, where illumination intensity can be very high, and illumination non-uniformity can be severe. The nature of recombination losses in the perimeter are evaluated here, in illuminated conditions as is representative for solar cells operating in a CPV setup. The influence of the outer cell perimeter is determined by specifically illuminating this area, or excluding it from illumination while characterization of the overall cell performance is performed. The analysis is performed on the triple junction and single junction GaAs cells, and not on single junction InGaP or Ge, as they have been shown to not contribute significantly to these effects in MJ cells [222].

Finally a comparison is made between the partially shaded performance of typical single shallow-junction (SSJ), and single deep junction [225, 226] (SDJ) GaAs solar cells, the latter of which have recently been shown by Bauhuis et. al [186] to display enhanced electrical performance under one sun illumination. GaAs cells with a device structure similar to the individual junctions in a CPV
multi-junction cell have been grown with respectively a shallow and a deep junction and characterized under one sun, and concentration while partially shaded, in order to show the benefit of using a deep junction GaAs subcell in multijunction CPV cells.

4.2 Experimental

4.2.1 Device description

The CPV MJ solar cells under test are Spectrolab CDO100 C3MJ type CPV assemblies. These are 11.1mm x 10.1mm InGaP/Ga(In)As/Ge CPV solar cell assemblies, equipped with anti-reflection coating (ARC), and front contact metal tabs. The cells feature a silver front contact grid consisting of parallel, equidistant lines with a total surface coverage of 8.8%, and are optimized to achieve maximum performance under the ASTM G173-03 spectrum [227]. All subcells of this structure have a commonly applied thin emitter, thick base or in other words shallow junction geometry. Therefore in this study these cells will be referred to as Triple Shallow Junction (TSJ) cells.

Additionally, GaAs solar cells with shallow as well as deep junctions were studied. These were grown on substrate using MOCVD under conditions described in previous work [228]. For convenience these cells will be referred to as Single Shallow Junction (SSJ) and Single Deep Junction (SDJ) cells. Both cell types cells possess a 20nm AlInP window and an AlGaAs back surface field. The emitter and base dopants are Si and Zn, respectively. The layer thicknesses and doping levels of the active layers of the investigated shallow and deep junction GaAs cells are summarized in table 4.1.

<table>
<thead>
<tr>
<th>cell type</th>
<th>emitter thickness (µm)</th>
<th>n-emitter doping (cm⁻³)</th>
<th>base thickness (µm)</th>
<th>p-base doping (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs SSJ</td>
<td>0.15</td>
<td>2 x 10¹⁸</td>
<td>3.50</td>
<td>3 x 10¹⁶</td>
</tr>
<tr>
<td>GaAs SDJ</td>
<td>2.40</td>
<td>1 x 10¹⁷</td>
<td>0.10</td>
<td>1 x 10¹⁸</td>
</tr>
</tbody>
</table>

Table 4.1: Structural parameters of the investigated GaAs single junction cells. The doping levels were determined from Hall measurements on separately grown layers.

The GaAs cell structures have been processed into test devices with an active area of 11.1mm x 10.1mm, and covered by a MgF₂/ZnS ARC. Gold was applied for metallization on the front and back side. The front contact consists of parallel, equidistant grid lines of 4µm thickness and a total surface coverage of 8.4%.
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Figure 4.1: The probestation used for application and alignment of the shading on the solar cells with a) showing the interior; and b) a plate is inserted in the mount and can be precisely moved into position by the turning spindles. A microscope is used to ascertain exact alignment of the shading plate with the solar cell and microscope equipped. The numbered components are 1) cell stage with brass back contact; 2) vacuum to ensure good back contacting; 3) front contact point; 4) clamp to hold the cell in place, simultaneously contacting front contact tabs; 5) moveable mount for shading plates; 6) microscope for checking alignment between shading plate and solar cell; and 7) spindles for moving the shading plate mount.

4.2.2 Electrical characterization

One sun I-V characterization of the solar cells is performed using an ABET technologies Sun 2000 Class AAA solar simulator, which provides a uniform AM1.5G illumination over a 100 x 100 mm² area, with a maximum angular offset of 2°. The setup is equipped with a Keithley 2600 sourcemeter and data acquisition is performed using ReRa Tracer3 software. The solar cells are kept at 25° during measurement using a water cooled thermostat. The setup is calibrated using a calibrated reference cell before each measurement series. The same setup is used for determining dark diode characteristics of the cells. Shown datapoints are averages of four separate measuring series taken from different solar cells of the same.

I-V curves under concentrated light are obtained using a multiple-flash setup that applies a different fixed bias voltage across the cell during each flash. A broncolor pulso G Xe arc lamp having a maximum energy of 3200 J is used to apply highly concentrated light. The UV protection dome was replaced by a quartz dome to allow for higher UV-content. In this way the applied Xe spectrum better resembles the AM1.5 spectrum. A reflector is used to achieve high concentrations. The lamp is driven by a broncolor topas A4 source for a 6 ms flash. A KEPCO BOP 20-50MG source is used to bias the cell at a specified voltage during the
4.2. EXPERIMENTAL

Figure 4.2: The applied shading patterns; a) 'center shading'; and b) 'edge shading'. For center shading an increasing shading factor $S$ causes a larger illuminated perimeter-to-area ratio.

flash. To measure the data a National Instruments DAQ board is integrated into the system. The irradiance level is monitored using a reference cell having a linear response to the illumination level. In this manner, in fact I-V pairs for a continuous range of concentrations are obtained for the specified bias voltage during a single flash. I-V curves at any particular concentration are subsequently constructed from datasets obtained from multiple flashes conducted under different bias voltages. In this fashion, a possible shift of limiting subcell during a flash because of temporal spectral variations will not cause artificial discontinuities in the I-V curves, as the irradiance for any single I-V curve can be considered constant when using this multiflash method. Therefore, the limiting subcell is constant for each I-V curve. It should be noted however, that slight reductions in the GaAs subcell $FF$ might be masked when InGaP is current limiting and vice versa. No more than one flash is executed for every 30 seconds to prevent heating of the lamp, which could result in a red shift of the spectrum. The concentrations reported hereafter are determined by division of the measured, concentrated short-circuit current by the calibrated one-sun short-circuit current, and are therefore the effective concentrations rather than geometrical.

4.2.3 Shading

In order to achieve reliable data when the solar cells are partially shaded, good alignment between the solar cell and the shading material should be achieved. To do this, the specially developed probe station shown in figure 4.1 is used. It features a stage where the solar cell is loaded and kept in place by vacuum which simultaneously functions as the back contact probe, and a cover lid that serves
as the front contact probe. Above the cell stage a mount is located that can be moved in the x and y directions very precisely. The mount can hold a 127mm x 127mm opaque shading screen that serves to apply partial shading to the solar cell. Various shading patterns are gained by the use of shading screens with differently shaped holes in. Using a microscope for inspection, precise alignment between the shading pattern and the solar cell is achieved. The microscope is removed before I-V characterization.

In this work two different shadow patterns are considered, which are illustrated in figure 4.2. We consider ‘center shading’, here represented by rectangular shading propagating from the middle of the cell towards the edges, as shown in figure 4.2a. In this way, the illuminated perimeter to illuminated area ratio $P_{ill}/A_{ill}$ increases more rapidly with the shading factor $S$ than in the rectangular case. Therefore this method is used to investigate the electrical performance at the perimeter of the cells compared to the bulk cell area. As an inverse of the previous, ‘edge shading’ is applied as shown in figure 4.2b. These methods are applied to the commercial TSJ CPV cells as well as the in house grown single junction cells discussed in section 4.2.1, under both 1 sun and concentrated illumination. The measurements on the single junction cells will be used to gain a more precise understanding on the TSJ cell electrical performance. Additionally the performance of the shallow junction cells are compared to that of their deep junction counterparts.

When cells of different types need to be compared, in order to be able to make good comparisons, the electrical parameters of the solar cells are normalized via:

$$\xi_N(S) = \frac{\xi(S)}{\xi(S = 0)}.$$  \hspace{1cm} (4.1)

where $X(S)$ is a cell parameter for a given $S$.

### 4.3 Results

#### 4.3.1 Shaded performance under one sun illumination

When center shading (figure 4.2a) is applied, $P_{ill}/A_{ill}$ increases rapidly with $S$. Conversely, when edge shading (figure 4.2b) is applied the outer cell perimeter is directly excluded from the overall cell performance. Therefore comparison of the cell electrical parameters under both conditions yields information on nonidentical performance of the center cell area as compared to the outer perimeter. The I-V characteristics of the triple junction cells, as well as SSJ and SDJ GaAs cells, for both center and edge shading have been determined for increasing shaded fraction $S$ ranging from 0 to 0.95. Figure 4.3 shows normalized electrical parameters of the solar cells under these conditions. The $I_{SC}$ (figure 4.3a) shows, for all three cell types, for both center and edge shading, a proportional decrease as a function of $S$, explained by the diminished overall illumination, via:

$$I_{SC}(S) = (1 - S) I_{SC}(S = 0).$$  \hspace{1cm} (4.2)
4.3. RESULTS

![Graphs showing normalized electrical parameters of solar cells under edge and center shading]

**Figure 4.3:** Normalized electrical parameters of triple shallow junction cells (circles), as well as single shallow junction (triangles) and single deep junction (squares) GaAs cells, under one sun illumination, as a function of edge shading (brighter hues) and center shading (darker hues). The datapoints are averages of four separate measuring series taken from different solar cells of the same type, with **a)** short-circuit current; **b)** open circuit voltage; and **c)** fill factor.

Besides $I_{sc}$ also $V_{oc}$ and $FF$ of the cells decrease with $S$ but only to a limited extent. Also, when considering $V_{oc}$ (figure 4.3b) differences between the cell types become apparent. The decrease in $V_{oc}$ is much less severe for the SDJ GaAs cells (green square markers) amounting to 9.5% relative decrease at $S = 0.95$, compared to 11.6% relative decrease for SSJ GaAs cells (yellow and red triangular markers) and 13.8% relative decrease for triple junction cells (blue circular markers). Within any single cell type however, no significant difference in electrical parameters is observed between center or edge shading. The observed $V_{oc}$ decrease for increasing $S$ can be only in part attributed to the lower irradiance for increasing $S$, as shown in figure 4.4. Here, $V_{oc}$ for all cells is shown as a function of $S$ on a logarithmic scale. $V_{oc}$ exhibits a $ln$ dependence on $I_{sc}$ and therefore on $S$, shown here by the dashed linear trend lines. For lower $S$ values, the $V_{oc}$ decreases according
to theory. However at high shading factors of $S > 0.7$, a disproportionate loss in $V_{OC}$ of a few per cent arises. Also from the $FF$ (figure 4.3c), the difference between the cell types is readily apparent. In this case the larger decrease of the SSJ GaAs $FF$ for increasing $S$ stands out, caused by its higher series resistance in comparison to the other cell types. Conversely, the SDJ GaAs and triple junction $FF$ are much more constant for increasing $S$, only showing a decrease of a few percent relative even when $S$ approaches 1. Again, center and edge shading yield the same results within any single cell type.

The results show that the overall cell performance under illumination is independent of the location of illumination, in spite of perimeter recombination effects. We suggest this occurs because the influence of perimeter recombination is equal in the edge - and center shaded cases because the generated current spreads out throughout the entire cell volume via lateral diffusion effects, so the perimeter recombination affects cell performance regardless of the location of illumination. In order to evaluate this, effects caused by the perimeter recombination at high $S$ are next studied in more detail. The dark curves of the SSJ and SDJ GaAs cells are considered here, and shown in figure 4.5. The dark recombination current is described by:

$$I_{rec} = I_{01} \left( \exp \left[ \frac{qV}{kT} \right] - 1 \right) + I_{02} \left( \exp \left[ \frac{qV}{2kT} \right] - 1 \right),$$

(4.3)
4.3. RESULTS

Figure 4.5: Dark diode characteristics of the SSJ and SDJ GaAs cells.

with \( n = 1 \) the radiative, and \( n = 2 \) non-radiative recombination. The non-radiative recombination mainly stems from the depletion zone and the perimeter. For large cells (\( \geq 1\text{cm}^2 \)), the perimeter recombination has a strong influence at voltages up to 1.1 V \cite{222} in the shallow junction case. For deep junction cells, at one sun conditions, at operating voltage, the contribution of non-radiative recombination is lower \cite{186}. The ratio between the recombination currents is voltage dependent; at low voltages non-radiative recombination effects are relatively stronger and vice versa. At constant voltage, for instance \( V_{OC} \), the following holds:

\[
I_{rec} = I_0 \left( \exp \left[ \frac{qV_{OC}}{nkT} \right] - 1 \right), \text{with } 1 \leq n \leq 2. \tag{4.4}
\]

If the shape of the I-V curve is assumed not to change with increasing irradiance, the total current becomes:

\[
I = I_{rec} - I_{SC}. \tag{4.5}
\]

At \( V_{OC} \) conditions \( I \equiv 0 \) and \( I_{rec} = I_{SC} \) so that for \( I_{SC} \gg I_0 \):

\[
V_{OC} = \frac{nkT}{q} \ln \left( \frac{I_{SC}}{I_0} \right). \tag{4.6}
\]

Hence the dark curve provides combinations of \( I_{SC} \) and \( V_{OC} \). Substitution of eq. (4.2) in eq. (4.6) yields an expression for \( V_{OC} \) that accounts for cell shading:

\[
V_{OC}(S) = n(S) \frac{kT}{q} \ln \left( \frac{(1 - S) I_{SC}(S = 0)}{I_0(S)} \right), \tag{4.7}
\]

with \( n \) and \( I_0 \) not constant as a function of \( S \). In order to determine the \( n \) and \( I_0 \) at different shading values, illuminated \( I_{SC} \) values for different shading have
been superimposed on the dark curves (figure [4.5]) yielding the corresponding \( V_{OC} \) values. Because the shape of the curve is assumed to be unaffected by irradiance, the dark curve directly yields corresponding \( V_{OC} \) values, and \( n \) and \( I_0 \) are determined from the slope of the curve. The latter are shown in figure [4.6]. The dark curves show clearly a lower \( n \) and \( I_0 \) for the SDJ design, which is a correlated to the n-type absorbers lower diffusion factor as explained in [225]. The difference in absorber doping level between the SDJ and the SSJ design can not account for this difference. Therefore an n-type absorber, in terms of low \( I_0 \), will show a better performance over a large range of doping levels [225][226]. Because of this, the SDJ design with its relatively thicker n-type absorber outperforms the SSJ design [2]. Therefore, especially in thin cells, the SDJ design is preferred. Clearly, \( n \) and \( I_0 \) both increase strongly at high \( S \) values. This occurs because the ratio of radiative and non-radiative recombination shifts towards non-radiative \((n = 2)\) at low irradiance. This explains the deviation from standard decrease of \( V_{OC} \) with \( S \), described in figure [4.4]. The \( V_{OC} \) values determined by the method described above constitute a theoretical decline of \( V_{OC} \) with increasing \( S \), which takes the increasing \( n \) and \( I_0 \) into account. These values are compared to the experimentally determined \( V_{OC} \) in figure [4.4] An excellent overlap between curves determined from illuminated I-V measurements and dark curve measurements is shown, for both the SSJ and SDJ cells. Additionally, both center and edge shaded experimental data agree very well with the theoretically determined \( V_{OC} \). Therefore it is clear that specifically including or excluding the outer cell perimeter from being illuminated does not alter the degree in which perimeter recombination effects affect the cell performance. Hence the lateral current spreading effect as suggested

\[ \text{[2]} \text{In the n-type absorber design one should be careful about using a proper absorber thickness and doping concentration. The implementation of n-type absorbers could be limited in cells on-substrate due to the lower diffusion length (substantially lower minority carrier mobility) of n-type absorbers than p-type ones. This may impact strongly the } J_{SC} \text{ as reported in [186].} \]

Figure 4.6: Cell parameters of SSJ and SDJ GaAs cells as a function of shading as determined from the dark curves, showing a) recombination current; and b) ideality factor.
above must be responsible for bringing carriers close to the outer perimeter where they recombine, even when no carriers are generated at those locations.

Summarizing, aside from a strongly diminished $FF$ for SSJ GaAs cells, the performance of the solar cells is quite robust in partially shaded conditions. For very high shading factors, a slightly diminished cell performance has been observed. This heavily shaded scenario - that results in only a minor effect - is of course a gross overstatement of the inhomogeneities in irradiance encountered in application. Therefore, the total illumination intensity of the cells can be considered to be the determining factor for the cell performance, and also for the magnitude of perimeter recombination effects, rather than the homogeneity of illumination intensity. Because of this, small inhomogeneities are not expected to cause severe detrimental effects on the cell performance in application.

### 4.3.2 Shaded performance under concentrated illumination

Concentrated light I-V characteristics have been determined for all three cell types using the multiple flash setup as described in sections 2.3.2 and 4.2.2. Using this setup, characteristics for a continuous range of concentrations are determined at once. However, for the sake of brevity and clarity, only two concentrations will be shown. For the TSJ cells, these are $C=500$ and $C=1000$, while for the GaAs cells, $C=250$ and $C=500$ are shown. These ranges are chosen because of current constraints of the equipment. The concentrations for the GaAs cells are lower than for the TSJ, because the GaAs cells produce roughly double the current of the TSJ for equal irradiance. Again, center and edge shading is applied to the solar cells with $S$ ranging from 0 to 0.95. Figure 4.7 shows normalized electrical parameters of the solar cells under these conditions. Here, the normalization holds the additional benefit of allowing comparison of measurements performed at different concentrations.

For all three cell types, for both center and edge shading, on all concentrations, $I_{SC}$ exhibits a linear decrease as a function of $S$, as shown in figure 4.7a. The relative decrease in $V_{OC}$ for concentrated illumination, shown in figure 4.7b, is much less than for one sun illumination. This occurs because $V_{OC}$ and also $I_0$ are higher in this scenario. Therefore $n$ approaches 1 and $I_0$ is virtually constant for increasing $S$. Additionally, the differences between the different cell types are far less pronounced. Again, differences in performance when the cells are edge shaded (lighter colours) or center shaded (darker colours) remain absent. The trends in the $FF$ (figure 4.7c) are vastly different for all cell types than at one sun illumination. This occurs mainly because the cells operate with a certain optimum concentration as will be further elaborated in section 4.3.3. First note that for all cell types, again no significant differences are found that can be linked to the location of illumination (edge vs center). For the TSJ cells, the $FF$ is quite constant as a function of $S$, with the average $FF$ being somewhat higher for $C=1000$ (open markers), compared to $C=500$ (full markers). This may occur because the optimum concentration for these cells lies around $C=800$, thus for $S = 0$, which is
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Figure 4.7: Normalized electrical parameters of triple junction cells (circles), as well as shallow junction (triangles) and deep junction (squares) GaAs cells, under concentrated illumination (as defined by the legend), as a function of edge shading (brighter hues) and center shading (darker hues), with a) short-circuit current; b) open circuit voltage; and c) fill factor.

the normalisation point, the cell operates closer to its optimum during the C=1000 measurement series. It should be noted however, that these differences in FF are only marginal (within 2% from 1) and therefore could be considered to be within the measurement error. For both SSJ and SDJ GaAs cells, for C=250 (full markers) the FF shows some deviations as a function of S. Again, the changes are very minor so the FF may be considered constant as a function of S in these cases. The effect is much more pronounced in the C=500 (open markers) measurements, as for S = 0 the cells operate further away from their optimum concentration in this scenario.

It is apparent that the partially shaded cell performance is predominantly determined by the total irradiance, rather than the location or homogeneity of illu-
4.3. RESULTS

Figure 4.8: Comparison of electrical parameters between shallow junction (yellow, red triangles) and deep junction (green squares) GaAs cells, under concentrated illumination (as defined by the legend), as a function of edge shading (brighter hues) and center shading (darker hues). The datapoints are averages of four separate measuring series taken from different solar cells of the same type, with a) short-circuit current; b) open circuit voltage; and c) fill factor.

Comparison of electrical parameters between shallow junction (yellow, red triangles) and deep junction (green squares) GaAs cells, under concentrated illumination (as defined by the legend), as a function of edge shading (brighter hues) and center shading (darker hues). The datapoints are averages of four separate measuring series taken from different solar cells of the same type, with a) short-circuit current; b) open circuit voltage; and c) fill factor.

minimization intensity under concentration as well as one sun illumination. The lesser decrease of $V_{OC}$ with increasing $S$ under concentrated light supports this. Also, the increasing $FF$ with $S$ for the GaAs cells point in the same direction, which becomes clear when total irradiance received by the shaded cell is considered via:

$$E_e(S) = E_e(S = 0) \cdot (C \cdot S),$$

so that the combination of $C=250$ and $S = 0.5$ is assumed to be equivalent to $C=125$. In this assumption, for a constant $C$ that is above the optimum concentration, increasing $S$ can be considered similar to decreasing $C$, thus getting closer to the optimum concentration. This agrees with the trends shown in figure 4.7c, and reinforces the suggestion that the generated current spreads out from
the illuminated area to fill the entire cell volume. Also under concentration, no significant differences in cell performance have been found for illumination of the outer cell perimeter or the cell center. Therefore, lateral spreading of the current density can be considered to bring perimeter recombination effects into play regardless of the location of illumination on the cell surface. Additionally it may be noted that under concentration, the individual subcells in a MJ stack operate at higher voltages dependent on the concentration. At higher voltages recombination is dominated by the quasi-neutral regions, so the impact of the perimeter recombination is relatively lessened. Again, a significant loss of cell performance is only observed at very high shading factors. Because of this, small inhomogeneities in illumination intensity across the cell surface are not expected to cause detrimental effects on the cell performance in CPV systems.

4.3.3 Enhanced performance of deep junction GaAs cell under concentration

In the previous two sections, the electrical parameters of SSJ and SDJ GaAs cells were shown to follow virtually the same trends for increasing shaded fraction $S$ for both one sun and concentrated illumination. However, it is important to note that while the cells exhibit a similar dependency on inhomogeneities in the illuminated profile, the actual electrical cell parameters as shown in figure 4.8 are not equal for the SSJ and SDJ cells. Figure 4.8a shows that for both cell types $I_{SC}$ drops proportionally to $E_e$ with increasing $S$ as described above. Moreover the figure shows that there is very little difference in current production between the SSJ and SDJ cells. Figure 4.8b on the other hand shows that under concentrated light, the SDJ cell always generates an increased voltage of over 43mV compared to its SSJ counterpart. As the generated voltage is a very important parameter in concentrator solar cells, this increase can be a major benefit in CPV cells. Similarly, figure 4.8c shows the increased $FF$ for the SDJ cells compared to the SSJ to be up to 2%. An interesting feature is that the $FF$ of both cell types remain fairly constant with increasing $S$ for the C=250 series, while they exhibit a significant increase in the C=500 series. This occurs because the cells have an optimum operating concentration, which is represented by the maxima of the curves shown in figure 4.9. In this figure, the $V_{OC}$ (a), $FF$ (b), and efficiency (c) of deep and shallow junction GaAs cells are compared as a function of light concentration. The effective concentration of each data point in figure 4.8 can be obtained by multiplication of the applied concentration for the series (C=250 or C=500) with the particular $S$ value. The C=250 series in figure 4.8c exhibits a fairly constant $FF$ with increasing $S$, because the effective concentration ranges from 250 to 10, i.e. providing $FF$ values relatively close to the maximum in figure 4.9b. For the C=500 series on the other hand the low $S$ values represent an effective concentration exceeding 250, i.e. well beyond the optimal concentration where the $FF$ values decrease rapidly (see figure 4.9b). Figure 4.9 further shows clearly that for the entire range of investigated concentrations, the SDJ cell exhibits an increased $V_{OC}$ and $\eta$ compared to the SSJ cell. For concentrations exceeding 10X, the SDJ
4.4 Conclusions

The electrical parameters of CPV solar cells under an extreme form of inhomogeneous illumination intensity profiles have been studied in detail. Local shading has been applied as a measure for inhomogeneity rather than variations in illumination intensity. This is done because shading represents the most extreme case of inhomogeneous intensity, so that possible effects on cell performance will be revealed most strongly. Commercially available InGaP/Ga(In)As/Ge cells, as well as

Figure 4.9: Comparison of electrical parameters between shallow junction (red triangles) and deep junction (green squares) GaAs cells as a function of concentration, showing a) \(V_{OC}\); b) \(FF\); and c) efficiency.

cell also exhibits a higher \(FF\) than the SSJ cell. The increased performance of the SDJ design over the SSJ was shown to persist under inhomogeneous illumination intensity in sections 5.3.1 and 4.3.2. Therefore use of this SDJ design for the GaAs subcell in CPV multi-junction solar cells may provide an interesting route towards cells with further enhanced performance.

4.4 Conclusions

The electrical parameters of CPV solar cells under an extreme form of inhomogeneous illumination intensity profiles have been studied in detail. Local shading has been applied as a measure for inhomogeneity rather than variations in illumination intensity. This is done because shading represents the most extreme case of inhomogeneous intensity, so that possible effects on cell performance will be revealed most strongly. Commercially available InGaP/Ga(In)As/Ge cells, as well
as shallow and deep junction GaAs cells resembling the GaAs subcell in the TSJ cells, have been I-V characterised when partially shaded. It has been shown that the electrical performance of the solar cells under partial shading is quite robust. A performance loss in the order of 4% has been observed for very high $S$. Such heavy shading grossly overstates the inhomogeneities in irradiance encountered in application. Hence, an inhomogeneous cell illumination intensity profile as commonly found in CPV systems, can be considered to have no influence on the overall electrical cell performance.

More importantly, the location of the shading on the solar cell area is also found to be of no consequence for the cell performance for the investigated conditions. In experiments where the outer perimeter of the cells are specifically illuminated, or excluded from illumination, the cell performance as a function of $S$ is equal for all cell types. Lateral spreading of the current density likely causes perimeter recombination effects to affect the cell performance regardless of the location of illumination. These perimeter recombination effects will therefore not have a further detrimental effect on the cell performance when the illumination intensity profile is not homogeneous. However, a reduction of these perimeter recombination effects altogether will be beneficial to the cell performance.

These findings show clearly that even partial shading in the cell illumination pattern caused by elaborate optical systems, such as the ones often applied in BICPV, do not inhibit the electrical performance of the solar cells strongly. Accordingly, an inhomogeneous illumination intensity profile may also be considered to have little impact on the cell performance. As a consequence, a large degree of design freedom exists for the optical systems. This offers many opportunities for the development of building integrated concentrator photovoltaics that meet all the design challenges of the built environment.

Additionally, shallow junction GaAs solar cells have been developed that resemble the GaAs subcell in a TSJ cell structurally, as well as a deep junction counterpart. The cells have been equipped with an ARC and front contact grid resembling that of the TSJ cells. The normalized electrical parameters of these cells exhibit similar trends when partial shading is applied. Therefore SDJ and SSJ cells can be considered to function equally well under inhomogeneous illumination intensity profiles. However, the SDJ cells have been shown to exhibit a significantly increased $V_{OC}$ (40 mV), $FF$ (2% absolute), and efficiency (2% absolute) under a wide range of concentrations compared to the SSJ cells. Therefore use of this SDJ design for the GaAs subcell in CPV multi-junction solar cells may provide an interesting route towards cells with further enhanced performance.

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Chapter 5

Inhomogeneous Illuminated Spectrum

Abstract

An important concern in concentrator photovoltaics (CPV) is inhomogeneity in spectral distribution on the cell caused by the applied optical systems. This is particularly the case in building-integrated CPV (BICPV) applications, where the inhomogeneities generally are larger than in field-based systems, on account of design constraints by the building incorporation. In this study, the electrical parameters of CPV solar cells under severe laterally split spectra are investigated experimentally. The short-circuit current is demonstrated to have no dependency on the lateral spectral inhomogeneity. For one sun illumination, the open circuit voltage and the fill factor show relatively small reductions with increasing spectral splitting. This is shown to occur because the carriers encounter a locally elevated series resistance as they travel laterally through the cell to compensate for local current mismatch. Also under concentrated light (>100X) the effect of extreme non-uniformity in spectral distribution was found to have only minor effects on the cell performance. Therefore, a large degree of design freedom exists to combine photovoltaics with a variety of concentrating optics in order to meet the specific design challenges of the built environment.

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1The study presented in this chapter is based on "Influence of laterally split spectral illumination on multi-junction CPV solar cell performance" by L.A.A Bunthof, E.J. Haverkamp, D. van der Woude, S. Veelenturf, W.H.M. Corbeek, G. Bauhuis, E. Vlieg, and J.J. Schermer, submitted
5.1 Introduction

In the last decades the interest in multi-junction (MJ) solar cells for use in concentrator photovoltaic (CPV) setups has dramatically increased because of their higher conversion efficiency compared to other PV technologies [22]. Still, the demand for higher efficiency cells continues to rise and drive the need for research in MJ solar cell technology. CPV systems aim to deliver electrical power at a lower cost than will be possible with traditional photovoltaics such as flat Si panels [73,100]. To achieve this goal, maximum performance from the MJ solar cells optimized for concentrators should be obtained, while minimizing the cost of the optical elements, temperature control and other balance-of-system items [198]. As demonstrated efficiencies for 3-, 4- and more junction III-V CPV cells continue to rise, the chances for economically viable CPV systems are increasing, but this also puts more demands on the concentrating systems. In recent years a noteworthy rise in building-integrated photovoltaics (BIPV) systems has occurred as a consequence of accepted policies regarding energy efficiency, in a trajectory towards energy neutral buildings.

BIPV systems contribute to the move towards energy neutral buildings by combining PV in the building design, applying several different integration methods. Examples include full roof systems [137,140], solar skylights [141,142], solar roof tiles [143,144], rain-screen solar façade [145], and solar curtain wall [146]. The current status of BIPV has recently been published by the Solar Energy Application Centre and the University of Applied Sciences and Arts of Southern Switzerland [148]. Added functionality in building-integrated photovoltaics can be realized through concentrator photovoltaics, by using the characteristics of CPV to address issues besides electricity generation. In this framework there are several building-integrated concentrator photovoltaics (BICPV) systems under development that besides generation of electricity, aim for an added functionality e.g. in the form of heat generation [149,157], or daylight regulation [150,158].

Design constraints introduced by this aim for multiple functionality, or by the building incorporation often leads to the use of concentrator optics with a complex geometry [157,158]. Generally, in CPV the light distribution across the solar cell surface suffers from inhomogeneities [190,207]. In BICPV applications in particular, these inhomogeneities will be strong as a consequence of the more complex optical systems. The nature and severity of such inhomogeneities, as well as the expected illumination pattern caused by a specific BICPV system, can be determined by ray tracing simulations, such as for example described in [229]. This can be a very valuable part of the design process, as problems and challenges may be detected early on. As the possibility for multiple functionality in BICPV systems will lead to their increased use, it is important that the solar cell performance under severely inhomogeneous illumination patterns is investigated. One aspect concerns the evaluation of the MJ solar cell performance when faced with lateral spectral inhomogeneity [160,161] in the illumination, which is caused by the wavelength dependent refraction of light.

Previous works [159,202,206,213,219,230] have examined the solar cell perfor-
 CHAPTER 5. INHOMOGENEOUS ILLUMINATED SPECTRUM

performance with non-uniformity in the illuminating spectrum. Several computational and cell performance models have been developed, either introducing multiple spectra [230], or modelling local spectral variations across the cell surface [213, 219]. Others have investigated this matter by experimental measurements using on-sun measurements [202], or indoor characterization methods [159].

In the current study the electrical parameters of typically applied III-V multi-junction CPV cells with lateral variations in the illuminating spectrum, are investigated experimentally by use of a homogeneous illumination source, while partially covering the cells with different optical filters. The optical filters have been chosen such that illumination of either the InGaP or the GaAs subcell is excluded locally, while the other subcells receive close to their regular illumination. Although lateral spectral variations generally occur at small scales in application, here stronger inhomogeneities are applied in order to identify any introduced debilitating effects on cell performance more strongly. Standard I-V characterization is used for one sun measurements, while concentrated data is obtained using a multiple flash setup. The electrical performance of the cells under these circumstances is compared to the electrical performance under regular illumination, and the performance inhibiting effects are identified and quantified.

5.2 Experimental

5.2.1 Cell characterization

In this study, the solar cells under test are 2.25\,\text{mm}^2 InGaP/Ga(In)As/Ge CPV solar cell assemblies, equipped with an anti-reflection coating (ARC), and front contact metal tabs, produced by AzurSpace. The cells feature a silver front grid contact consisting of parallel, equidistant lines with a width at their bases of 11\,\mu m and a total surface coverage of 8.8% excluding the busbars, and are optimized to achieve maximum performance under the ASTM G173-03 spectrum. The InGaP and GaAs subcells are current matched under this spectrum. In these conditions the Ge subcell produces an excess current. Therefore in this study the focus will be on the InGaP and GaAs subcells.

External Quantum Efficiency (EQE) measurements are performed with a ReRa SpeQuest Quantum Efficiency system. Data acquisition is performed using ReRa Photor 3.1 software. The system uses both a Xenon and halogen light source to address all wavelengths present in the solar spectrum. A monochromator is used to generate quasi-monochromatic light and a chopper for intensity modulation. This generates a test light of variable wavelength while a continuous bias light is used to put the cell under test in operating conditions. The EQE per subcell is shown in figure 5.1.

One sun I-V characterization of the solar cells is performed using an ABET Technologies Sun 2000 Class AAA solar simulator, which provides a uniform illumination resembling the AM1.5G spectrum, over a 100 x 100 mm² area, with a maximum angular offset of 2°. An Ushio 550W Xenon short arc lamp is used to
approximate the AM1.5 spectrum. The setup is equipped with a Keithley 2600 sourcemeter and data acquisition is performed using ReRa Tracer3 software. The solar cells are kept at 25° during measurement using a water cooled thermostat. The setup is calibrated using a calibrated reference cell before each measurement series.

I-V curves under concentrated light are obtained using a multiple-flash setup that applies a different fixed bias voltage across the cell during each flash. A broncolor pulso G Xe arc lamp having a maximum energy of 3200 J is used to apply highly concentrated light. The UV protection dome was replaced by a quartz dome to allow for higher UV-content. In this way the applied Xe spectrum better resembles the AM1.5 spectrum. A reflector is used to achieve high concentrations. The lamp is driven by a broncolor topas A4 source for a 6 ms flash. A KEPCO BOP 20-50MG source is used to bias the cell at a specified voltage during the flash. To measure the data a National Instruments DAQ board is integrated into the system. The irradiance level is monitored using a reference cell having a linear response to the illumination level. In this manner, in fact I-V pairs for a continuous range of concentrations are obtained for the specified bias voltage during a single flash. I-V curves at any particular concentration are subsequently constructed from datasets obtained from multiple flashes conducted under different bias voltages. In this fashion, a possible shift of limiting subcell during a flash because of temporal spectral variations will not cause artificial discontinuities in the I-V curves, as the irradiance for any single I-V curve can be considered constant when using this
multiflash method. Therefore, the limiting subcell is constant for each I-V curve. It should be noted however, that slight reductions in the GaAs subcell $FF$ might be masked when InGaP is current limiting and vice versa. No more than one flash is executed for every 30 seconds to prevent heating of the lamp, which could result in a red shift of the spectrum. The concentrations reported hereafter are determined by division of the measured, concentrated short-circuit current by the calibrated one-sun short-circuit current, and are therefore the effective concentrations rather than geometrical.
5.2. EXPERIMENTAL

5.2.2 Lateral spectral variations

Optical filters are used to locally restrict specific wavelengths from reaching the solar cell. The filters applied are: i) a coloured glass filter that blocks all wavelengths shorter than 700 nm; and ii) an interference film coated glass filter that blocks wavelengths in the 660-1265 nm range. As is evidenced by the transmission curves in figure 5.2 (supplied by the respective manufacturers), these filters each exclude one subcell (InGaP and GaAs respectively) from receiving illumination, while allowing close to regular illumination of the remaining two. However, the transmission of illumination to the remaining junctions is not equal to 1. The wavelength dependent effective illumination on the remaining junctions $NE_e(\lambda)$ is calculated from the transmission curve in figure 5.2, the EQE of the junction (figure 5.1), and the AM1.5 spectrum, via:

$$NE_e,GaAs(\lambda) = \frac{EQE_{GaAs}(\lambda) \cdot AM1.5(\lambda) \cdot TA(\lambda)}{EQE_{GaAs}(\lambda) \cdot AM1.5(\lambda)}$$  \hspace{1cm} (5.1)$$

when InGaP illumination is extinguished by transmission spectrum $TA$, and

$$NE_e,InGaP(\lambda) = \frac{EQE_{InGaP}(\lambda) \cdot AM1.5(\lambda) \cdot TB(\lambda)}{EQE_{InGaP}(\lambda) \cdot AM1.5(\lambda)}$$  \hspace{1cm} (5.2)$$

when GaAs illumination is extinguished by transmission spectrum $TB$. Integration over the entire spectrum yields $NE_e,GaAs = 0.83$ when $TA$ is applied, and $NE_e,InGaP = 0.66$ when $TB$ is applied. Applying these filters side by side produces an overall illumination pattern with very strong spectral inhomogeneity across the solar cell surface. In these experiments, this will be referred to as ‘split illumination’. Locally one subcell (either InGaP or GaAs) is effectively turned ‘off’ while the remaining two subcells remain ‘on’. Current produced in the ‘on’ subcells at that location must therefore circumvent or navigate the ‘off’ subcell area to be collected. This represents local current mismatch due to spectral inhomogeneity as encountered in CPV applications, taken to its extreme. As such it allows a good identification and determination of negative impact on the cell performance caused by spectral inhomogeneity.

In order to achieve good alignment between the solar cells and the optical filters, a specially developed probestation shown in figure 5.3 is used. It features a stage in which the solar cell is loaded (using vacuum to ensure a good contact) as well as retaining clamps for the optical filters, resting on slides slightly above the cell surface. The clamps can be slid across the cell surface by means of micrometer spindles. The setup is such that at all times 75 mm$^2$ of the solar cell surface is illuminated by spectrum A (area A), 75 mm$^2$ of the cell is illuminated by spectrum B (area B), and 75 mm$^2$ of the cell is not illuminated. This is done in order to keep the irradiance between the subsequent measurements constant, as further illustrated in figure 5.4. A first measurement is performed as shown in figure 5.4, in which the area illuminated by spectra A and B are directly next to one-another (X = 0). In this situation, a current excess generated in the GaAs subcell of area A might be expected to circumvent the locally ‘turned off’ InGaP subcell in area...
A because of the close proximity of the ‘turned on’ InGaP subcell of area B, and vice versa. In subsequent measurements as illustrated in figure 5.4b, this circumvention is made more difficult by introduction of an area of increasing width, in which the entire subcell stack is excluded from illumination. This unilluminated area is achieved by clamping an opaque metal strip with a width $X$, between the two optical filters. By increasing the width of this unilluminated area, a measure for the severity of the lateral spectral variation is achieved. The electrical parameters of the solar cells are determined for $X$ increasing in steps of 200$\mu m$ from 0 to 3000$\mu m$ i.e. for increasing severity of local spectral inhomogeneity. As baseline measurements, these experiments are also performed with the optical filters removed from the setup, so the cell is illuminated by the regular AM1.5-resembling spectrum of the solar simulator. The experiments are performed for one sun illumination, as well as higher concentration levels. To allow good comparisons, the electrical parameters of the solar cells are normalized via:

$$\xi_N(X) = \frac{\xi(X)}{\xi(X = 0)}$$

(5.3)

where $\xi(X)$ is a measured cell parameter ($J_{SC}$, $V_{OC}$, $FF$, or $\eta$) for a given unilluminated area of width $X$. 

**Figure 5.3:** Probestation developed for generating lateral variations in the illuminating spectrum across the solar cell surface, with important components marked in the photograph.
5.3 Results

5.3.1 One sun illumination

Firstly, the impact of the illumination pattern (strips of illuminated cell surface, with shading in between, but no filters applied) on the cell parameters is investigated. This is done to deconvolute effects caused by application of this pattern, if any, from effects caused by application of the optical filters. So this experiment can be regarded as a 'baseline' measurement. The impact of the pattern on the cell parameters, is shown to be negligible in figure 5.5, as recorded I-V curves at different X are virtually identical. In the same figure, the effect of applying the optical filters is also shown. Comparison of the two blue I-V curves (with and without filters) clearly shows the diminished electrical parameters of the solar cell if the filters are applied. Most prominently, the $I_{SC}$ in the filtered case, drops to 33% of its value in the bare case. This occurs because of the diminished illumination caused by the transmission curves TA and TB. As detailed in the previous section, $E_{e,GaAs} = 0.83$ in areas where TA is applied, and $E_{e,InGaP} = 0.66$ in
areas where TB is applied. In the case of a multi-junction cell, the current output is limited by the least producing subcell, in this case InGaP at [0.66 x bare illumination]. Now, take into account TB is applied on exactly half of the illuminated area, and it is clear that this causes the overall current production to be [0.33 x bare illumination]. Similarly the slight drop in $V_{OC}$ can be attributed to the changed illumination. The $V_{OC}$ of each subcell is described by:

$$V_{OC, subcell} = \frac{n k T}{q} \ln \left( \frac{J_{SC}}{I_{0n}} \right)$$  \hspace{1cm} (5.4)

with $n$ the ideality factor, $k$ the Boltzmann constant, and $I_{0n}$ the dark saturation current. The total $V_{OC}$ then equals:

$$V_{OC, total} = V_{OC, InGaP} + V_{OC, GaAs} + V_{OC, Ge}$$  \hspace{1cm} (5.5)

Because of the $ln$ dependence of the respective $V_{OC}$'s, the decrease between bare and filtered illumination is small. For increasing $X$, both a drop in $FF$ and a slight reduction of $V_{OC}$ are observed. This is represented in detail in figure 5.6, where normalized electrical parameters of the bare and filtered illuminated I-V curves are shown. Figure 5.6 clarifies that $V_{OC}$ exhibits a slight disproportionate loss with increasing $X$, amounting to nearly 1% for $X = 3000 \mu m$. At $X >
2000µm, the voltage drop levels off in the bare case, while it continues for the split case. This may be caused by the diminished $E_e$ in this case, as non-radiative recombination is relatively stronger than radiative recombination at lower illumination and vice versa. Therefore the ideality factor $n$ may be slightly higher when spectral filters are applied, resulting in an increased voltage drop [232]. The most distinct difference between the bare and split situations is in the $FF$, shown in figure 5.6b. The $FF$ is highly constant as a function of X for bare illumination, but when the spectral inhomogeneity is introduced, $FF$ shows a decrease for increasing X, amounting to 4% relative for $X = 3000µm$. To investigate the origins of this decrease, an equivalent circuit model was developed in LTspice, in which every subcell is modeled as five parallel connected diodes in order to replicate the illumination patterns from the experiments. This is done to be able to reproduce both the shading caused by opaque material, and the local illumination strength caused by TA and TB. Figure 5.7 shows a simplified overlay of the model and the experiment for clarification. For clarity reasons, all current sources associated with the 15 diodes, and all resistors have been omitted from the figure, but it does illustrate how each individual diode is used to represent one specific area of the solar cell, with its associated illumination conditions. In this way the parameters of the five parallel diodes in each junction can be individually altered to account for absent or partial illumination. Simulated I-V curves following from the model closely resemble the curves from the actual cells as shown in figure 5.5. The used diode characteristic[2] are shown in table 5.1. Note that each of the five diodes in

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2As the tested cells are commercial specimens, we have no direct specifications for the $n$ and $I_0$ of the subcells. Therefore, the values are based on findings by Hoheisel et.al [233] who investigated similar cells. The data for $J_{01}$ and $J_{02}$ found in this paper are used to construct dark curves for the subcells to determine $n$ and $I_0$ at the measured $I_{SC}$ level.
any single subcell is approximated to have the same $n$, $I_0$, and $V_{OC}$ values. The fact that the generated current and voltage change little as a function of X, indicates that no significant amount of carriers is lost. This implies that the carriers are being transported laterally between the illuminated parts of the subcells, through a spreading effect similar to what is described in a previous study \cite{219}. Thereby the local current mismatch is alleviated. If significant lateral carrier transport takes place in the cell, this likely results in an elevated local series resistance $R_S$, the presence of which is also suggested by the shape of the curves in figure 5.5. LTspice model simulations have been performed with an incrementally increased local series resistance in the illuminated area of the InGaP subcell. The I-V characteristics following from these simulations are shown in figure 5.8a. The change in curve shape for increasing local InGaP series resistance corresponds well to the change in curve shape for increasing X when spectral splitting is applied (figure

<table>
<thead>
<tr>
<th>subcell</th>
<th>$n$</th>
<th>$I_0$ (A)</th>
<th>$V_{OC}$ (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaP</td>
<td>1.26</td>
<td>$4.1 \times 10^{-21}$</td>
<td>1.408</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.31</td>
<td>$1.3 \times 10^{-15}$</td>
<td>1.032</td>
</tr>
<tr>
<td>Ge</td>
<td>1.01</td>
<td>$2.3 \times 10^{-06}$</td>
<td>0.237</td>
</tr>
</tbody>
</table>

Table 5.1: Diode parameters of the subcells, used in the equivalent circuit model.
5.3. RESULTS

Figure 5.8: LTspice equivalent circuit model simulations; a) I-V curves when the spectral splitting is modeled, for different values of InGaP subcell series resistance; and b) normalized fill factor. In b) the solid blue line just connects the datapoints following from the model simulations while the dotted lines indicate the experimentally determined NFF values for the maximally applied separation width and the width corresponding to the knee-point in the curve.

From the simulated curves the normalized fill factor is calculated and shown in figure 5.8b, as a function of the InGaP series resistance. The figure shows that initially the FF reduces only slightly with increasing series resistance in the InGaP cell indicating that $R_{S,\text{InGaP}}$ is not a dominant contribution to the overall series resistance of the cell. For $R_{S,\text{InGaP}}$ above 20$\Omega$ however, the FF starts to decrease rapidly, indicating that the resistance in the InGaP subcell starts to become a dominating factor. Experimentally this more rapid decline corresponds to a subcell separation width greater than 200 $\mu$m. LTspice simulations with increasing series resistance in the GaAs subcell yield very similar results to those described above for an increasing local $R_S$ in the InGaP subcell. Therefore under filtered illumination it seems evident that the current from the InGaP to the GaAs subcell simultaneously flow along the InGaP base and the GaAs emitter to cross the non-illuminated area. The simulations show that a locally increased series resistance due to lateral carrier transport is a likely cause for the reduction in FF.

This extremely large local spectral mismatch is a gross overstatement of the mismatch occurring in a real application, yet it only results in a very minor decrease in solar cell parameters. Therefore it is apparent that the impact on the cell performance caused by the much smaller local variations in spectrum encountered in application, will be negligible, at least at one sun irradiance. Hence any loss of cell performance caused by local spectral mismatch is more likely to be caused by local heating of the solar cell rather than local current mismatch.
5.3.2 Concentrated illumination

At higher concentration ratios, the impact of parasitic resistances on the cell performance is much larger than at one sun. Therefore detrimental effects of lateral spectral variations can be expected to affect the cell performance more severely at higher concentrations. On the other hand, the high current levels and increased voltage change the diode characteristics in a way that is beneficial for the cell performance as ideality factors shift towards $n = 1$ and the saturation currents are lessened (see table 5.2). I-V curves have been determined at many concentrations between 50X and 1000X, using the setup described in sections 2.3.2 and 5.2.1. For the sake of clarity, only a limited number will be treated here to illustrate the generally observed trends. For several concentration ratios, figures 5.9a and b show the split illumination I-V curves under bare and filtered illumination respectively. For bare illumination, curves for 100X, 300X, and 500X are shown.

![Figure 5.9: Concentrated I-V curves of the cells under split illumination; a) bare, showing the C = 100X (triangles), C = 300X (squares), and C = 500X (circles) curves; and b) filtered, showing the C = 500X (circles), and C = 1000X (diamonds) curves. For clarity, only curves at X = 0µm (blue), X = 1400µm (green), and X = 3000µm (red) are shown.](image)

<table>
<thead>
<tr>
<th>subcell</th>
<th>n</th>
<th>$I_0$ (A)</th>
<th>$V_{OC}$ (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaP</td>
<td>1.01</td>
<td>$2.0 \times 10^{-25}$</td>
<td>1.553</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.01</td>
<td>$8.5 \times 10^{-20}$</td>
<td>1.212</td>
</tr>
<tr>
<td>Ge</td>
<td>1.00</td>
<td>$2.0 \times 10^{-06}$</td>
<td>0.400</td>
</tr>
</tbody>
</table>

Table 5.2: Diode parameters of the subcells under 500 suns concentration, calculated from the dark curves using data in [233] and measured $I_{SC}$ and $V_{OC}$. 
while for spectrally filtered illumination the 500X, and 1000X curves are depicted. These ranges are chosen because of current constraints (10A limit) in the data acquisition module of the multiple flash setup. The figure shows near identically shaped I-V curves for the entire range of X in the bare cell scenario. Therefore, like in one sun illumination conditions, the existence of the shaded areas in the middle and at the edges of the solar cell can be considered to have no disproportional effect on the cell performance in itself. However when the lateral spectral splitting is applied, clearly the shape of the curve changes with increasing X. This is shown in more detail in figure 5.10, where the normalized cell parameters (for all shown concentrations) as a function of X are compared. Like at one sun, no notable effect on the current is observed. However, while the $V_{OC}$ is virtually constant for increasing X in the bare case, a loss of $V_{OC}$ with increasing X is observed when lateral spectral splitting is applied. While at one sun this $V_{OC}$ drop was limited to 1% relative, it increases up to 3% under 500X to 1000X filtered concentration. This can be explained by the locally elevated series resistance as discussed in the previous section. As the impact of such parasitic resistance on the electrical power output of the cell has a quadratic dependency on the generated current, it is understandable that its impact under concentration is increased compared to one sun conditions, but the results obtained in this study indicate that even under high concentration and and extreme case of spectral inhomogeneity, the detrimental impact of lateral spectral inhomogeneity is limited to only 3% in $V_{OC}$ while the effect on the $FF$ can actually be positive. Therefore in applications, where the spectral inhomogeneity will be much less severe than applied in this work, such detrimental effects on the performance can be expected to be very minor.

A striking feature in the I-V curves obtained under filtered illumination, and particularly at 500X and 1000X concentration appears around the 'knee' of the curves. For these curves, when $X = 0\mu m$ (blue curves), the slope between $I_{SC}$ and the knee is steeper than usual, and the position of the knee lowered. This normally indicates that a reduced shunt resistance causes an alternative path for the current where power is dissipated. But when X is increased, this effect lessens, and finally disappears for X approaching 3000\mu m. Related to this effect $FF$ even increases rather than decreases with increasing separation width (see figure 5.10a). A possible explanation for these results can be related to the fact that the $FF$ is lowest when a multi-junction cell is perfectly current matched [221]. Consequently, increasing the split distance might also be considered as an increasing local current mismatch resulting in an increased $FF$.

From figure 5.10 it is clear that the $FF$ and $V_{OC}$ values as obtained under concentrated light suffer from an enhanced fluctuation as compared to the data obtained at one sun. This is related to the fact that in our set-up during a flash the current of the reference cell, the current of the cell under test and the voltage of the cell under test are sequentially measured in a continuous data stream. As a consequence there is a small time lapse between the determination of these three values which one would actually like to assess at exact the same time. By interpolation between subsequent measurements for each of the three parameters their value at the exact same points in time are determined. Nevertheless, this
approach results in minute deformations in the obtained I-V curves (compare figure 5.5 and figure 5.9) and therefore small fluctuations in the extracted cell parameters. As can be seen in figure 5.10, the fluctuations are sufficiently small to justify the conclusion that in high concentration circumstances, the cell performance is quite insensitive to spectral inhomogeneity (at most 4% variation in $V_{OC}$ and 15% in $FF$). However, the aberrations are too large to perform an in-depth analysis of the trends as a function of the split width, as was done for the one sun measurements. In subsequent research this may be performed by application of simultaneous multi-channel data acquisition approach as described in [234].

Nevertheless, the observed effects on the cell parameters introduced by the spectral inhomogeneity are quite small. This further implies that the impact on the cell performance caused by the much smaller local variations in spectrum encountered in application, will be negligible.

5.4 Conclusions

The electrical parameters of InGaP/Ga(In)As/Ge triple junction CPV solar cells under laterally split spectral illumination profiles have been studied in detail. In this approach two areas of the cell were illuminated with a different spectral distribution that effectively turned off either the GaAs or the InGaP subcell. The
5.4. CONCLUSIONS

separation width between the two areas is taken as a quantifiable measure for the spectral inhomogeneity. This extreme case of non-uniform spectral distribution was applied to reveal any cell performance inhibiting effects most strongly. In this configuration the electrical parameters of the cells have been characterized, for one sun, as well as concentrated illumination. It was demonstrated that the short-circuit current has no dependency on the spectral separation width. At one sun illumination, the open circuit voltage shows a minor reduction for increasing spectral inhomogeneity of up to 1% at a separation width as large as 3000 µm. Also a reduction in fill factor was found, of up to 4%. Using LTspice equivalent circuit model simulations, it was shown that this is likely caused by a lateral spreading of the carriers through the solar cell volume. Because of this, the carriers encounter locally an elevated series resistance in the cell resulting in the slightly reduced $V_{OC}$ and $FF$ values. Applying the spectrally split illumination approach it was furthermore demonstrated that even under concentration ratios of several hundred times, spectral inhomogeneity in illumination only has a minor effect on the cell performance.

Overall, the reductions in cell performance as a consequence of the introduced lateral spectral splitting are very minor. That is remarkable, given the spectral splitting applied to the cells in this study is a gross exaggeration of the inhomogeneities caused by even very complex concentrator optics. These findings clearly demonstrate that spectral inhomogeneities caused by concentrating optics applied in BICPV systems, do not inhibit the solar cell performance strongly. Therefore, a large degree of design freedom exists to combine photovoltaics with a variety of concentrating optics. This offers good opportunities for the development of building integrated concentrator photovoltaics that meet the specific design challenges of the built environment.

Acknowledgements

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Chapter 6

Inhomogeneous Illumination Angle

Abstract

CPV systems aim to deliver electrical power at lower cost than will be possible with traditional photovoltaics. To achieve this, maximum performance from the solar cells should be obtained, while minimizing the cost of balance-of-system. Therefore it is important that CPV optical systems are evaluated in terms of their impact on solar cell performance. One attribute of particularly lens based CPV systems is the variance in incidence angles of light at the solar cell surface, especially when a secondary optic element is employed. The electrical performance of TJ CPV solar cells for varying angles of incident illumination is studied in detail. The solar cells suffer a loss of performance of up to 58% for oblique illumination. Calculations and ray tracing simulations show that optical losses are caused by Fresnel reflections off the ARC, and scattered reflections off the front metal grid due to surface roughness. Additionally the merit of using secondary optics in spite of this effect is shown for symmetrical CPV systems. For asymmetrical (e.g. prism based) systems however, the loss of performance may be substantially larger. Therefore grid orientation and design in respect to the optical system should be taken into account and optimized in such systems.

6.1 Introduction

Concentrated photovoltaic (CPV) systems aim to deliver electrical power at a lower cost than will be possible with traditional photovoltaics [73,100]. To achieve this goal, maximum performance from the multijunction solar cells optimized for concentrators should be obtained, while minimizing the cost of optics, temperature control and other balance-of-system [198]. As efficiency limits for 3-, 4- and more junction III-V CPV cells continue to rise [22] the chances for economically viable CPV systems are increasing, yet this also puts more demands on the concentrating systems. Therefore it is important that these optical systems are evaluated in terms of their impact on the solar cell performance [159, 178, 181, 235]. One attribute of in particular lens based CPV systems is the variance in incidence angles of light at the solar cell surface. Another important concern is inhomogeneity of the light distribution on the cell introduced by the optical system [199–202]. This may cause loss of performance due to an increased series resistance, as well as current mismatch between junctions [208]. Therefore, many concentrator system designs aim to minimize this inhomogeneity by means of a homogenizing Secondary Optical Element (SOE) [132,133]. SOEs can reduce spatial and spectral inhomogeneity via (multiple) internal reflections of the incident light. In addition, a SOE usually adds secondary concentration to a CPV system. However, while the performance is increased and the irradiance homogenized, in general the average angle of incidence (AOI) on the cell surface also increases further as illustrated in figure 6.5. As solar cells are typically optimized for use with near-perpendicular illumination, CPV cells - especially in conjunction with a SOE - will suffer from loss of performance by the AOI variance caused by the optics. For instance the Anti Reflection Coating (ARC) may show an angular dependency, but also the exact form and orientation of the front contact grid fingers will have an increasing impact on cell performance as the average AOI increases.

Current CPV systems mostly utilize high efficiency InGaP/Ga(In)As/Ge solar cells with a grid contact for optimal performance under perpendicularly incident light. The surface coverage by the grid is kept as low as possible, yet typically up to 10% to minimize resistive losses. The contact lines are also quite high in the order of 5 to 6µm for the same reason. Under oblique AOIs however, a high aspect ratio becomes a disadvantage as the grid lines will increasingly block the light.

In this paper the impact of oblique illumination on CPV solar cell performance is studied in detail. Previous work into this angular dependence has been dedicated to the optical coupling differences between junctions as a function of AOI and temperature [236]. Here we study the total electrical output of CPV solar cells as a function of the AOI, and also the lateral direction of illumination as explained in section 6.2.1. Additionally the optical benefits of using a SOE are investigated. Finally the optical benefit of employing a SOE and the hinderance in electrical power generation caused by it are evaluated. For this purpose generally applied square InGaP/Ga(In)As/Ge solar cells with unidirectional front contact grid lines are used. The AOI of incident illumination is varied along two directions - parallel to the grid lines, and orthogonal to it - in order to decompose several causes of
cell performance loss. Additionally, 3D ray tracing simulations are performed to study the effects of geometrical light reflections at the grid metal, as well as to study the AOI distributions caused by three different secondary optical elements.

6.2 Theory

6.2.1 Definition of incident angles

The AOI of light on the solar cell surface is described here using a spherical coordinate system based on the *zenith angle* \( \theta \), and the *azimuth angle* \( \varphi \). Due to the influence of the grid line shape and orientation, the cell performance will not only depend on \( \theta \) but also increasingly on \( \varphi \) for more oblique illumination. In this work, the influence of the azimuth angle \( \varphi \) on the cell performance is investigated by considering the AOIs in the two most distinctive planes across the cell. Firstly the plane that propagates in parallel direction to the grid lines (where \( \varphi = \varphi_p \)) is considered. In this plane the metal grid will not cause additional reflections or shading for any \( \theta \) compared to normal incidence. Secondly the plane that propagates in orthogonal direction to the grid lines (where \( \varphi = \varphi_s \), from the

Figure 6.1: a) Schematic representation of the device under test. The cell surface with front grid metallization and contact tabs. Note that the image is not to scale. The parallel (\( \theta_p \)) and the orthogonal (\( \theta_s \)) incident angles are shown. Figures b), c) and d) are 3D simulation exports that illustrate grid finger slopes of resp. 90°, 65° and 55° and a light source incident angle of 27°. The brightness gradients of the lines show the trace direction in between surface interactions. Photons travel from dark towards bright.
6.2. THEORY

Figure 6.2: Cross-section of a grid finger with an incident light beam under angle $\theta_s$. For the analyses the beam of light is divided into four fractions ($L_\alpha, L_\beta, L_t$ and $L_s$) and also the cell surface is divided in a number of fractions ($l_\alpha, l_\beta, l_\gamma, l_\theta, l_t,$ and $l_s$) that are defined in the figures, together with a number of geometrical parameters that determine the shape of the grid finger ($l_t, h$ and $\gamma$).

German *senkrecht*) is considered. In this case, any influence of the metal grid on the cell performance will be maximal. Zenith angles will be labeled $\theta_p$ and $\theta_s$, denoting the plane in which the AOI is varied. This is further illustrated in figure 6.1a.

6.2.2 Metal grid reflections

For increasing $\theta_s$ an increasing fraction of the incident light will interact with the sides of the metal grid, as illustrated in figure 6.2, potentially preventing it from reaching the semiconductor surface. Only if the sides of the grid fingers behave as perfect mirrors and are inclined perpendicular to the cell surface, can cell performance for the orientations $\theta_p$ and $\theta_s$ be expected to be equal for equal AOI, as the light would in this case simply reflect at the grid metal and reach the solar cell surface under the same angle as the directly incident light (figure 6.1b). If the sidewalls are not perpendicular to the cell surface, a fraction of incident light will reach the cell at different AOI, as shown in figures 6.1c and 6.1d. Figure 6.2 shows a schematic cross-sections of a grid finger with side walls inclined under an angle $\gamma$ with the cell surface. The blue arrows coming from the top represent the parallel incident light which is divided into four fractions: light that makes it to the underlying solar cell directly ($L_s$), light reflecting on the top of the grid finger ($L_t$), the light reflecting on the front side of the grid finger ($L_\alpha$) and, when present light reflecting on the back side of the grid finger ($L_\beta$), analogous to $L_\alpha$. The lowercase fractions $l_i$ are the virtual projections of $L_i$ on the solar cell plane such that $L_i = l_i \cos \theta_s$, for any fraction $i$. When $\theta_s \leq 90 - \gamma$, incident light is reflected on both sides of the grid finger towards the solar cell surface at angles $\alpha$.
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Figure 6.3: Roughness/scattering simulations. Surface roughness is assumed to cause scattered reflection of incident photons. Upon reflection at the grid finger, the surface normal is virtually altered with a fixed angle of a) 5°; b) 15°; and c) 25° in a random direction. To illustrate the ‘conical scattering’, a set of several reflecting photons is drawn on each image. In the performed simulations, a single photon is reflected into a single random direction on the edge of the cone – never within.

and β with the surface. However when \( \theta_s \geq 90 - \gamma \), a shadow is cast on the solar cell by the grid finger, represented by the difference \( l_\theta - l_\gamma \), decreasing the size of \( l_s \).

Also, in practice these side walls will be rough on a micrometer scale depending on the technologies applied to deposit the metal contact and/or define the lateral dimensions of the grid fingers. As a result, part of the light incident on the side walls will scatter away from the cell as illustrated in figure 6.3.

6.2.3 Short circuit current densities for oblique irradiation

With the increase of \( \theta \), the irradiance \( E_e \) on a tilted solar cell diminishes with \( \cos \theta \) where \( E_0 \) is the benchmark one-sun irradiation density of 1000W/m\(^2\) at \( \theta = 0^\circ \):

\[
E_e(\theta) = E_0 \cos \theta \quad (6.1)
\]

As a first order approach, the short circuit current density \( J_{SC} \) is commonly presented as proportional to \( E_e \):

\[
J_{SC} = C E_e \quad (6.2)
\]

where \( C \) is a constant which depends on the light spectrum and the external quantum efficiency (EQE) of the solar cell. This study demonstrates however, that variations in \( J_{SC}(\theta) \) cannot be explained solely by resulting variations in \( E_e(\theta) \) i.e. \( \frac{dC}{d\theta} \neq 0 \).

When observing \( C \) on the level of spectral irradiance (i.e., the irradiance per wavelength, \( \frac{dE_e(\lambda)}{d\lambda} \)), and including the AOI of incident illumination, it can be shown that:

\[
C(\lambda, \theta) = \frac{e \lambda}{h c} \frac{EQE(\lambda, \theta)}{dE_e(\lambda)} \quad (6.3)
\]
with $e$ the elementary charge, $c$ the speed of light, and $h$ the Planck constant. Here, incident irradiation density is translated into photon flux via division by the photon energy ($\frac{h}{\lambda}$). Substitution and integration over the spectrum of light yields an expression for $J_{SC}$ as a function of $\theta$:

$$J_{SC}(\theta) = C(\theta)E_e(\theta) = \frac{e \cos\theta}{h c} \int_{\text{spectrum}} \lambda \ EQE(\lambda, \theta) \ \frac{dE_0(\lambda)}{d\lambda} \ d\lambda \ \ (6.4)$$

In this study the angular dependency of $J_{SC}$ caused by other factors than $E_e$ is studied using J-V measurements for oblique incident light both parallel and orthogonal the front contact metal grid. In this way any influence of the metal grid on the current generation of the solar cells is decomposed from effects caused by the epitaxial cell structure and ARC. To account for the decreasing illumination at the cell surface under inclined angles, all measured data is normalized to $J_{SC}(0) \cdot \cos\theta$ via:

$$N_{J_{SC}}(\theta) = \frac{J_{SC}(\theta)}{J_{SC}(0) \cdot \cos\theta} \ \ (6.5)$$

Additionally, the transmission through the ARC (the applied ARC will be described in section 6.3.1 $T_{ARC}$, will diminish for increasing AOI. This parameter is calculated here based on the Fresnel equations for refraction of light, while interference effects are neglected, as they will have a minor impact. Again, these values are normalized to $T_{ARC}(0) \cdot \cos\theta$ via:

$$N_{T_{ARC}}(\theta) = \frac{T_{ARC}(\theta)}{T_{ARC}(0) \cdot \cos\theta} \ \ (6.6)$$

Because $N_{J_{SC}}$ and $N_{T_{ARC}}$ both represent a measure for the light entering the solar cell, they can be directly correlated to one another as long as $IQE(\theta) = IQE(0)$.

6.3 Experimental

6.3.1 Concentrator solar cell structure

In this study, the solar cells under test are 14.9 x 15.3mm² InGaP/Ga(In)As/Ge CPV solar cell assemblies, equipped with an ARC for use with glass SOE and front contact metal tabs, produced by AzurSpace. The cells feature silver front grid contact (see figure 6.1h) with fingers having inclined sides as is shown in the SEM image in figure 6.4. An average top width of 6μm, an average base width of 11μm and an average height of 5.7μm as was measured using optical microscopy. The heart-to-heart distance of the fingers is 125μm and the surface coverage by the grid is 8.8% excluding the busbars.

For uncoated solar cells, the transmittance of incident photons to the semiconductor material is heavily dependent on the AOI. A cell equipped with an ARC will show a different transmission curve, but generally these cells also show in-
Figure 6.4: SEM image of one grid finger of the device under test. The inclined sides of the finger are visible. From SEM and optical microscopy images it is determined that average dimensions for the fingers are: \( \text{topwidth} = 6 \mu m, \text{basewidth} = 11 \mu m, \text{height} = 5.7 \mu m, \) which makes the incline angle \( \gamma = 66.3^\circ \).

creased reflections at oblique AOI. The applied ARC on the studied cells consists of 65nm \( Al_2O_3 \) on 50nm \( TiO_x \).

6.3.2 Electrical characterization

J-V characterization of the solar cells is performed using an ABET technologies Sun 2000 Class A solar simulator, which provides homogeneous, parallel illumination over a 100 x 100 mm\(^2\) area. An Ushio 550W Xenon short arc lamp is used to approximate the AM1.5 spectrum. The setup is equipped with a Keithley 2401 sourcemeter and data acquisition is performed using ReRa Tracer3 software. The J-V curves of three cells have been measured in duplicate for AOI of 0 to 83°.

\(^2\)\( AlO_x \) and \( TiO_x \) have refractive indices of \( n_{AlO_x} \approx 1.4 - 1.6 \) and \( n_{TiO_x} \approx 3 \) respectively, according to SOPRA data. Based on partial reflections on the ARC layers as described by the Fresnel equations, neglecting the minor fraction of reflections at the top subcell (InGaP), a close match between calculation and experimental data is achieved.
The AOI is modified by pivoting the cell along the $\theta_p$ and $\theta_s$ orientations, the resp. angles quantified using a digital level with an error margin of 0.1°. During measurement, the solar cell is kept at 25 °C by water cooling.

### 6.3.3 Geometrical grid finger analysis

As will be shown in section 6.4, the AOI dependency of current generation is non-identical for $\theta_p$ and $\theta_s$ orientations. This difference must be explained by the orientation and geometry of the front metal grid.

The ratio of the different fractions of light $L_i$ and $l_i$ (as defined in section 6.2.2 and figure 6.2) is evaluated analytically for each $\theta$. Also the incidence angles of light for fractions $L_\alpha$ and $L_\beta$ on the cell surface will differ from that of $L_s$ for most $\theta$ due to the inclined sides of the grid finger; these angles are also determined. The experimental data from $J_{SC}(\theta_p)$ is used to determine $EQE(\theta)$ at the semiconductor surface, accepting/neglecting the minor error caused at the $J_{SC}(\theta_p)$ measurements for the fractions $L_\alpha$ and $L_\beta$ (at 2.13% each), where the AOI at the semiconductor surface is larger than that of the vast direct fraction, $L_s$.

Upon reflection at the grid finger, as a result of surface roughness, diffusion or reflective scattering may occur. For that reason, in addition to the analytical calculation, 3D ray tracing simulations are performed using Scientrace ray tracing software described in chapter 3, that allow the inclusion of reflective scattering at the grid finger surfaces. In these simulations, upon reflection at the surface, the surface normal about which reflection occurs is virtually modified with a static angle in a random direction determining the reflected direction. Note that changing the surface normal with angle $\Delta \psi$ results in a possibility cone with a side-to-side angle of $4\Delta \psi$. Typical reflection alterations are illustrated in figure 6.3.

### 6.3.4 SOE concentrator models

Common examples of SOEs are based on external reflection at coated surfaces or refraction, sometimes combined with full internal reflection, using transparent dielectrics. A basic configuration, as illustrated in figure 6.5a, is simulated to study the effects of refractive SOEs on the distribution of incident angles at the solar cell. A PMMA (Appendix A.1) Fresnel lens with a 40x40mm$^2$ square surface and a focal distance of 80mm is simulated as a primary optic. The simulated SOEs are given the optical properties of standard BK7 glass, further detailed in Appendix A.2.

The SOE shown in figure 6.5b is a truncated pyramid (TP). This is an example of a kaleidoscope-type glass SOE or F-RTP system as described by Mohedano and Leutz. The top and bottom squares are resp. 6x6mm$^2$ and 2x2mm$^2$. The height of the pyramid is 10mm. The base of the Double Truncated Pyramid (DTP),

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3 An open source, programmable, 3D geometric ray tracing application developed at Radboud University. Available online at http://scientrace.org/

4 The Scientrace ray tracing source files used in this study can be downloaded from https://github.com/JoePB/Cscientrace/tree/master/example_simulations/aoi_study_simulations
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Figure 6.5: Secondary optics models overview. All images show the same four traces with their distinct colors. A square Fresnel lens, the bold red area in figure a), projects the incident light at the top entrance of a BK7 glass SOE. The Truncated Pyramid (TP) in b) has a flat top, whereas the Double Truncated Pyramid (DTP) in c) has the same base structure, but is extended with a second short truncated pyramid on its top. The flat plate (FP) in d) is added to the plain cell for comparison with the TP and TPD SOEs. The FP SOE does not increase the optical concentration, but it does alter the incident angle at the cell.

6.3.5 SOE ray tracing

The PMMA Fresnel lens used to simulate the optical efficiency of the different COE configurations described above, is made up of 128 Fresnel planoconvex rings. The flat side of the lens points towards the light source. ‘Aspheric-like lens behaviour’ is obtained in the simulations by using spherical Fresnel rings with a radius optimised for each ring.

As shown in figure 6.5c is equal to that of the TP SOE, but on top a second, shorter, truncated pyramid is adjoined. The top and bottom squares of this second pyramid are resp. $2\times2\,mm^2$ and $6\times6\,mm^2$, but the height of this top truncated pyramid is only $0.4\,mm$. This geometry creates an angle of $90^\circ$ between the adjoining sides of the two pyramids, adding additional concentration by refraction to the basic TP shape as the edges normals are now directed at the cell center. For a quantitative comparison of incident angles at the cell, the reference setup shown in figure 6.5d has only a glass flat plate (FP) with the same optical properties as the TP and the DTP SOEs. In all setups, the focal point of the Fresnel lens is aimed at the topmost surface of the SOE.
The refractive properties of the PMMA cause the focal point of the lens to be wavelength dependent. The defined focal distance of the lens has only a single concentration wavelength ($\lambda_c$) for projection. $\lambda_c$ which will be determined to produce the best performance for a given spectrum using Scientrace. The spectrum used in the simulations is derived from the NREL ASTM G-173 Direct + Circumsolar spectrum [21], and can be found in the Scientrace repository on Github [245].

Other factors influencing system performance are the angular aperture of the sun, and errors in the optical components and/or their alignment. Instead of modeling roughnesses and errors of the optical components the angular aperture of the incident light ($\theta_s$) at the Fresnel lens has been increased from the sunlights default of $\theta_s = \pm 0.25^\circ$ up to $\theta_s = \pm 0.75^\circ$.

6.4. RESULTS AND DISCUSSION

6.4.1 Electrical performance

As a part the J-V curve measurements, short circuit current densities for the AOI ranges $\theta_s$ and $\theta_p$ are obtained using four-terminal sensing. Averages for $N_{Jsc}(\theta_p)$ and $N_{Jsc}(\theta_s)$ over six separate measurement series are plotted with their standard deviations in figure 6.6. The obtained experimental data for $N_{Jsc}(\theta_p)$ (continuous blue line in figure 6.6) drops below 1 when $\theta \geq 35^\circ$, indicating a loss of performance in the solar cell efficiency for illumination angles exceeding this point. The deviation increases severely as the AOI increases further; up to an efficiency loss of 40% for AOI of 83°. In a first order approximation of the amount of light actually entering the semiconductor volume, $N_{Jsc}(\theta_p)$ and the theoretical transmission through the ARC $N_{TARC}(\theta_p)$ (dashed blue line in figure 6.6) are compared. $N_{TARC}(\theta_p)$ is based on partial Fresnel reflections while reflections off the InGaP surface, and interference effects are neglected. A close overlap between the two curves is observed, indicating that the increased reflections at the ARC surface under oblique angles are the major cause of the noted efficiency loss.

For $N_{Jsc}(\theta_s)$ (continuous orange line in figure 6.6) an even stronger efficiency loss of an additional 18% at 83° AOI is observed, and also it starts from a lower AOI of approximately 20°. In this case the incident light beam is oriented orthogonal to the inclined sides of the grid fingers as shown in figure 6.2. Therefore as AOI increases, an increasing fraction of light will fall on these side walls as opposed to directly on the ARC. Reflections off these inclined surfaces will cause this increasing fraction of light to reach the solar cell surface at an even more oblique angle, as is further detailed in Appendix B. The cumulative effects of an increasing fraction of light reaching the cell at angles steeper than the set AOI is a cause for the noted difference in cell efficiency for $\theta_p$ and $\theta_s$ illumination orientations. Yet when these effects are taken into account in the calculation of the theoretical transmission

Note that the cells under test are equipped with an ARC for use with a glass SOE while measured in air. However if a glass cover or SOE is placed in front of the cell, similar Fresnel reflections would occur on the air-glass interface, yielding similar loss of performance in the solar cell.
Figure 6.6: Measured short circuit current densities and calculated/simulated transmission of light through the ARC as a function of $\theta_p$ and $\theta_s$. All data is normalized to their value under normal incident light and divided by $\cos \theta$ to correct for the decreasing light intensity under inclined angles. The resp. measured $J_{SC}$ values are represented in continuous lines by the average value over 6 separate datasets (3 different cells, 2 measurements per cell) with vertical bars showing the standard deviation. The dashed lines represent the transmission through the ARC based on Fresnel reflections, when reflections off the grid metal is respectively neglected (blue) or included (red).

Through the ARC for orthogonal beam orientation, $N_{TARC}(\theta_s)$ (dashed red line in 6.6), no satisfactory overlap with $N_{JSC}(\theta_s)$ is found for AOI beyond 30°. The calculation displays a fast drop at this point that is not noted in the measurements. In these calculations the grid fingers were treated as perfect reflectors, and the fast drop occurs when the increasing fraction $l_\alpha$ enters the semiconductor surface at an incident angle of 80°. This increases to horizontal reflection (90°) at $\theta_s = 40°$. At this point, this fast drop in the $N_{TARC}(\theta_s)$ curves ends, since $\alpha(\theta_s = 40°) = 90°$, hence the entire reflected fraction is lost at $\theta_s \geq 40°$. As is apparent, in a real solar cell these grid fingers will not be perfect mirrors.

### 6.4.2 Geometrical grid finger analysis

As shown in figure 6.6, the fast drop in $N_{TARC}(\theta_s)$ is absent in the measurements for $N_{JSC}(\theta_s)$. Because in a real device the grid fingers are rough on a micrometre scale (see also figure 6.4), reflective scattering at the grid will take place. Here, we
introduce this scattering into the analysis in an effort to explain the discrepancy between the calculated \( N_{\text{ARC}}(\theta_s) \) and experimentally obtained \( N_{J_{\text{SC}}}(\theta_s) \) values. As these analyses are too complex to perform analytically they are performed using 3D ray tracing simulations. To visualise the equivalence between the analytical calculations and ray tracing, results from simulations without scattering (\( \psi = 0^\circ \)) are included figure 6.6 as \( N_{\text{ARC, sim}}(\theta_s) \). This clearly shows that the results of the simulations perfectly match the analytic calculations \( N_{\text{ARC}}(\theta_s) \).

Figure 6.7a shows the simulated normalized transmission \( N_{\text{ARC, sim}}(\theta_s) \) for various grid finger slopes \( \gamma \), as a function of \( \theta_s \). For increasing \( \gamma \), the transmission at near normal incident irradiation (0 - 20 \(^\circ\)) decreases. That occurs because the light fractions \( L_\alpha \) and \( L_\beta \) on the sides of the grid fingers, become smaller for increasing \( \gamma \) in favour of a larger fraction \( L_t \) on the top of the grid fingers, which is inherently lost. For \( \gamma = 45^\circ \) the transmission first increases with \( \theta_s \) before going through an optimum. This is explained as at this grid finger inclination, at \( \theta_s = 0^\circ \) the entire light fractions \( L_\alpha \) and \( L_\beta \) reflect horizontally and are lost, while for larger \( \theta_s \) part of the reflection is pointed towards the cell surface. For \( 45^\circ \leq \gamma \leq 90^\circ \) all normalized transmission curves show the previously discussed fast drop. With increasing \( \gamma \) the fast drop occurs at higher \( \theta_s \) and becomes less pronounced as it occurs at an increasingly steeper part of the curve. Again, the location signifies the AOI for which \( L_\alpha \) undergoes horizontal reflection with respect to the cell surface and is therefore lost.

The studied concentrator solar cells have have grid lines with \( \gamma = 65^\circ \). In figure 6.7b normalized transmission simulations for a solar cell with this grid configuration are compared to the experimentally obtained \( N_{J_{\text{SC}}}(\theta_s) \). Each curve represents a different degree of scattered reflections at the grid metal, quantified by \( \psi \) as described in section 6.3.3. The figure shows that the introduction of scattered reflections smooths out the AOI dependent transmission curve, rapidly eliminating the fast drop.

For \( \psi = 25^\circ \) the simulated transmission closely matches the experimentally obtained \( N_{J_{\text{SC}}}(\theta_s) \) data, indicating that the observed differences between \( J_{\text{SC}}(\theta_s) \) and \( J_{\text{SC}}(\theta_p) \) can be fully explained by scattered reflection from the sloping sides of the gridfingers. Figure 6.7 also shows that enhanced scattering is beneficial for the transmission of light to the solar cell as it salvages part of the increasing fraction of light that would otherwise reflect away from the solar cell for oblique illumination angles.

### 6.4.3 SOE ray tracing simulations

The optical properties of three model secondary optics have been investigated, in order to compare the benefit of using a SOE to the introduced loss of performance caused by the increased average illumination angle of the solar cell. The optical efficiency \( \eta_{\text{opt}} \) of the SOE concentrator models is determined for the AM1.5 spectrum as a function of the concentration wavelength (\( \lambda_c \), figure 6.8a) using Sc inventrace. This analysis shows that the FP model is most susceptible to dispersion related losses, while the concentrating SOEs (TP and DTP) are barely influenced.
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Figure 6.7: (a) Transmission of light through the ARC for several grid finger slopes $\gamma$, as a function of the orthogonal incident angle ($\theta_s$) as obtained by ray tracing simulations; and (b) normalized simulated transmissions and measured short circuit current density as a function of the orthogonal incident angle ($\theta_s$) for several values of the scattering parameter $\psi$.

In favour of the short wavelength photons in the spectrum, that are usually limiting the performance of concentrator solar cells, and as a compromise for all SOE models, $\lambda_c$ is defined at 650nm in all of the following simulations. The benefit of the concentrating SOEs is also illustrated by figure 6.8 where $\eta_{opt}$ is determined as a function of the angular aperture of the incident light. The TP and DTP SOEs still are able to function well at lesser beam qualities.

The dashed line shows that when a FP is employed, in order to reach a similar optical efficiency as when using a TP SOE, the angular aperture should be reduced by a factor of 2.8. A very similar result has been found for a Compound Parabolic Concentrator (CPC) by Victoria et.al. as plotted in their figure 2 [243]. Although the TP and the CPC have different base geometries, in many aspects they behave similar. It should be noted that the acceptance angle described in the referred study is not the same as the angular aperture in this study, but both variables can readily be used to describe the sensitivity/robustness of the optical system. In addition, the referred simulation does not include dispersion effects from the $\eta_{opt}$, the fraction of the light that is emitted to reach the surface of the solar cell, cell reflection and performance are excluded.
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Figure 6.8: a) The optical efficiency ($\eta_{\text{opt}}$) with the different SOEs as a function of the lens concentration wavelength ($\lambda_c$). Dispersion of the incident AM1.5 spectrum by the PMMA Fresnel lens causes the focal point to shift as a function of the wavelength. Here, the focal point is always kept at the top of the SOE. Additional losses are due to the angular aperture of the incident light of $\pm 0.75^\circ$ and partial reflections at the lens (2x) and SOEs (1x); b) $\eta_{\text{opt}}$ as a function of the angular aperture ($\theta_\alpha$) of the incident light for different SOE’s. The dashed line shows the value of the FP plot where $\eta_{\text{opt}}$ is plotted against $\theta_\alpha/2$, suggesting a virtually increased acceptance angle of 2.8x.

primary optics nor do the dimensions of the used optics match. Despite these differences in setup, the improvement of the system by both SOEs show clear similarities. For the CPC optic an increase in angular transmission by a factor of 3.33 was found for 90% optical efficiency, and 2.85 for 80% optical efficiency, compared to a steady increase of a factor 2.8 for the TP optic in the current study.

Figure 6.9 shows the the optical efficiency of light on the solar cell as a function of the incidence angle for the three SOE configurations. As such, it reflects the distribution of AOIs for incident photons for each configuration, and shows how the use of the SOEs alters the AOI distribution at the cell surface. Here, the "overall angle" represents $\theta$ for a photon incident at the cell surface regardless of its orientation $\varphi$. Conversely in the "plane angle" graph $\theta$ is deconvoluted into its projections $\theta_p$ and $\theta_s$. Due to rotational symmetry in the studied SOEs, these distributions overlap completely. The figure shows that while for the FP system $\theta$ remains at near-normal incidence, for the TP and DTP configurations the average $\theta$ increases as light incident at the cell surface in the 20-50$^\circ$ range is introduced. Note that $\theta$ in the 20-30$^\circ$ range arise due to a single internal reflection in the SOE, while higher values of $\theta$ are caused by two or more internal reflections. Therefore the angular distributions are integrated for these intervals seperately and shown
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Figure 6.9: The angular optical efficiency, $d\eta_{opt}/d\theta$, as a function of $\theta$ and $\theta_p$, for the basic concentrator model (standard conditions: $\theta_\alpha = \pm 0.75^\circ$, $\lambda_c = 650\text{nm}$). The top figure plots the angular optical efficiency against the ‘overall incident angle’, whereas the bottom figure uses the incident angle decomposed in ‘plane angles’ $\theta_p$ and $\theta_s$. The pink lines separate different incident angle ranges.

Figure 6.10: The optical efficiency integrated over the ranges as denoted in figure 6.9, showing both the ‘overall angle’ integrals and those of the ‘plane angle’ decompositions.

in figure 6.10, Here, we show that although the average AOI is greatly increased when a SOE is employed, this is offset by an increase in optical efficiency exceeding 10%. However, it should be considered that $30^\circ$ angle in a BK7 medium ($n \approx 1.5$) equals a $49^\circ$ angle in vacuum ($n \equiv 1.0$), whereas $40^\circ$ in BK7 equals $75^\circ$ in vacuum ($\alpha_{vac} = \sin^{-1} n_{BK7} \alpha_{BK7}$). Especially for the latter, grid orientation related losses can become over 10%. Therefore if an asymmetric CPV system is being considered, or inhomogeneous primary optic illumination is expected, this
effect should be taken into account. For instance when using a regular straight grid the cell should be oriented carefully with respect to the optics to minimize these grid-induced optical losses. Alternatively, more advanced grid patterns may also provide a way to minimize these effects [246].

6.5 Conclusions

Using the normalized current density as a parameter, the electrical performance of TJ CPV solar cells for varying angles of incident illumination has been studied in detail. While the $\lambda$ in $EQE(\lambda, \theta)$ (eq. 4) is almost entirely related to semiconductor properties, this study shows that $\theta$ can be explained almost entirely by the ARC and the grid contact configuration and morphology. During experimental testing, the solar cells perform considerably, and increasingly worse as illumination becomes more oblique. A performance reduction of up to 58% has been determined for an AOI of 83°. This loss of performance is mainly attributed to the optical properties of the ARC because calculated AOI dependent transmission through this coating correlates excellently with the observed AOI dependent cell performance. A second loss mechanism has been identified and attributed to the front contact grid by propagating the AOI orthogonal to the grid fingers. In this case an increasing fraction of illumination will interact with the sides of the grid metal for increasing AOI. Therefore the specific shape and orientation of the grid fingers become an increasingly important source of cell performance loss for oblique illumination. As a consequence, an additional loss in current generation of up to 18% has been attributed to the front grid. This loss of performance cannot be fully explained by increased Fresnel reflections off the ARC for the fraction of incident light that reflects off the grid. Ray tracing simulations however, demonstrated that the additional loss in electrical performance can be fully explained by scattered reflections off the grid fingers, which were shown to exhibit a rough surface on a microscopic scale. Because of this, the electrical losses in the solar cell at oblique angles would actually be higher if the sides of the grid fingers are perfectly smooth.

The optical properties of three model SOEs have been investigated, in order to compare the benefit of using a SOE, to the introduced loss of performance caused by the increased average illumination angle of the solar cell. The optical efficiency of the system as a function of photon wavelength has been shown to be significantly higher for the studied truncated pyramid SOEs compared to a flat glass plate, with more than 15% absolute increase in optical efficiency for each wavelength. Also a strong increase in angular acceptance of a factor of 2.8 has been shown for the TP SOEs. On the other hand the SOEs introduce illumination angles in the 20-50° range, while simultaneously diminishing the fraction of near-normal (0-10°) illumination compared to the glass plate. When all three of these factors are taken into account, both TP and DTP SOEs display an optical efficiency that exceeds that of the glass plate by more than 10%, which clearly illustrates the benefit of using a SOE in a lens based CPV system. In the current study this was demonstrated
for a system with a circular Fresnel lens primary optic, and SOEs that have 90°
rotational symmetry. In CPV systems where either optic is not symmetric (i.e.
parabolic trough and/or prism based systems) however, the performance dimin-
ishing effect of the non-normal illumination may be greater due to the influence of
the front grid as demonstrated in this work. Therefore grid orientation or design
with respect to the optical system should be taken into account and optimized in
such systems. It should also be noted that the degree of electrical performance loss
introduced by the secondary optics is wholly dependent on the optics geometry.
It can be expected that more elaborate secondary optics increase the average cell
illumination angle more strongly than simple ones. It is therefore advisable to
evaluate the cost and benefit of using any specific secondary optical element in a
concentrator design using the methods described in this work.

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6.6 Appendices

A: Refractive indices for simulated volumes

The photon wavelength ($\lambda_{\mu m}$) is defined in micrometers for these equations.

**Poly(methyl methacrylate), PMMA**

$$n = 1.478 + \frac{4.53 \times 10^{-2}}{\lambda_{\mu m}^2}$$

**BK7 glass**

$$n^2 - 1 = \frac{1.03961212 \lambda_{\mu m}^2}{\lambda_{\mu m}^2 - 0.00600069867} + \frac{0.231792344 \lambda_{\mu m}^2}{\lambda_{\mu m}^2 - 0.0200179144} + \frac{1.01046945 \lambda_{\mu m}^2}{\lambda_{\mu m}^2 - 103.560653}$$
B: Calculation of orthogonal incident transmission

The surfaces \( l_\alpha \) and \( l_\beta \) are virtually shadowed / reflected by the grid finger slopes:

\[
l_\theta = h \tan(\theta_s), \quad l_\gamma = \frac{h}{\tan(\gamma)}
\]

\[
l_\alpha = \begin{cases} 
  l_\gamma + l_\theta, & \text{if } l_\gamma + l_\theta < l - l_t \\
  l - l_t, & \text{otherwise}
\end{cases} \quad (6.7)
\]

\[
l_\beta = \begin{cases} 
  l_\gamma - l_\theta, & \text{if } \theta_s + \gamma < 90^\circ \\
  0, & \text{otherwise}
\end{cases} \quad (6.8)
\]

The incident angles with the semiconductor surface normal after geometric reflections upon the grid sides:

\[
\beta = 180^\circ - \theta_s - 2\gamma \quad (6.9)
\]

\[
\alpha = 180^\circ + \theta_s - 2\gamma \quad (6.10)
\]

The length of the semiconductor area in between the grid fingers that is directly irradiated:

\[
l_s = l - (l_t + l_\alpha + l_\beta) \quad (6.11)
\]

The total orthogonal transmission based on the incident fractions and the resp. cold ARC transmissions:

\[
T_{ARC,s}(\theta_s) \equiv \frac{l_s}{l} T_{ARC}(\theta_s) + \frac{l_\alpha}{l} T_{ARC}(\alpha) + \frac{l_\beta}{l} T_{ARC}(\beta) \quad (6.12)
\]
6.6. APPENDICES
Chapter 7

Partially Shaded Building-Integrated CPV

Abstract

Recently adopted energy efficiency policies in the EU induce a movement towards energy-neutral buildings. Building integrated photovoltaics technology connects with this ambition, as aside from the generation of electrical energy, it allows additional benefits such as heat generation, or daylight regulation by transmission of diffuse sunlight through transparent parts of the system. In this study three Concentrator Photovoltaic (CPV) system configurations that allow for the construction of semi-transparent building façade elements are investigated outdoor. The systems are a Fresnel lens based concentrator, a novel flat planar optic concentrator, and a 4x4 panel of these flat optics. The flat optic has no air cavity to account for optical focal depth which is highly beneficial when integrated in a window. In particular the energy production of the systems when partially shaded is investigated, as adjoining systems will move behind one another during sun tracking, because the optics spacing must be small to achieve good daylight regulation. The planar optic concentrator displays similar performance as a Fresnel lens based concentrator of similar concentration. For a multi-receiver panel, shading introduces a loss of performance ranging from 7 to 12% which is attributed to electrical interconnection as individual receivers do not suffer this loss.

1The study presented in this chapter is based on
and
7.1 Introduction

Forty per cent of the European energy consumption is attributed to buildings [136]. The European Union actively adopts energy efficiency policies to reduce this amount and has defined in the Directive on the Energy Performance of Buildings the ”20-20-20” objectives: 20% decrease in greenhouse gas emissions, 20% share of renewable energy and 20% improvement in energy efficiency by 2020. Building-Integrated Photovoltaic (BIPV) systems address these goals perfectly. Among BIPV technologies, Building-Integrated Concentrating Photovoltaic (BICPV) systems possess additional features that make them particularly interesting for building integration, such as the possibility of heat generation [149], or daylight regulation [150]. Also the replacement of expensive semi-conductor cell area by cheaper and more environmentally friendly concentrating optics can make for a more viable system in terms of both cost and environment [247]. On the other hand it should be noted that the light-to-electricity efficiency is generally smaller for BICPV systems because of optical losses, uncollected diffuse irradiation etc. However, in the particular case of window integrated CPV, this uncollected insolation can be transmitted inside, providing natural lighting while converting the blinding direct component into electricity. In recent years, there has been an increase in BICPV for integration in either the roof or the façade. Chen et al. designed a diffusive solar cell window which transfers solar radiation to solar cells at the edge of the window [151]. Aste et al. show a new generation luminescent solar concentrator (LSC) for façade integration. They show a better energy performance ratio for the LSC compared with standard PV modules [152]. Gomes et al. studied shading in asymmetric Photovoltaic Thermal (PVT) collectors caused by oblique solar angles and found that impact by shading can be reduced by transparent end gables, as well as by reducing the cell area [149]. Sharma and Mallick discuss a dielectric compound parabolic concentrator suited for building integration in higher latitude locations. Real time outdoor performance of the concentrator is compared to a non concentrating flat plate and the superior output power of the concentrator is shown both for sunny and rainy days [122]. Zacharopoulos et al. have shown that at higher sun tilt angles, non-imaging dielectric linear concentrators for façade integration collects far more solar radiation than a flat plate PV of the same area [153]. Baig et.al. discuss several low concentration systems for building integration. Emphasis is placed on non-uniformity in illumination and temperature across the PV as well as detailed modeling and performance analysis of the systems [248, 250]. Chemisana et al. designed a holographic concentrator for building integration that protects the solar cell from overheating as the infrared is not concentrated in this setup. They find that the use of the concentrator increases the efficiency of the PV cell by 3%. Also they designed a façade integrated PVT collector based on two reflecting strips and stationary PV. They show the increased performance of this system compared to reference [251, 252]. Voarino et al. introduce a CPVT system for roof incorporation that relies on a prism combined with a parabolic mirror that rotate separately to track the sun instead of using a heavy and bulky tracking system [157]. Many of these systems
CHAPTER 7. PARTIALLY SHADED BUILDING-INTEGRATED CPV

Figure 7.1: A representation of a simple concentrating system. Direct illumination (red) is concentrated to the PV cell and converted into electrical energy, while diffuse illumination (green) is not concentrated and passes by the system. Here we seek to use this characteristic to employ the CPV as a façade integrated daylight regulation system; removing the harsh direct component of the illumination while allowing the diffuse light inside the building.

are designed to be stationary with low concentration, while others are designed for high concentration. Higher concentration systems have a low acceptance angle, thus are more restrictive towards the use of the diffuse part of the insolation and often require sun-tracking to function properly, yet they also offer the greatest reduction in cell area which allows for good cost-efficiency. Additionally, because the bright direct fraction of light is concentrated to the PV while diffusive light is not concentrated in high concentration setups (as detailed in figure 7.1), these offer the best opportunity to include a daylight regulation functionality, which will be the focus of the systems discussed in this work.

In this paper we study the concept of integrating CPV in a building skin to simultaneously act as an energy generating façade, and a means of daylight regulation. This concept entails the removal of the harsh direct illumination by the system to be converted into energy, while allowing natural lighting of the building interior, as diffuse light passes through transparant parts of the system. Three model CPV systems are considered in this context. Firstly a common Fresnel based system
7.2 Experimental

7.2.1 Device description

The first device under test, shown in figure 7.2, features a 10cm x 10cm Fresnel lens made of PMMA as a concentrating optic, which has a focal depth of 10cm. A 10mm x 10mm TJ cell mounted on a ceramic printed circuit board (PCB) and equipped with a bypass diode is placed in the lens' focal point, giving the system a geometric concentration factor of 100. Secondly a planar optic receiver is investigated, which consists of a 4cm x 4cm planar focusing optic, a 1.3mm x 1.3mm TJ III-V cell, a bypass diode, a copper heat sink and integrated wiring. The benefit of using this type of receiver compared to more regular optics is that...
Figure 7.2: The tested Fresnel lens based system. Left shows a photograph of the system whereupon the lens and receiver are mounted for outdoor tracked measurement. Right the structure of the receiver integrated with the lens.

Figure 7.3: The tested multi-receiver panel. Left a photograph of the panel. Right a representation of the electrical interconnection of the system where each receiver is represented by a photodiode in parallel with a bypass diode. Sets A - D consist of 4 parallel connected receivers each. The sets are in turn interconnected in series.

The optical system does not have an air cavity to account for the focal distance of the optics and thus is flat. This significantly enlarges its potential for utilization in building-integrated systems. The receiver has been described elsewhere [253] and will not be further detailed here. The receiver has a high geometrical concentration factor of 920.

Finally a 16 receiver panel of these planar optics is investigated, which is shown in figure 7.3. It consists of a 4 x 4 array of planar optic receivers with integrated solar cell assembly, which are interconnected in 4 parallel strings that are in turn connected in series. In application, multiple panels will be enclosed in a transparent glass enclosure. Figure 7.4 shows a schematic representation of such a setup consisting of nine panels with \( w \) and \( h \) the width and height of a panel respectively, and \( d_{hor} \) and \( d_{vert} \) the horizontal and vertical heart-to-heart distance between pan-
Figure 7.4: Schematic representation of a nine panel system in a building façade oriented due south. The shadow cast on the panels by the building (black) and other panels (gray) is shown for different tracking positions. The sun position relative to the building is a) perpendicular; b) elevation 30°, azimuth 0°; c) elevation 30°, azimuth -30°; and d) elevation 30°, azimuth -60°. Note that azimuth is defined with respect to the south, and elevation of 90° is defined as directly overhead.

The system layout is optimized primarily with daylight regulation in mind, in such a way that apparent full coverage of the façade is achieved at any time during the day as a function of the sun position. Thus, if sunlight is incident from the figure can also be noted that in application, the system needs a space in front of the window to enable mechanical tracking.
perpendicular to the façade, the individual panels are located side by side, fully covering the façade without covering each other (thus $d_{\text{hor}} = w$ and $d_{\text{vert}} = h$). The system tracks the sun by tilting and rotating the individual panels. As can be seen from figure 7.4b, c, and d, during tracking a panel may be shadowed by the building (black) or another panel (gray). The shadowing by the building around the semi-transparent system is highly dependent on the way it is integrated with the façade and becomes less important as the system becomes increasingly larger. However, shading by adjacent panels is an intrinsic phenomenon in the above described concept. Therefore its influence on the electrical output of the system will be evaluated in detail in this study.

### 7.2.2 Measuring procedure

In order to determine the electrical energy production of the three systems, outdoor current-voltage (I-V) measurements have been performed to closely approximate actual operating conditions. Aside from investigating the electrical performance of the systems, also shadowing experiments have been performed. A procedure similar to that of Rodrigo et.al. [235] has been used for the shadowing experiments. Although they used high concentration Fresnel based systems with secondary optics as opposed to our low concentration Fresnel lens system and high concentration flat plate systems, the primary optic shadowing procedure is applicable in all cases. Opaque metal plates were slid incrementally over the systems, causing a rectangular shadow shape. Of course, as can be seen from figure 7.4 in practice not only rectangular shadow shapes will be caused in the panels. Depending on the tracking position also diagonal shadows will be present. However, due to symmetry in the studied systems, application of a horizontal resp. vertical shadow on the optics allows for deconvolution of different sources of current generation loss. Data was collected on the performance of the entire panel, as well as the individual receivers. The latter was achieved by blocking all other receivers of the panel with an opaque metal plate. This approach is possible because of the integrated bypass diode in each receiver, which allows current to bypass a non-functioning cell. This was done on the single-receiver level in order to make a pure comparison between the work on a Fresnel lens based concentrator and the planar optic receiver considered here, as well as on the panel level to investigate the total device performance.

Outdoor urban I-V characterization of the panel was performed at the Applied Materials Science group of the Radboud University (Nijmegen, The Netherlands 51.82°N; 5.87°E). The setup is shown in figure 7.5. The panel was enclosed in a metal harness so it could be mounted on an EKO STR 22 Sun Tracker. The harness features grooved slots for the feeding of metal plates for controlled in situ shadowing of the panel. Ambient temperature and humidity are obtained by Campbell Scientific CR1000 measurement and control datalogger. Wind speed is measured by RM Young RM05103 wind meter. Global, horizontal and tracked insolation are monitored by EKO 402 pyranometers. Finally direct normal illumination (DNI) is measured with a Hukseflux DR02 pyrheliometer. In-field I-V characteristics are acquired using a Keithley 2601 source metre. I-V curves contain
7.2. EXPERIMENTAL

Figure 7.5: The outdoor measurement setup with the multi-receiver flat plate system attached to the tracker. Also shown are the pyrhiometer and pyranometers.

data on the parameters used to determine the solar cell quality and performance. Here, the considered parameters are the generated current in short-circuit conditions \( I_{SC} \), cell potential in open circuit conditions \( V_{OC} \), and the current and potential corresponding to maximum power output under load \( I_{MP} \) and \( V_{MP} \) respectively. From this and the DNI the maximum generated power:

\[
P_{MP} = I_{MP} \cdot V_{MP}
\]

(7.1)

and cell efficiency:

\[
\eta = \frac{P_{MP}}{DNI}
\]

(7.2)

are calculated. Experimental I-V data retrieval and processing are performed with ReRa Solutions Tracer 3 software. As multi-junction concentrator solar cells are influenced by changes in irradiance, cell temperature and incident light spectrum \[261][263\], measurements are performed in such a way as to keep these factors constant. For this purpose, measurements were performed on very clear days around noon so air mass, clouds, turbidity and precipitable water vapour can be considered stable during the measurements. Therefore the spectral distribution was considered constant across each measurement set taken in a limited time frame of maximally 30 minutes. Even so, cell temperature will strongly decrease with shading because the irradiance across the solar cell is reduced. Therefore, between
Figure 7.6: Electrical power output of the Fresnel lens system for measuring conditions: DNI = (0.987 ± 0.007)kW/m², T = (15.2 ± 0.3)°C, v_{wind} = (1.6 ± 1.0)m/s. a) I-V curves for different shading factors show that $I_{SC}$ drops linearly as a function of shading factor while $V_{OC}$ shifts slightly, in accordance with the relative illumination; and b) normalized maximum power as a function of shading factor. The dotted line represents the best linear fit through the data points, starting at $NP_{MP} = 1$

I-V measurements the opaque plate is removed so the cell is fully illuminated. In order to keep cell temperature constant across the measurement series, curves are measured rapidly after the plate is replaced.

7.3 Results

7.3.1 Fresnel lens system

Figure 7.6 shows the electrical performance of the Fresnel lens based system for various shadow fractions $s$. The I-V curve for an unshaded lens (top blue curve in figure 7.6a) shows an $I_{SC}$ of 819mA at the specified atmospheric conditions. For 1-sun illumination (1000W/m²) this would amount to a short-circuit current $I_{SC,Fresnel}^{sys}$ of 830mA. From this and the cell’s short circuit current measured in the lab: $I_{SC,Fresnel}^{cell} = 13.4$mA, the concentration factor of the Fresnel lens system is determined via:

$$C = \frac{I_{SC,Fresnel}^{sys}}{I_{SC,Fresnel}^{cell}}$$  \hspace{1cm} (7.3)

which yields $C = 62$ for this system. Given the geometric concentration factor of 100 for this system, the concentration efficiency of the system can be defined as:

$$N = \frac{C}{C_{geo}}$$  \hspace{1cm} (7.4)
which is 0.62 for this system. The lens has been shaded for \( s = 0, 0.1, \ldots, 0.8, 0.9 \) and I-V curves for each increment are shown in figure 7.6a. For increasing shading factor, the effective illumination of the lens and thus the cell becomes less, and the data show the accompanying drop in generated current by the solar cell to be linear and proportional, in a very similar fashion as is described in [235] for a Fresnel lens system featuring a secondary optic element (SOE). Maximum power values, normalized to the unshadowed case \( NP_{MP} \), are shown in figure 7.6b. Here we also find a linear decrease in maximum power for increasing shadow factor, similar to what is described for a higher concentration Fresnel system with SOE. From the fit, a loss of performance in the order of 4% is noted here, while for a system that includes a SOE and a heat sink this amounts to 0%. This difference can be attributed to the homogenizing properties of the SOE, as the other measuring conditions are similar for both systems.

### 7.3.2 Single planar optic concentrator

The performance of individual planar optic receivers has been studied without disassembling the panel, by covering 15 of the 16 receivers of the panel with an opaque plate, to determine variations in performance needed for understanding the total I-V curves of the entire system as will be described in section 7.3.3. The I-V curve for an unshaded receiver (top blue curve in figure 7.7a) shows an \( I_{SC} \) of 129mA at the specified atmospheric conditions. For 1-sun illumination (1000W/m\(^2\)) this would amount to a short-circuit current \( I_{SC,planar} \) of 156mA. From this and cell specifications for the short circuit current \( I_{cell,planar} = 0.24 \text{mA} \),
the concentration factor of the planar optic receiver is determined via equation (7.3) - where the "Fresnel" subscripts are exchanged for "planar" - to be 647 for this particular receiver. When similar calculations are performed for all receivers, C values in the range of 610 to 710 are found. Via equation (7.4) this amounts to a concentration efficiency for the planar optic system of $N = [0.66 - 0.77]$. Therefore the functionality of this flat plate concentrator may be considered at least equal to a common Fresnel lens based system.

Additionally, to investigate the sensitivity of the planar optic concentrator to inhomogeneous illumination, the unblocked receiver has been incrementally shaded by a metal plate. Shading factors of $s = 0, 0.125, 0.250, ..., 0.750, 0.875$ were investigated. Typical I-V data for one receiver are shown in figure 7.7a. For increasing shading factor, the effective illumination of the receiver becomes less, and the data show the accompanying drop in generated current by the solar cell to be linear and proportional, in a very similar fashion as both the low concentration Fresnel lens based system discussed above, and high concentration Fresnel systems described in [235]. Maximum power values, normalized to the unshadowed case $NP_{MP}$, are shown in figure 7.7b. Here we also find a linear decrease in maximum power for increasing shadow factor. Therefore we conclude that the planar concentrating optic handles inhomogeneous or partial illumination very well, and therefore it is suitable for use in the same conditions in which a Fresnel optic of similar concentration factor can be used.

### 7.3.3 Flat plate panel

Figure 7.8 shows the I-V curves of the entire 16 receiver panel, as shown in figure 7.3 during outdoor measurement. The curves feature four distinct steps in the current for increasing voltage. These arise because of the parallel interconnection of the receivers, in combination with a slight current mismatch between the individual solar cells. As the panel consists of four sets of four cells connected in parallel, each set generates a total current equal to the sum of its constituent cell currents, which for the panel under investigation varies slightly between the sets. The total generated current for any given voltage is then governed by the series interconnection between sets. Therefore at low voltage we measure the current of the best performing set, while at higher voltage the current is limited by weaker performing sets, resulting in the stepped shape of the total I-V characteristic with steps appearing at the $V_{OC}$ of a set - or the sum of $V_{OC}$’s from multiple sets. During operation the system is kept at its maximum power point ($P_{MP}$) so electricity generation is maximum at all times. For an unshaded system $P_{MP}$ occurs at 10.54V. As can be seen from figure 7.8, this means that the system operates at a current limited by the set that shows the least performance, as can be expected from the series connections of the sets. During testing the panel showed an average maximum power output of $4.4 \pm 0.1W$ and a conversion efficiency of $24 \pm 0.6\%$. The interconnection between several components in the BICPV panel also has consequences for the electrical output if shading of the system is present. Due to the presence of both parallel and series interconnections, various shapes of shad-
7.3. RESULTS

Figure 7.8: Electrical output of the panel for different shading factors along the line of the parallel interconnections. Measuring conditions: DNI = (0.794 ± 0.003) kW/m², T = (27.0 ± 0.4) °C, $v_{wind} = (2.7 ± 1.0)$ m/s. **a)** I-V curves for different shading factors show that the $I_{SC}$ drops quite linearly as a function of shading factor while $V_{OC}$ remains roughly constant, as can be expected for diminishing illumination; and **b)** normalized maximum power as a function of system shading. The dotted line represents the best linear fit through the data points, starting at $NP_{MP} = 1$.

ows will have different effects on the performance of the panel. To investigate this effect, the panel was incrementally shadowed in two directions; along the parallel connections, and along the series connections. Sixteen increments in shading have been applied, so that each set of adjoining receivers is shaded $s = 0, 0.25, 0.50, 0.75, 1$. The I-V data for shading the panel along the parallel direction are shown in figure 7.8a, where each successive downward step represents an increase in shading. The data show a linear decay in generated current as a function of increased shading, which is expected as each set is shaded to an equal amount. Figure 7.8b shows that the generated maximum power also decays in a linear fashion across almost the entire series, indicating that $V_{MP}$ remains roughly constant, unless the panel is nearly entirely shaded, allowing straightforward maximum power point (MPP) tracking in the application.

The I-V curves for shading along the series direction are shown in figure 7.9a. Here, a more severe effect is observed. In this case one set is shaded fully before the next receives any shading, so the current level of individual steps in the I-V curve decreases consecutively as sets are excluded from contributing to the current generation. This not only leads to a decrease in $P_{MP}$, but also in $V_{MP}$ for increasing shading factors as shown in figure 7.9b. Furthermore, the maximum power output decreases in a stepwise fashion and more strongly than would be expected from a linear dependency. A linear fit through the data points indicates that on average, the difference between the observed power output and a linear
Figure 7.9: Electrical output of the panel for different shading factors along the line of the series interconnections. Measuring conditions: DNI = (0.809 ± 0.002) kW/m², T = (27.2 ± 0.3) °C, v_{wind} = (2.4 ± 0.8) m/s. 

a) I-V curves for different shading factors show that the $I_{SC}$ drops quite linearly while $V_{OC}$ remains roughly constant, unless a parallel string is completely blocked, at which point the $V_{OC}$ drops proportionally, causing a quite erratic characteristic; and 

b) normalized maximum power as a function of system shading showing a stepwise decrease as is emphasized by the continuous line through the data points. The dotted line represents the best linear fit through the data points, starting at $NP_{MP} = 1$.

decrease is 12% of the maximum output of the system. Also, distinct steps in $V_{MP}$ can be noted, which occur when one set is entirely deprived of illumination and thus no longer provides voltage. This shifting of $V_{MP}$ is clearly of consequence for the MPP tracking of the panel. From this can be concluded that for this panel a shadow of arbitrary shape will at best reduce the electrical output proportionally to the shadowed area and at worst cause an additional 12% loss of performance. More generally it can be noted that any BICPV system is less robust to external shading if more series interconnections are present. If there are no restrictions on the system voltage, reduction of the amount of series interconnections is suggested to be beneficial for the overall system performance in areas where system shading is common.

7.4 Conclusions

The concept of using semi-transparent CPV elements for a façade integrated daylight regulation system, as well as an energy source has been introduced. Because in this context, adjacent CPV receivers will partially slide behind and shadow one another, the electrical power output of three model CPV systems when partially shadowed has been investigated. Outdoor I-V measurements were used to approximate the actual working conditions of a BICPV system closely, and to analyze
the current and power generation parameters of the systems in detail. A novel concentrating panel based on flat planar optics that offers the benefit of lacking an air cavity to account for optical focal depth is compared to a reference Fresnel lens based system, and the promise of these flat concentrators for use in BICPV applications has been shown.

It has been shown that the electrical power output of a Fresnel lens based concentrator system without secondary optic has a linear dependency on shadow factor. A loss of performance in the order of 4% has been observed in this system, compared to 0% previously reported for a system featuring a SOE. The concentration efficiency of this system is determined to be 0.62.

The novel planar optic concentrator system with integrated TJ solar cell has also been regarded. The current and power generation parameters of these flat receivers are similar to those of a Fresnel lens based system of comparable concentration. High concentration factors exceeding 610 have been experimentally determined for these receivers, much larger values than other systems in the BICPV field where concentrations less than 50 are more common. A concentration efficiency in the range of 0.66-0.77 is noted for the planar optic concentrator, which is in the same range as the Fresnel lens system. The net conversion efficiency of this system (in standard test conditions) was determined to be in the order of 24%. Shadowing of the optic of a single receiver has been shown to lead to a proportionate loss in generated power, showing an extra loss of performance of 0%, like Fresnel lens based systems using a SOE. The electrical power generation is comparable to a lens based system, but these concentrators are flat, and allow easier daylight regulation than more bulky lens based CPV systems. Therefore these planar optic concentrators can be considered very adequate for use in BICPV.

For a multi-receiver panel with interconnections both in series and in parallel, the maximum output power shows a disproportionately large decrease as a function of shadow fraction: between 7% along the parallel interconnections, and up to 12% in the series direction. This decrease can be fully attributed to the interconnection design of the panel as the single optics have been shown not to suffer from such performance loss. Therefore this can be mitigated or alleviated by making alterations to system or building design for specific applications. This can for instance be achieved by reducing the amount of series connections, or orienting the panels such that shadowing along the series direction is minimal.

**Intellectual property**

Note that this publication illustrates principles and technologies which are part of the intellectual property of Morgan Solar. The technology discussed in this paper falls under various international patents and patent applications as specified in [253].
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Summary

Recently adopted energy efficiency policies in the EU induce a movement towards energy neutral buildings. Therefore, building-integrated photovoltaics have been on the rise. They can offer the benefits of local generation of electrical energy, as well as being more aesthetically pleasing than typical rooftop solar panels. Added functionality in building integrated photovoltaics can be realized through concentrator photovoltaics, that apply optics to focus large areas of sunlight on small, high-efficiency solar cells. Because of the focusing nature of such systems, aside from electrical energy generated by the solar cell, an elevated heat level is also obtained at the focal point. Therefore, building-integrated concentrator photovoltaics (BICPV) offer an excellent possibility to combine the generation of electrical power and usable heat. Additionally, in concentrator systems only the direct fraction of light is focused on the solar cell, while the diffuse fraction is not, but is typically distributed in the plane around the cell. If the cell is mounted in a transparent medium, this characteristic can be employed as a way to regulate daylight entering into the interior of buildings. Clearly, BICPV is a very promising technology to address the increasing, and many-faceted energy demand. Building integration and multiple functionality give rise to specific challenges as it e.g. puts size, weight, and geometrical constraints on system design. To meet these challenges, the applied optics generally have a more complex geometry than those applied for field-based CPV systems. Examples studied in this thesis include i) a light-weight rooftop system that uses a Fresnel prism in conjunction with a multi-lobed parabolic mirror for concentration to combine the generation of electricity and heat; and ii) a semi-transparent, profiled plate, light-guide system for façade integration that combines daylight regulation and electricity generation.

One aspect of BICPV systems is that the complex optics provide much more inhomogeneous illumination patterns than in field-based concentrators. These inhomogeneities can come in the form of an illumination intensity distribution across the cell surface, as well as spatial differences in spectral distribution, due to the wavelength dependent refraction of light. In this thesis, the electrical performance of the typically applied triple junction concentrator solar cells under such inhomogeneous illumination conditions is studied using techniques described in chapter 2. Specific variations on commonly applied characterization methods have been developed to investigate the effects of different types of inhomogeneous illumination
In chapter 4 the influence of inhomogeneity in cell illumination intensity is studied. By modulating the illumination of a homogeneous solar simulator using optical filters, the electrical performance of the solar cells under varying degrees of inhomogeneous illumination is investigated in a very controlled and precise fashion. Surprisingly, the decrease in electrical performance of the solar cells under partial shading is found to be highly proportional to the amount of shading. A more than linear performance loss in the order of only 4% is observed for very high shading levels across a wide range of concentrations. Such heavy shading grossly overstates the inhomogeneities in irradiance encountered in practical applications. In further experiments where the outer perimeter of the cells are specifically illuminated, or excluded from illumination, the cell performance as a function of shading was demonstrated to be independent of the location of illumination. This means that perimeter recombination affects the cell performance regardless of whether the outer cell perimeter is illuminated directly. This was determined to be caused by lateral spreading of the current density throughout the solar cell. Therefore, inhomogeneous illumination patterns will not cause the perimeter recombination to have a further detrimental effect on the cell performance. However, a reduction of these perimeter recombination effects altogether will benefit the cell performance. Additionally, an alternative (deep junction) cell structure is shown to exhibit significantly improved electrical performance under concentration, compared to its traditional (shallow junction) counterpart. Deep junction cells show an increased open circuit voltage, fill factor, and efficiency of 40 mV, 2%, and 2% respectively. Therefore use of this cell structure, rather than shallow junctions, for the GaAs subcell in CPV multi-junction solar cells may provide an interesting route towards cells with further enhanced performance.

In chapter 5 the electrical performance of triple junction CPV cells under inhomogeneous spectral conditions is studied. In this case optical filters are used to locally restrict the cell illumination to either the top+bottom subcells, or the middle+bottom subcells. In this way a model for an extreme lateral spectral inhomogeneity, and the accompanying local current mismatch is obtained. The distance between these areas of partial illumination is varied as a method to control the gravity of the inhomogeneity, in order to study its effects on the electrical solar cell parameters. Remarkably, under both one sun, and concentrated light conditions, the cell performance is barely affected by these conditions. The generated current is shown to not be affected by this local spectral inhomogeneity at all. Only a minor loss of voltage is observed, amounting to 1% under one sun, and increasing to 3% at high concentration. A minor reduction in fill factor of up to 4% is found, and attributed to an increased series resistance under these conditions. Using simulations of an equivalent circuit model, it was demonstrated that the generated carriers flow laterally through emitter of the middle subcell and the base of the top subcell to circumvent the unilluminated parts of the subcells.

The findings described in these chapters show clearly that any increased inhomogeneities in the cell illumination pattern caused by more complex optical systems, only have a minor influence on the electrical performance of the solar
cells. As a consequence, a large degree of design freedom exists for these optical systems. This offers many opportunities for the development of BICPV that meet the particular design challenges of the built environment.

Other points of attention of the more complex optical systems applied in BICPV are the guidance of light to the solar cell, and the average angle of light incidence onto the cell. To assist in the first issue, a secondary optical element can be used to capture light that would otherwise not reach the cell. Additionally, the secondary optic can provide extra concentration, and homogenize the light. However, secondary optics also elevate the average cell illumination angle, therefore adding to the second issue. The solar cell performance as a function of the illumination angle is studied in chapter 6. The solar cells were found to suffer a major loss of performance of up to 58% for oblique illumination (83°). This loss could be attributed to the anti reflective coating that covers the front of the cell to transfer maximum irradiance to the active layers of the solar cell. This coating is usually optimized for illumination angles orthogonal to the cell surface, and was determined to cause significant reflections under non-orthogonal illumination. An additional performance loss of up to 18% could be attributed to reflections off the front metal contact of the cells. The in-house developed ray tracer described in chapter 3 was used to compare the optical performance of three model secondary optic elements. For the concentrating elements, it was demonstrated that the increased light trapping of the optics results in an increased electrical performance, exceeding the performance loss caused by the increased illumination angle. However, it can be expected that secondary optical elements with more complex geometries will increase the average cell illumination angle more strongly than the relatively simple ones evaluated in this thesis. It is therefore necessary to evaluate the cost and benefit of using any specific secondary optical element in a novel concentrator design.

Finally, BICPV systems face challenges from the building itself. Whereas traditional concentrator systems are normally deployed in open space to ensure a complete illumination of the system at all times, a building incorporated system may encounter shading e.g. by supporting elements of the building, external objects (trees, other buildings), or overlapping elements of the CPV system itself. In chapter 7, a system is studied that relies on multiple semi-transparent sun tracking panels to provide daylight regulation, as well as energy generation. As the system is designed for deployment in building façades, it is subject to partial shading of its overlapping optical elements. The impact of such shading on the electrical performance of the system is studied and compared to that of a benchmark Fresnel lens based system. The disproportional performance losses introduced by the shading have been determined to be low, in the order of 10%, compared to 4% for the benchmark system. More importantly, the performance loss was attributed to the electrical interconnections in the system rather than the optical elements, which allows for optimization of performance, based on building orientation, geometry and design.
Outlook

Already for decades, the highest light conversion efficiencies are obtained by multi-junction cells based on III-V materials. Although promising technologies such as perovskite solar cells have been on the rise in recent years, it will likely take quite some time before they can match the efficiency and stability of the three-fives. The main benefits of the III-V cells are i) the distribution of the solar spectrum across several junctions with different bandgaps so absorption - and thermalization losses are minimized; and ii) the virtually perfect surface passivation by epitaxially grown lattice matched window and back surface field layers, which is difficult or impossible to obtain for most other materials. Because of these traits, III-V cells are likely to remain the technology of choice for high concentration photovoltaics for a long time to come. Although the studies in this thesis show that multi-junction III-V cells handle inhomogeneous illumination as generated by concentrator systems rather well, perimeter recombination effects are still a major cause of performance loss. In this thesis it is demonstrated that they affect the solar cell performance, even when the edge of the solar cell receives no illumination. These effects occur because the termination of the solar cell crystal structure at the cell edges results in inter bandgap energy states. Development of a proper edge passivation technique is far from straightforward as the edge of the cell is a layered structure consisting of a sequence of different subcells and delicate tunnel junctions. Still, dealing with the perimeter recombinations will be one of the major challenges on the road to solar cells with efficiencies exceeding 50%.

Another important factor is the high cost of the concentrator solar cells. They are expensive because they are i) produced on small scales (typically MWp annual production) mainly for the space industry, unlike for instance silicon panels that are mass produced in vast factories (typically GWp annual production); and ii) produced using batchwise, epitaxial growth processes such as metal organic chemical vapour deposition (MOCVD). The batchwise production results in low throughput as manual handling, heating and cooling times etc. slow the production. Recently there have been major developments on the faster production of III-V solar cells, by use of hydride vapour phase epitaxy (HVPE)\[264][266]. HVPE relies on a gas-filled chamber to grow structures rapidly. Therefore, one of the normal drawbacks
of HVPE is the slow and difficult transition from one gas to the next\footnote{Which is one of the areas in which MOCVD shines.}. This was circumvented by using different growth chambers and quickly transitioning the growing cell between chambers in-line. Hence several of the slow batch processing steps are eliminated and a faster production is achieved. Additionally, epitaxial layer growth is faster in HVPE than in MOCVD. Herein lies the major difficulty for applying HVPE for the growth of multi-junction cells. HVPE growth is too fast to produce in sufficient quality the very thin (10-50 nm) tunnel junctions, that provide a low electrical resistance and optically low-loss connection between subcells. Therefore, the in-line combination of HVPE and MOCVD reactors, is an interesting route towards the fast and high-throughput (and hence cheaper) production of high-efficiency, multi-junction solar cells.

Finally, one of the main points of attention for CPV in the coming years will be deployment. Currently, the PV market is dominated by traditional silicon panels, with some upcoming applications for thin film technologies and only a minor role for CPV. CPV systems are mostly deployed in rural areas, in the form of vast arrays (up to 30 metres across) driven by massive, heavy two-axis trackers. This means that i) the generated electrical energy needs to be transported to urban sites where the energy demand is highest; ii) generated heat and diffuse light are not used directly, or lost entirely; and iii) active cooling to protect the solar cell from overheating is needed. This sub-optimal situation drives the cost of CPV up to a point at which it is not cost-competitive to silicon. BICPV can address these issues perfectly, by allowing on-site energy generation, and alleviating cost by multi-functionality such as daylight regulation or the direct use of heat. Therefore BICPV allows the best possibilities for CPV technology to become cost-competitive, as well as being an excellent way to address multiple facets of the energy demand. Additionally, in this thesis it has been demonstrated that the applied III-V solar cells are well equipped to handle the illumination patterns that the complex BICPV optics provide. This allows a large degree of system design freedom, which means that the technology can meet the challenges of any specific building or build site. Hence, the future of BICPV is looking bright.
Samenvatting

Vanwege recent in de EU aangenomen regelgevingen omtrent energie gebruik vinden ontwikkelingen richting energie neutrale gebouwen plaats. Om die reden zijn gebouw-geïntegreerde zonne-energie toepassingen in opkomst. Een voordeel van zulke systemen is naast het lokaal opwekken van energie, dat ze vaak esthetisch veel aantrekkelijker zijn dan de typische zonnepanelen op het dak. Additionele functionaliteit in de gebouw-geïntegreerde zonne-energie, kan gerealiseerd worden middels zogeheten concentrator zonne energie, waarbij optische elementen worden gebruikt om een groot oppervlak aan invallend licht te focussen op een kleine, hoog efficiënte zonnecel. Vanwege de concentratie van het licht wordt er in het brandpunt van het optisch element, naast elektriciteit die wordt opgewekt door de zonnecel, ook een verhoogd warmteniveau gegenereerd. Daarom bieden gebouw-geïntegreerde concentrator zonne-energie (building-integrated photovoltaics, BICPV) systemen, een uitstekende kans om het opwekken van elektrisch vermogen én bruikbare warmte, te combineren. Bovendien wordt in een concentrator systeem enkel de directe fractie van het zonlicht op de zonnecel gefocuseerd, terwijl diffuus licht typisch in een vlak rond de cel wordt verspreid. Als de cel in een transparant medium wordt gepakt, kan deze eigenschap worden gebruikt om de hoeveelheid daglicht die een gebouw binnenvalt te reguleren. BICPV is duidelijk een veelbelovende technologie die antwoord zal kunnen bieden in het toenemende energie vraagstuk. Gebouw integratie en gecombineerde functionaliteit zorgen voor specifieke uitdagingen omdat er onder andere restricties in afmeting, gewicht, en geometrie opgelegd worden aan het systeemontwerp. Om deze uitdagingen aan te gaan hebben de gebruikte optische elementen vaak een veel complexere geometrie dan in conventionele CPV systemen die in het open veld geplaatst worden. Voorbeelden van zulke systemen die in dit proefschrift worden bestudeerd zijn i) een lichtgewicht systeem bedoeld voor op het dak, dat een Fresnel prisma combineert met een meerlobbige parabolische spiegel om concentratie te bewerkstelligen, en generatie van elektriciteit en warmte combineert; en ii) een semi-transparant systeem voor gevel-integratie, dat gebaseerd is op een lichtgeleidende geprofileerde plaat, die het opwekken van elektriciteit combineert met daglicht regulatie.

Eén aspect van BICPV systemen is dat de belichtingsprofielen van de complexere optica veel minder homogeen zijn dan in veld gebaseerde concentrators. Zulke inhomogeniteit kan zich uiten in de vorm van een inteisiteits distributie over het
celoppervlak, of als plaatsafhankelijke verschillen in het opvallende lichtspectrum, vanwege de golflengte afhankelijke breking van licht. In dit proefschrift worden de elektrische parameters van typisch toegepaste drie laags (triple junctie) zonnecellen bestudeerd middels methodieken beschreven in hoofdstuk 2. Geval specifieke variaties op regulier toegepaste karakterisatie methoden zijn ontwikkeld om de effecten van verschillende vormen van inhomogene belichting op de cellen te onderzoeken.

In hoofdstuk 4 wordt de invloed van inhomogeniteit in de belichtingsintensiteit onderzocht. Door het belichtingsprofiel van een homogene zonnesimulator aan te passen middels optische filters, kunnen de elektrische parameters van de zonnecel als functie van verschillende mate van inhomogene belichting op zeer gecontroleerde en precieze wijze worden onderzocht. Verrassend genoeg is vastgesteld dat de elektrische prestaties van de zonnecel zeer proportioneel afhankelijk zijn de hoeveelheid beschaduwing van het celoppervlak. Een meer dan lineair prestatieverlies in de orde van slechts 4% is waargenomen voor een hoge beschaduwingsgraad, voor een breed gebied aan concentraties. Dergelijke beschaduwing is veel extremer dan de inhomogeniteit in belichtingsintensiteit zoals deze in de praktijk voorkomt. In verdere experimenten waarin de buitenste rand van de cellen specifiek belicht, of uitgesloten van belichting werd, is aangetoond dat de prestaties van de zonnecel onafhankelijk zijn van de locatie van belichting. Dat betekent dat rand recombinatie effecten de cel prestaties beïnvloeden, zelfs als de rand niet direct belicht wordt. Het is vastgesteld dat dit veroorzaakt wordt door een lateraal uitsmeren van de stroomdichtheid in de zonnecel. Daarom zal een inhomogene belichtingsprofiel er niet voor zorgen dat rand recombinatie de cel prestaties verder belemmert. Echter zal het onderdrukken van dergelijke rand recombinatie effecten wel een verbetering van de cel prestaties opleveren. Aanvullend is bij een alternatieve (diepe junctie) cel structuur een significant verbeterde elektrische prestatie aangetoond in vergelijking met een traditionele (ondiepe junctie) cel. Diepe junctie cellen tonen een verhoogde open klem spanning, vul factor, en efficiëntie van respectievelijk 40 mV, 2%, en 2%. Daarom is het gebruik van deze cel structuur, in plaats van een ondiepe junctie, voor de GaAs subcel in CPV multi-junctie zonnecellen, een interessante insteek om cellen met verder verbeterde prestaties te produceren.

Daarom wordt het gebruik van deze cel structuur in plaats van een ondiepe junctie, sterk aangeraden in de productie van concentrator multi-junctie zonnecellen.

In hoofdstuk 5 worden de elektrische prestaties van triple junctie CPV cellen onder invloed van inhomogene spectrale condities bestudeerd. In dit geval worden optische filters gebruikt om lokaal de cel belichting te beperken tot danwel de bovenste+onderste subcellen, danwel de middelste+onderste subcellen. Dit staat model als een zeer extreme laterale spectrale inhomogeniteit, met bijbehorend de lokale verschillen in stroom generatie in de subcellen. De afstand tussen deze gebieden van partiële belichting wordt gevarieerd als manier om de zwaarte van de inhomogeniteit in te stellen. Er is vastgesteld is dat de cel prestaties nauwelijks beïnvloedt worden door dit effect, wat opmerkelijk is. De gegeven stroom toont helemaal geen afhankelijkheid van spectrale inhomogeniteit.
klein verlies in spanning is waargenomen; minder dan 1% onder 1 zon belichting, toenemend tot 3% onder hoge concentratie. Een kleine verlaging van de vul factor tot 4% is waargenomen, en toegekend aan een toename van de serie weerstand onder deze condities. Een equivalent stroomkring model is gebruikt om aan te tonen dat de stroomdragers lateraal door de emitter van de middelste subcel en de basis van de bovenste subcel bewegen om onbelichte delen van de subcellen te omzeilen.

De bevindingen beschreven in deze hoofdstukken tonen duidelijk aan dat een toegenomen inhomogeniteit in cel belichting, veroorzaakt door complexere optische systemen, slechts een klein effect hebben op de elektrische prestaties van de zonne-cel. Als gevolg kan gesteld worden dat er een grote ontwerp vrijheid bestaat voor deze optische systemen. Dat biedt veel kansen voor de ontwikkeling van BICPV systemen die aan de specifieke ontwerp eisen van de bebouwde kom voldoen.

Andere aandachtspunten van de meer complexe optische systemen die toegepast worden in BICPV zijn het geleiden van licht naar de zonne-cel, en de gemiddelde hoek van belichting van de cel. Als oplossing van de eerste kwestie, kan een secundair optisch element gebruikt worden om licht in te vangen dat de cel anders niet zou bereiken. Bovendien kan de secundaire optica extra concentratie leveren, en het licht homogeniseren. Echter wordt door het secundair optisch element ook de gemiddelde belichtingshoek van de zonne-cel verhoogd, waardoor het de tweede kwestie verergert. De zonne-cel prestaties als functie van de hoek van belichting worden bestudeerd in hoofdstuk 6. De zonne-ellen lijden een sterk prestatieverlies tot 58% voor scherende belichtingshoeken (83°). Dit verlies is toegekend aan de reflektie laag die de voorzijde van de zonne-ell bedekt en bedoeld is om maximale belichting naar de actieve lagen van de zonne-ell over te brengen. Deze laag is gewoonlijk geënternaliseerd voor belichtingshoeken die niet veel van loodrecht afwijken. Het is aangetoond dat deze echter significante reflecties veroorzaakt bij schuine belichtingshoeken. Een additioneel prestatieverlies tot 18% is toegekend aan reflecties vanaf het metalen voorcontact van de zonne-ellen. De in-huis ontwikkelde ray tracer, beschreven in hoofdstuk 3, is gebruikt om de optische efficiëntie van drie modellen voor secundair optische elementen te vergelijken. Van de concentrerende elementen is vastgesteld dat de grotere hoeveelheid ingevangen licht, resulteert in verhoogde elektrische cel prestaties, die het prestatieverlies vanwege de toegenomen belichtingshoek, overtreffen. Echter is het te verwachten dat secundair optische elementen met een complexere geometrie, de gemiddelde belichtingshoek sterker verhogen dan de relatief eenvoudige exemplaren die in dit proefschrift zijn geëvalueerd. Daarom is het nodig de voor - en nadelen van het gebruik van een specifiek secundair optisch element in nieuwe concentrator ontwerpen zorgvuldig tegen elkaar af te wegen.

Ten slotte, staan BICPV systemen voor uitdagingen van het gebouw waarin ze geïncorporeerd zijn zelf. Terwijl traditionele concentrator systemen typisch in het open veld geïnstalleerd worden zodat het systeem te allen tijde volledig belicht is, is dat geen gegeven voor een gebouw-geïntegreerd systeem. Een dergelijk systeem
kan te maken krijgen met beschaduwing door bij voorbeeld structurele onderdelen van het gebouw, externe objecten (bomen, andere gebouwen), of overlappende onderdelen van het CPV systeem zelf. In hoofdstuk wordt een systeem onderzocht dat meerdere semi-transparante, de zon volgende, panelen gebruikt om daglicht regulatie te combineren met productie van elektriciteit. Omdat dit systeem bedoeld is om ingebouwd te worden in gevels, krijgt het te maken met gedeeltelijke beschaduwing van zijn elkaar (deels) overlappende optische elementen. De impact van dergelijke beschaduwing op de systeem prestaties is onderzocht en vergeleken met een Fresnel lens gebaseerd referentie systeem. Het is vastgesteld dat het disproportionele prestatieverlies dat wordt geïntroduceerd door de beschaduwing klein is, in de orde van 10%, waar dat 4% is voor het referentie systeem. Belangrijker is, dat dit prestatie verlies toegelaten is aan de elektrische verbindingen in het systeem, en niet aan de optische elementen. Dit biedt mogelijkheden tot optimalisatie van systeemprestatie, aan de hand van gebouw oriëntatie, geometrie, en ontwerp.
Vooruitzichten

Al decennia lang, worden de hoogste licht conversie efficiënties behaald door multi-junctie zonnecellen gebaseerd op III-V materialen. Hoewel veelbelovende technologieën zoals perovskiet zonnecellen de afgelopen jaren in opkomst zijn, zal het waarschijnlijk nog een behoorlijke tijd duren voordat deze de efficiëntie en stabiliteit van de drie-vijven kunnen evenaren. De grootste voordelen van de III-V cellen zijn i) de distributie van het zonne spectrum over meerdere jucnties met verschillende bandgaps waardoor absorptie - en thermalisatie verliezen worden geminimaliseerd; en ii) de virtueel perfecte oppervlakte passivatie door epitaxiaal gegroeide, kristalrooster overeenkomstige voor - en achtervlakken, wat lastig of onmogelijk te bereiken is voor de meeste andere materialen. Door deze eigenschappen zullen III-V zonnecellen waarschijnlijk nog lange tijd de standaard technologie blijven voor hoge concentratie zonne-energie systemen. Hoewel de studies in dit proefschrift aantonen dat multi-junctie III-V cellen behoorlijk goed kunnen omgaan met inhomogene belichting zoals die voorkomt in concentrator systemen, blijven rand recombinatie effecten een grote oorzaak van prestatieverlies. In dit proefschrift is gedemonstreerd dat rand recombinatie effect heeft op de zonnecel prestaties, zelf wanneer de rand van de zonnecel niet belicht wordt. Deze effecten bestaan omdat het afbreken van de kristalstructuur aan de randen van de zonnecel, resulteert in energietoestanden binnenin de bandgap. De ontwikkeling van een geschikte rand passivatie techniek is verre van eenvoudig, omdat de zonnecel een gelaagde structuur is, bestaande uit een opeenvolging van verschillende subcellen en delicate tunnel jucnties. Toch zal het verhelpen van de rand recombinaties een van de grote uitdagingen zijn op weg naar zonnecellen met efficiënties van boven de 50%.

Een andere belangrijke factor betreft de hoge kosten van de concentrator cellen. Ze zijn prijzig omdat ze i) op kleine schaal worden geproduceerd (typisch MWp jaarlijkse productie), hoofdzakelijk voor de ruimtevaart industrie, anders dan bij voorbeeld silicium panelen die massa geproduceerd worden in enorme fabrieken (typisch GWp jaarlijkse productie); en ii) in partijen worden geproduceerd middels epitaxiale groei processen zoals metaal organische chemische gas depositie (metal organic chemical vapour deposition, MOCVD). Zulke processen hebben een lage doorvoer omdat handmatig transport, opwarm - en afkoeltijden etc. de productie vertragen. Er hebben recent grote ontwikkelingen plaats gevonden in het sneller
produceren van III-V zonnecellen, door gebruik te maken van hydride gas fase epitaxie (hydride vapour phase epitaxy, HVPE) \[264\,266\]. HVPE gebruikt kamers gevuld met gas om kristallijne structuren snel te kunnen groeien. Daarom is een van de nadelen van HVPE de trage en lastige transitie van één gas naar het volgende. Dit is opgelost door verschillende groei kamers te gebruiken en de groeiende zonneel snel in-lijn te verplaatsen van de ene kamer naar de andere. Op deze manier worden meerdere van de langzame partij verwerkings stappen geëlimineerd en de productie versneld. Daarnaast is de groei van epitaxiale lagen sneller in HVPE dan in MOCVD. Daardoor is het moeilijk om multi-junctie cellen te groeien met HVPE: de groeisnelheid is te hoog om in voldoende kwaliteit, de erg dunne (10-50nm) tunnel junctions te groeien, die een verbinding met lage elektrische weerstand en weinig optisch verlies tussen subcellen zijn. Daarom is de in-lijn combinatie van HVPE en MOCVD reactors een interessant pad naar de snelle en hoge doorvoer (en dus goedkopere) productie van hoog efficiënte, multi-junctie zonne cellen.

Ten slotte zal een van de voornaamste aandachtspunten in CPV in de komende jaren de uitrol van systemen zijn. Momenteel wordt de zonne-energie markt gedomineerd door traditionele silicium panelen, met een aantal opkomende toepassingen voor dunne laag technologieën en slechts een kleine rol voor CPV. CPV systemen worden vooral ingezet in het landelijk gebied, in de vorm van enorme opstellingen (tot 30m doorsnede) aangedreven door grote, zware twee-assen zonne volg systemen. Dit betekent dat i) de gegenereerde energie getransporteerd moet worden naar stedelijk gebied waar de energie vraag het hoogst is; ii) gegenereerde warmte en diffuus licht niet direct gebruikt worden, of volledig verloren gaan; en iii) actieve koeling nodig is om de zonnecellen tegen oververhitting te beschermen. Deze sub-optimale situatie drijft de prijs van CPV omhoog tot een punt waar het niet kosten competitief is met silicium. BICPV kan deze zaken perfect aangrijpen en geeft opties tot energie opwekking op locatie, en een kosten reductie door multi-functionaliteit zoals daglicht regulatie of het directe gebruik van warmte. Daarom biedt BICPV de beste kansen om kosten competitieve CPV technologie in de markt te zetten, en biedt het mogelijkheden om meerdere facetten van het energie vraagstuk simultaan aan te pakken. Bovendien is in dit proefschrift aange- toond dat de toegepaste III-V zonnecellen goed in staat zijn met de inhomogene belichtingsprofielen die door BICPV optica worden veroorzaakt om te gaan. Dat staat een grote mate van vrijheid in systeem ontwerp toe, wat betekent dat de technologie de uitdagingen aan kan van ieder specifiek gebouw of locatie. Vandaar ziet de toekomst van BICPV er zonnig uit.

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\[4\] Wat een van de dingen is waarin MOCVD uitblinkt.
## Abbreviations

In order of first use

### Chapter 1

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>PV</td>
<td>photovoltaics</td>
</tr>
<tr>
<td>c-Si</td>
<td>crystalline silicon</td>
</tr>
<tr>
<td>CdTe</td>
<td>cadmium telluride</td>
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<tr>
<td>a-Si</td>
<td>amorphous silicon</td>
</tr>
<tr>
<td>CIGS</td>
<td>copper (indium gallium) selenide</td>
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<tr>
<td>MJ</td>
<td>multiple junction</td>
</tr>
<tr>
<td>GaAs</td>
<td>gallium arsenide</td>
</tr>
<tr>
<td>InGaP</td>
<td>indium gallium phosphide</td>
</tr>
<tr>
<td>Ge</td>
<td>germanium</td>
</tr>
<tr>
<td>TJ</td>
<td>triple junction</td>
</tr>
<tr>
<td>CSP</td>
<td>concentrated solar power</td>
</tr>
<tr>
<td>CPV</td>
<td>concentrator photovoltaics</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>IMM</td>
<td>inverted metamorphic</td>
</tr>
<tr>
<td>ELO</td>
<td>epitaxial lift-off</td>
</tr>
<tr>
<td>MOCVD</td>
<td>metal organic chemical vapour deposition</td>
</tr>
<tr>
<td>HVPE</td>
<td>hydride vapour-phase epitaxy</td>
</tr>
<tr>
<td>DNI</td>
<td>direct normal incidence, direct normal illumination</td>
</tr>
<tr>
<td>PVT</td>
<td>photovoltaic-thermal</td>
</tr>
<tr>
<td>CPC</td>
<td>compound parabolic concentrator</td>
</tr>
<tr>
<td>DTIRC</td>
<td>dielectric totally internally reflecting concentrator</td>
</tr>
<tr>
<td>PMMA</td>
<td>polymethyl methacrylate</td>
</tr>
<tr>
<td>SOE</td>
<td>secondary optical element</td>
</tr>
<tr>
<td>BIPV</td>
<td>building-integrated photovoltaics</td>
</tr>
<tr>
<td>BICPV</td>
<td>building-integrated concentrator photovoltaics</td>
</tr>
<tr>
<td>CPVT</td>
<td>concentrator photovoltaic-thermal</td>
</tr>
</tbody>
</table>

### Chapter 2

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS</td>
<td>Applied Materials Science</td>
</tr>
<tr>
<td>Ga(CH₃)₃</td>
<td>trimethyl-gallium</td>
</tr>
<tr>
<td>Al(CH₃)₃</td>
<td>trimethyl-aluminium</td>
</tr>
<tr>
<td>In(CH₃)₃</td>
<td>trimethyl-indium</td>
</tr>
<tr>
<td>AsH₃</td>
<td>arsine</td>
</tr>
<tr>
<td>PH₃</td>
<td>phosphine</td>
</tr>
<tr>
<td>Si₂H₆</td>
<td>disilane</td>
</tr>
<tr>
<td>Zn(N(CH₂)₂)</td>
<td>diethyl-zinc</td>
</tr>
<tr>
<td>InP</td>
<td>indium phosphide</td>
</tr>
<tr>
<td>ARC</td>
<td>anti-reflective coating, anti-reflection coating</td>
</tr>
<tr>
<td>pcb</td>
<td>printed circuit board</td>
</tr>
</tbody>
</table>
Xe  xenon

Chapter 3
XML  Extensible Markup Language
PDP  photon distribution plot
csv  comma separated values

Chapter 4
TJS  triple shallow junction
SSJ  single shallow junction
SDJ  single deep junction
AlInP  aluminium indium phosphide
MgF₂  magnesium fluoride
ZnS  zinc sulfide

Chapter 5
-

Chapter 6
AOI  angle of incidence
SEM  scanning electron microscope
Al₂O₃  aluminium oxide
TiOₓ  titanium oxide
TP  truncated pyramid
DTP  double truncated pyramid
FP  flat plate

Chapter 7
LSC  luminescent solar concentrator
Symbols

In order of first use

Chapter 1
\( \eta \)
light to electricity conversion efficiency

Chapter 2
\( E_{ph} \)
photon energy
\( E_{gap} \)
semiconductor bandgap energy
\( I \)
electrical current
\( I_{01}, I_{02}, I_{0n} \)
diode dark saturation current
\( q \)
 elementary charge \( \equiv 1.602 \times 10^{-19} \text{C} \)
\( k \)
Boltzmann constant \( \equiv 1.381 \times 10^{-23} \text{m}^2 \text{kgs}^{-2} \text{K}^{-1} \)
\( T \)
temperature
\( I_L \)
light generated current
\( n \)
solar cell ideality factor, ranging from 1 to 2
\( I_{SC} \)
short-circuit current, at zero voltage
\( V_{OC} \)
open circuit voltage, at zero current
\( P_{mp} \)
maximum output power
\( MPP \)
maximum power point
\( I_{mp} \)
current at MPP
\( V_{mp} \)
voltage at MPP
\( FF \)
fill factor
\( P_{in} \)
input power
\( R_S \)
series resistance, that dissipates power in the solar cell
\( R_{SH} \)
shunt resistance, signifying an alternative current path
\( C \)
concentration factor
\( EQE \)
external quantum efficiency, which includes optical losses
\( E_e \)
illuminated power density
\( h \)
Planck’s constant \( \equiv 6.626 \times 10^{-34} \text{m}^2 \text{kgs}^{-1} \)
\( c \)
speed of light \( \equiv 2.998 \times 10^8 \text{ms}^{-1} \)
\( \lambda \)
wavelength of light
\( A \)
absorption (ratio)
\( R \)
reflection (ratio)
\( IQE \)
internal quantum efficiency, which excludes optical losses

Chapter 3

Chapter 4
\( P_{ill} \)
illuminated perimeter
\( A_{ill} \)
illuminated area
\( S \)
shading factor, with 0 \( \equiv \) fully illuminated and 1 \( \equiv \) fully shaded
\( \xi(S) \)
a given electrical parameter as a function of \( S \)
\( \xi_N(S) \) a given electrical parameter, corrected for shading
\( I_{\text{rec}} \) dark recombination current
\( E_e(S) \) illuminated power density in shaded conditions

**Chapter 5**

\( NE_{e,\text{subcell}} \) effective illumination on subcell
\( TA \) transmission through filter A
\( TB \) transmission through filter B
\( X \) width of unilluminated cell surface
\( \xi(X) \) a given electrical parameter as a function of \( X \)
\( \xi_N(X) \) a given electrical parameter, corrected for split distance

**Chapter 6**

\( \theta \) zenith angle
\( \varphi \) azimuth angle
\( \theta_p \) zenith angle with \( \varphi \) parallel to front metal grid lines
\( \theta_s \) zenith angle with \( \varphi \) orthogonal to front metal grid lines
\( \gamma \) grid finger inclination with respect to solar cell surface
\( L_i \) fraction of illumination that undergoes interaction \( i \)
\( l_i \) virtual projection of \( L_i \) on the solar cell plane
\( E_0 \) conventional one sun illumination density \( \equiv 100 \text{mWm}^{-2} \)
\( J_{SC} \) short-circuit current density
\( C \) constant dependent on light spectrum and EQE
\( N_{J_{SC}} \) normalized short-circuit current density
\( T_{ARC} \) transmission through anti-reflection coating
\( N_{T_{ARC}} \) normalized transmission through anti-reflection coating
\( \Delta \psi \) angle of scattered reflections
\( \lambda_c \) concentration wavelength
\( \theta_{\alpha} \) angular aperture of an optical component
\( \eta_{\text{opt}} \) optical efficiency
\( n \) index of refraction
\( \alpha \) angle of refraction

**Chapter 7**

\( w \) width of a flat plate CPV panel
\( h \) height of a flat plate CPV panel
\( d_{\text{hor}} \) horizontal heart-to-heart distance between panels in an array
\( d_{\text{vert}} \) vertical heart-to-heart distance between panels in an array
\( C_{\text{geo}} \) geometric concentration ratio of a concentrating optic
\( N \) concentration efficiency
\( N_{PM} \) normalized maximum output power
List of Publications

Influence of laterally split spectral illumination on multi-junction CPV solar cell performance
Submitted

Partially shaded III-V concentrator solar cell performance
Paper accepted in Solar Energy Materials and Solar cells; available online [197]

Scientrace: An open source, programmable 3D ray tracer
J. Bos-Coenraad, L.A.A. Bunthof, and J.J. Schermer
Solar Energy 155 (2017), pages 1188-1196

The illumination angle dependency of CPV solar cell electrical performance
L.A.A. Bunthof, J. Bos-Coenraad, W.H.M. Corbeek, E. Vlieg, and J.J. Schermer
Solar Energy 144 (2017), pages 166-174
Article awarded for excellence in sustainable and clean energy research by Renewable Energy Global Innovations [267].

Impact of shading on a flat CPV system for façade integration
L.A.A. Bunthof, F.P.M. Kreuwel, A. Kaldenhoven, S. Kin, W.H.M. Corbeek, G.J. Bauhuis, E. Vlieg, and J.J. Schermer
Solar Energy 140 (2016), pages 162-170

Effects of primary optics shading on electrical performance of CPV systems for building-integration
L.A.A. Bunthof, F.P.M. Kreuwel, M.M. van Steen, J. Bos-Coenraad, W.H.M. Corbeek, G.J. Bauhuis, and J.J. Schermer
Proc. 43rd IEEE Photovoltaic Specialists Conference, Portland OR (2016), pages 560-562
Dankwoord

Hoewel enkel mijn naam op de kaft staat komt zo’n proefschrift niet tot stand door het werk van één mens alleen. Het is dan ook niet meer dan passend om hier de tijd te nemen een aantal mensen te bedanken. We beginnen met de grote leiders. Allereerst mijn begeleider John Schermer, omdat je juist mij voor deze plek hebt uitgekozen (zowel de beste beslissing die je ooit hebt genomen), maar zeker ook voor alle adviezen en discussies. We zijn op veel fronten heel verschillende mensen, en ik heb de afgelopen jaren een boel kunnen leren uit de dynamiek die dat oplevert. Ook wil ik mijn promotor Elias Vlieg bedanken voor het doornemen van manuscripten en discussies bij de workmeetings, maar vooral voor je tomeloze enthousiasme over escape rooms. Dat geeft de burger moed! Ten slotte de eigenlijke baas Ine Hendriks, enorm bedankt voor alle secretariële ondersteuning, het op peil houden van de koffie voorraad en de wilde verhalen uit Loosbroek. Ik hoop met een passie dat je het de volgende keer van de boerenkool stronk zal winnen.

Graag bedank ik voor de goede sfeer op de afdeling ook mijn andere collega’s bij Applied Materials Science. Ashkan Tavakoliyarak, André Kaldenhoven, Balachander Krishnan, Mike Cherwin, Yu-Ying Hu, Remi Aninat, Aryan de Jong, Günther Bissels, Niek Smeenk en Maarten van Eerden, bedankt voor de gezelligheid, pauzes, sportdagen, borrels, afdelingsuitjes en etentjes. Speciaal wil ik dynamisch duo Peter Mulder en Gerard Bauhuis bedanken voor jullie hulp bij de vormgeving van mijn projecten, het produceren van zonnecellen en vele potjes darts, en in het bijzonder voor jullie, uh, nuchtere..? manier van naar de wereld kijken; heel verhelderend, dat. Thieu Asselbergs, Erik Haverkamp en Wil Corbeek betuig ik extra veel dank voor al jullie ondersteuning bij de ontwikkeling van meet apparatuur. Ik heb daarbij nogal veel op jullie geleund en heb veel respect voor jullie kennis van en vaardigheid in jullie respectievelijke specialismen. Zonder jullie hulp was ik waarschijnlijk niet geweest waar ik nu ben. Linda van

5Ook besef ik me dat dit voor vrijwel iedereen de enige sectie is die ze echt gaan lezen, dus ik zal mijn best doen er iets van te maken!
6En voor het voordragen, natuurlijk.
7In English for the people that are acknowledged here who have not quite mastered Dutch: I really want to thank my colleagues over at Applied Materials Science for the great atmosphere at the department. Thank you all for the good times, breaks, sports days, drinks, department days out (day outs? I honestly cannot say what is correct here...) and nice dinners.
Leest bedankt voor de vele gesprekken over opleiden, en voor de frequentie Latex hulp. Natasha Gruginskie, ik ga er van uit dat je Nederlands inmiddels zo goed is dat je dit wel ontcijferd krijgt. De laatste jaren van mijn promotie hadden er vast heel anders uit gezien zonder jouw enthousiasme, bereidwilligheid om verhitte discussies te voeren en je alomtegenwoordige zin om iets te doen. We zijn het vaak eens, en hebben de beste gesprekken wanneer we het niet eens zijn. Dat jij er bij kwam maakte het weggaan van 'de oude garde' een stuk minder naar voor mij.

Dan nog het andere dynamische duo: Joep 'de wereldverbeteraar' Bos-Coenraad, en Jon 'je moet hier de hele rotzooi verkopen en lekker in een hutje in Frankrijk gaan wonen lekker wij verbouwen paar geitjes erbij voor de kaas, lekker!' Feenstra. Het komt niet vaak voor dat ik mensen ontmoet die significant luider zijn dan ik. Stel je daarom mijn verbazing voor toen ik uitvond dat jullie dat wel zijn. Laat staan tegelijkertijd! Met jullie 'schitterende ideeën' en eindeloze energievoorraad zijn jullie een ware natuurkracht. Ik vind het geweldig hoe jullie altijd goed voor ons mindere Goden hebben gezorgd via de organisatie van activiteiten als TheoTime, de loempiaborrel, bootcamp, Wallytje, en natuurlijk het lunchpauze 'gokken'. Onvergetelijk! Heren, bedankt voor de mooie tijden.

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---

8 Again, for the non-dutch speakers in there: Thank you guys very much for all the coffee - and lunchbreaks, drinks, barbequeues, activities, the sense and the nonsense, all the times I was fortunate enough to be able to give you advice, and all the times you were part of - or the target of my silliness. I had a jolly good time.
Veelenturf. Ik heb de afgelopen vier jaar regelmatig tegen mijn collega promovendi en mijn ook promoverende vriendjes mogen opscheppen over hoe goed ‘mijn’ studenten wel niet waren, en ik was fortuinlijk genoeg dat ik daar geen woord van hoefde te liegen. Kijk, als promovendus ben je toch een beetje een eiland; de enige in de groep die op jouw onderwerp zit. Dankzij jullie was dat echter voor mij alles behalve het geval, en dat heb ik ongelofelijk prettig gevonden. We hebben veel vruchtbare en diepe discussies gehad over het werk en we hebben ook echt samen het project vorm gegeven. Jullie harde werk en tomeloze inzet voor de onderzoeken naar het beschaduwen van cellen en optica, het meten aan volledige systemen en het ontwikkelen van meetopstellingen heeft bijgedragen aan de tot stand koming van aantal mooie artikelen waar we trots op mogen zijn. Ik heb ontzettend veel waardering voor de manier waarop jullie stuk voor stuk tegenstallen om hebben gebogen in successen, en hoe jullie onvermoeibaar de resultaten waar we naar zochten hebben nagejaagd. Ontzettend bedankt! Ik kan verder hooguit hopen dat het voor jullie net zo leerzaam en plezierig is geweest als voor mij.

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de die een groot deel van mijn ontspanning zijn. Ik heb er altijd veel plezier in en, het moet gezegd, Thunk is nog altijd een van mijn beste creaties ooit en dat had ik zonder jullie niet gekund.

Een wijs man leerde me ooit: “Je moet goed eten, anders ga je dood”, en die richtlijn bepaalt een ander sterk aspect van mijn ontspanning. Dus bedankt voor alle gezellige etentjes (in willekeurige volgorde): Ila (en een lineaire combinatie van \{0\}, Sjors, Melvin en Rob), ook voor de weekendjes weg en andere trips waar Sjors en ik weliswaar soms niet bij zijn omdat we dat niet aankunnen (i.e. La La Land, den Moderne ende Abstracte Uitvoering van Sneeuwwitje ende den Zeven Dweragen); Guy en Claire waarbij het invariant zo gezellig wordt dat we de tijd vergeten. Het is maar goed dat het in Newcastle een uur eerder is; en Lobke en Mathijs en sinds kort Kleine Fernando Bas wie ik met trots in alles behalve naam familie noem. Lobke bedankt dat je me geadopteerd hebt als geaccepteerd aanhangsel van je bij je geboorte reeds gekozen ‘zusje’.

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*I feel that it is proper to also acknowledge the people of Wizards of the Coast (Magic: the Gathering, Dungeons and Dragons) and Steamforged Games (Guildball) for their substantial contributions to our game nights.*
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10Knipoog-emoji kan natuurlijk niet in een proefschrift dus die houden we impliciet.
Curriculum vitae

Leon Bunthof was born on the 10th of March 1989 in Oss, the Netherlands, under his "boy’s name": van Sandwijk. In 2007 he graduated from secondary school at BSV Markenhage in Breda, where his interest in science was sparked by chemistry teacher Ad Belleter. Subsequently he studied chemistry at the Radboud University in Nijmegen. During this time he worked in numerous jobs ranging from cleaner, janitor, cafeteria employee; to audiovisual technician and tutor, often several at the same time. He graduated in 2013 on an NMR study of preferential dopant sites in SiAlON based fosfors used in the LED industry under supervision of Ernst van Eck, and a study on the crystallisation of an organic based print resist at Océ Technologies under supervision of Marjette de Jong and Richard van Hout. Following this he started his PhD research at the Applied Materials Science department of the Radboud University under supervision of John Schermer and Elias Vlieg. The results of this research are presented in this thesis.