Development and Characterisation of Silicon Solar Cells with Recombination Interconnects for Future Tandem Solar Cell

Author: Marika Gugole

Supervisor: Jonathan Scragg

July 4, 2018
Abstract

In this project commercial BSF Si solar cells have been processed in order to develop a suitable interconnect for a possible tandem solar cell. The Ag original top contacts have been removed and replaced with TiSi$_2$ formed using the SALICIDE process at 3 different temperatures: 500 °C, 650 °C and 750 °C. Raman spectroscopy and EDS maps have been used to prove the successful formation of the TiSi$_2$ contacts for the 750 °C temperature. As part of this work we also developed a MATLAB script which successfully fits the measured IV curve of a Si solar cell and extrapolates the values of the components of the equivalent circuit. The script also identifies and quantifies the energy losses percentage for different loss mechanisms. The script was used to characterize commercial BSF Si solar cells and to simulate their behavior in a tandem configuration by IV measurements under filtered light. The results of this characterization was used to predict the requirements of a possible top solar cell for a tandem configuration.
Kiselbaserade solceller är den vanligaste typen av solceller och solcellsmarknaden består ungefär av 90% kiselceller. Men, kiselbaserade solceller når snart sin begränsning i form av effektivitet. I Bild 1 ses rekord uppnått effektivitetsmätning per år och vi ser att de kiselbaserade cellerna närmar sig 27%. Den teoretiska effektiviteten benämns på engelska som Shockley-Queisser limit och utstakas till ungefär 33%. Däremot, om man kombinerar flera celler på varandra (så att de arbetar i en tandemkonfiguration) eller koncentrerar ljuset så kan högre effektivitet uppnås. En väg att gå för att tillverka en sådan tandemcell kan vara att använda sig av en kiselcell som bas och kombinera denna med en tunnfilms solcell som toppcell.

Contents

1 Introduction 1

2 Theoretical background 3
  2.1 Theory of solar cells ............................................. 3
    2.1.1 Semiconductor materials ........................................ 3
    2.1.2 Doping of semiconductors ...................................... 4
    2.1.3 The p-n junction .............................................. 4
    2.1.4 The solar cell .............................................. 5
    2.1.5 The current-voltage characteristic (IV) ...................... 6
    2.1.6 Losses during the energy conversion process .................. 7
    2.1.7 The equivalent circuit ...................................... 8
    2.1.8 Quantum efficiency (QE) ..................................... 10
  2.2 Tandem solar cells ............................................. 10
  2.3 Metal-semiconductor contact .................................... 11
    2.3.1 Ag paste contacts .......................................... 13
    2.3.2 Silicides and SALICIDE process .............................. 14

3 Method 15
  3.1 BSF Silicon solar cells ......................................... 15
  3.2 IV measurement setup .......................................... 15
  3.3 IV curve fitting and loss analysis ............................. 16
  3.4 QE measurement setup .......................................... 19
  3.5 Behavior of the cells under filtered light (IV and QE) .......... 20
  3.6 SEM (Scanning Electron Microscope) ............................ 20
  3.7 Raman spectroscopy ............................................. 21
  3.8 Replacing the Ag contacts ..................................... 22

4 Results 23
  4.1 IV curve fitting and loss analysis ............................. 23
  4.2 Behavior of the cells under filtered light (IV and QE) .......... 23
  4.3 Replacing the Ag contacts ..................................... 24

5 Discussion 28
  5.1 IV curve fitting and loss analysis ............................. 28
  5.2 Behavior of the cells under filtered light (IV and QE) .......... 29
  5.3 Replacing the Ag contacts ..................................... 30

6 Conclusion and outlook 31

7 Acknowledgements 32

A The diode equation 33

B Measured and extracted parameters 34
1 Introduction

Silicon based solar cells are the most common type of solar cells, consisting in 90% of the market. However, this technology is approaching its limit in term of efficiency. Figure 1 shows the record efficiencies for the different technologies and the Si technology is recorded to be 26.1%, for mono-crystalline Si under no concentration, and 27.6% for mono-crystalline Si under concentration. According to the Shockley-Queisser detailed balance the theoretical efficiency limit for Si technology is estimated to be 32% [1]. On the other hand, the limit for multi-junction (or tandem) solar cells, consisting in, as the name suggest, in a stack of more than one cell working “in tandem”, is estimated to be 42% under no concentration and 55% under concentration, for two cells in the stack [2]. One approach in the multi-junction technology is to combine a Si solar cell with a low band gap (1.14 eV), as bottom cell, and a wider band gap ($\approx$ 1.7 eV) thin film solar cell as top cell. To reach this goal, there are two main challenges to address. The first challenge regards the development of a suitable high band gap top cell and the second challenge regards the development of a suitable “recombination interconnect”. The combination of a Si solar cell and a wider band gap top cell has already the great advantage of using the well known and economically convenient Si technology for the bottom cell, resulting in the need of only developing a suitable top cell. In particular it could have a great advantage from an economical and environmental point of view, if one consider the upcycling of pre-existing Si cells. As mentioned in the beginning of this introduction, the Si technology has the biggest part of the PV market. This means that there will be a large amount of Si based PV modules that will soon have to be disposed. However, if the PV modules will not be efficient anymore, some of the single Si cells that make up the module could in principle still be efficient. The reason behind this is that the major causes of efficiency loss of the PV modules are related with the degradation of the modules themselves and not with the degradation of all the solar cells which are part of the module [3]. Hence, these cells could be recycled, or better, upcycled, as bottom cell for a tandem cell. The challenge resides in the development of a suitable ”recombination interconnect”, where the electrons collected from the bottom cell can efficiently recombine with the holes collected from the top cell in order to allow a continuous current flow through the stack. In particular, there is the need of replacing the Silver-Lead paste based contacts [4]. Silver would indeed diffuse towards the p-n junction of the solar cell during the deposition of the top cell, at temperatures higher than 500$^\circ$, hence shunting the solar cell. In this project, the focus is on the replacement of these Silver-Lead based contacts with a Titanium Silicide interconnection since Titanium Silicide is known to make a good contact with both p- and n-type Si and at the same time resist high temperatures [5][6]. However, the Silicide formation requires a ”clean” Si surface, especially, it requires an intimate contact between the Si and the metal. In the Si technology, standard cleaning procedures are used to prepare the Si surface, for example to clean and prevent oxides, which unfortunately cannot be used on a finished solar cell, if there is a need to preserve the other components of the device. Hence, a cleaning procedure and Silicide formation process have to be developed for this particular case. The aim of this project is then, first, to develop and test this procedure, and then optimize the Silicide formation process in order to achieve, if possible, a good interconnect. As a side project, for both get used to the characterisation techniques and to better understand the behavior of the cells in a possible tandem configuration, the cells are characterised under filtered light.
Figure 1: Efficiency chart. Taken from [7]
2 Theoretical background

In this first section, a basic theory of semiconductors materials and solar cell devices is presented to allow the reader to understand the reasons behind the project and the work that has been done to achieve the results. In the first section (2.1), the semiconductor materials are briefly introduced and the concepts of conduction and valence band are explained, with a focus on Si, which is the material used in this project (Section 2.1.1). In the second section (2.1.2), the doping process of semiconductors is described, in order to understand the working principles of a p-n junction (2.1.3) both with and without a bias voltage applied. These first 3 sections are the base for understanding the application of semiconductor materials in solar cell devices (Section 2.1.4). A section about the losses during the energy conversion process explains the different kinds and mechanisms behind the inability of convert 100 % of the solar spectrum energy into electricity (2.1.6). This section will provide the reader the necessary basic knowledge to understand the loss analysis that has been done during the characterization of the samples used in this work (Section 3.3), together with Section 2.1.7 which presents the different equivalent circuits typically used to model the behavior of a solar cell. In Section 2.1.5 and Section 2.1.8 the two most common characterization techniques are presented and explained from a more physical and fundamental point of view. Later in the report these techniques will be presented again from a practical point of view, with the description of the measurement setups (Section 3.2 and 3.4). Section 2.2 introduces the tandem configuration of solar cells and presents the requirements of such design, with a focus on the recombination interconnect. The last section (Section 2.3) gives a theoretical introduction about the metal-semiconductor contact, which is the main focus of the project, and in Section 2.3.1 a specific kind of metal contacts, which are present in the solar cell design used in this project, is described from the point of view of the materials and contact formation process. Section 2.3.2 is a brief description of the properties of silicides and their formation process, which will then be reproduced and discussed later in the report (Section 3.8).

2.1 Theory of solar cells

2.1.1 Semiconductor materials

A semiconductor is characterized by a gap between the valence band (highest band still occupied by electrons) and the conduction band (first unoccupied band) of $0 < E_G < 3 \text{ eV}$ [8]; Figure 2 shows a simplified energy band diagram in a semiconductor.

![Simplified Energy Band Diagram](image)

Figure 2: A simplified energy band diagram at $T > 0 \text{ K}$ for a direct band gap semiconductor. In the case of an indirect band gap semiconductor (like Si), the conduction band would be shifted in momentum: an electron requires both a photon and a phonon (lattice vibration, carrying momentum) to pass from the valence to the conduction band.

In the figure above we can see that some of the electrons (black dots) in the valence band are released from their bonds and are occupying a state in the conduction band leaving a hole (white dots) in the valence band. This process is known as electron-hole pair generation and it is a consequence of the thermal movement of the electrons in the crystal; the reverse process is known as electron-hole pair recombination and it occurs when the electron falls back to the valence band. These two processes happen continuously
in the crystal and the average number of electrons and holes in the material is called intrinsic carrier concentration ($n_i$).

### 2.1.2 Doping of semiconductors

The semiconductor materials in a solar cell are doped. The doping is the process by which the electrical conductivity of a semiconductor is modified by introducing foreign atoms into the semiconductor crystal. There are two different kinds of doping: n-doping and p-doping. In the n-doping instead of the original atom there is an atom which has one electron more than the semiconductor atom (called donor atom), for example Phosphorus in the case of doping of silicon. Phosphorus has one valence electron more than Silicon, hence it will not find an open bond and it will be available as a free electron at room temperature ($e^-$). In the p-doping, on the other hand, instead of the original atom there is an atom which has one electron less than the semiconductor (called acceptor atom) like, for example, Boron which has only three valence electrons available and hence will leave a free bond ($h^+$). The densities of the free electrons and holes are called doping densities, more specifically donor density, $N_D$, and acceptor density, $N_A$. In practice the doping densities are very low. For instance, even if only every hundred-thousandth Silicon atom is replaced by a doping atom the conductivity of the material can be increased significantly by factors of 10 [8].

### 2.1.3 The p-n junction

A p-n junction consists of a p-doped and an n-doped semiconductor put next to each other, as shown in Figure 3. The two parts are electrically neutral, since they are made of electrically neutral atoms. When they are put next to each other, the free electrons and holes diffuse due to a concentration gradient and start to recombine leaving fixed electric charges and consequently an electric field is created, which opposes to the diffusion current with a drift current. When the field and diffusion current balance each other an equilibrium is established and a space charge region is formed at the interface of the two doped materials, as shown in Figure 3.

![Figure 3: p-n junction and consequent arising of the electric field.](image)

The p-n junction is the fundamental part of a solar cell. When the photon creates the electron-hole pair, the electric field separates the two charged particles, which are sent in opposite direction towards the borders of the p- and n- side where they are collected and allowed to recombine in the external circuit. In absence of the electric field, the electron-hole pair would rapidly recombine and not produce a current.

*The biased p-n junction*

There are two ways of connecting a voltage to a p-n junction. In the forward bias configuration, a voltage is applied with the positive terminal on the p-side and the negative terminal to the n-side (see
Figure 4.a). The electrons in the n-side and the holes in the p-side move towards the junction and the space charge region is reduce in width, thus reducing the electric field in the region and the resistivity of the junction. In the reverse bias configuration, a voltage is applied with the negative terminal on the p-side and the positive terminal to the n-side (see Figure 4.b). The electrons in the n-side and the holes in the p-side are moved away from the junction and the space charge region is enlarged in width, thus enhancing the electric field in the region and the resistivity of the junction [12].

A simple theoretical model of a solar cell in the dark is a biased p-n junction. In the case of an illuminated solar cell, also the generated current has to be taken into account. More about this will be presented in the following section (Section 2.1.5).

2.1.4 The solar cell

The working principle of a solar cell is essentially based on the conversion of sunlight into current by a semiconductor device. When a photon hits the semiconductor atom, it can knock out one of its electrons due to excitation, hence leaving a hole in its original energy level (Photoelectric effect). Electrons and holes are then forced to move in opposite directions and then recombine in an external circuit generating a current, called photocurrent. The active part of a solar cell is a p-n junction, but other components are necessary for the successful conversion of the solar energy. Figure 5 shows the different parts that make up a solar cell. The n$^+$-emitter and the p-base form the p-n junction and create the space charge region where the electrons and holes are force to move towards the respective contacts. The electrons are sent towards the front contact, which is typically in form of a grid, and the holes are sent towards the back contact. Electrons and hole which are collected by the two contacts contribute to the photocurrent. The two contacts are connected to an external load. As it can be seen in the figure, the p-n junction is asymmetric, because the emitter is usually more doped than the bulk. The reasons for this are essentially two. First, the more the space charge region is broaden in the bulk, the more probability the electrons and holes have to reach the contacts before recombine (the space charge region is the more "safe" region, where recombination is very low). Second, there is a need to have a high voltage, which depends on the doping level of the semiconductor. Hence, one of the two types have to be highly doped to provide a higher voltage.
There are different designs of solar cells (see Ref. [9]), however, their introduction is not necessary to understand the work that has been done in this project. The specific design used here will be introduced and described later in the report (Section 3.1).

2.1.5 The current-voltage characteristic (IV)

The current-voltage characteristic (also known as IV curve) represent the relation between the current flowing through the cell and the voltage at its ends. It is one of the two most common way used to characterize a solar cell, together with the quantum efficiency (Section 2.1.8). The IV relation can be measured under illumination (Figure 6, standard illumination conditions: 1000 W/m², AM 1.5 \(^1\) spectrum and temperature of 25 °C) or in dark conditions.

---

\(P_{mp} = V_{mp} \times I_{mp} = FF \times V_{oc} \times I_{sc}\)

---

\(^1\)the so-called AM 1.5 reference spectrum stands for Air Mass 1.5, which means that the spectrum is considered to travel through 1.5 atmospheres. This is the consequence of the fact that the sun is considered to be not at 0 solar zenith angle, but at 48.2 °.
– **Short circuit current** ($I_{sc}$): the current when the cell is short circuited ($V = 0$).

– **Open circuit voltage** ($V_{oc}$): the voltage when no current is flowing through the solar cell ($I = 0$).

– **Maximum power point** ($P_{mp}$): the maximum achievable power output. The voltage and current at this optimal operating point are indicated as $V_{mp}$ and $I_{mp}$ respectively.

– **Fill Factor (FF)**: the ratio between the maximum power output and the product of $I_{sc}$ and $V_{oc}$.

\[
FF = \frac{P_{mp}}{I_{sc}V_{oc}} = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}
\]  

– **Efficiency ($\eta$)**: the ratio between the power produced by the solar cell and the power incident on it.

\[
\eta = \frac{I_{mp}V_{mp}}{P_{light}} = \frac{FFI_{sc}V_{oc}}{P_{light}}
\]

2.1.6 **Losses during the energy conversion process**

With the term loss we here indicate all the processes that prevents the solar cell to convert 100% of the solar spectrum into electricity. This losses are related with the non utilization of all the photons of the solar spectrum (*Generation losses*), with the recombination of the electron-hole pair before being collected (*Recombination losses*), with the non utilization of the whole photon energy (*Thermalisation losses*), with the high resistivity of the contacts (*Resistive losses*) and with other losses mechanisms, for example due to the reflection of the photons from the front surface.

**Generation Losses**

In order to create an electron-hole pair, a photon must have a sufficient energy to move the electron from the valence to the conduction band. Hence, only those photons with energies equal, or larger, than the energy band gap of the semiconductor can be used to produce a current:

\[
E_{\text{photon}} \geq E_G
\]

The photons that do not satisfy this requirement, can for example being absorbed by an electron in the conduction band, but it will just release the energy in terms of heat while relaxing to the lower energy state. In general, these photons pass the semiconductor material and are reflected by the back contact.

**Thermalisation losses**

If the photon energy is larger than the band gap, the excess of energy is not used. The electron is excited to the conduction band and it thermalises to the lowest energy level in the band. Hence that energy is lost as heat (see Figure 7).

![Figure 7: Thermalisation process for an electron in the conduction band.](image)
Recombination losses

There are three main recombination processes: radiative recombination, Shockley-Read-Hall (SRH) recombination and Auger recombination.

![Figure 8: a) Radiative recombination b) SRH recombination c) Auger recombination.](image)

In the **radiative recombination**, Figure 8.a, an electron occupying a higher energy state, as it would under thermal equilibrium, makes a transition to an empty lower-energy state with all (or most) of the energy difference between the states emitted as light [10]. This kind of recombination process occurs more rapidly in direct band gap semiconductors, since in indirect band gap semiconductors this process would also require a phonon (see Figure 2 in Section 2.1.1). The **SRH recombination** originates from the presence of impurities in the semiconductor, which can give rise to allowed energy levels within the band gap [10][11]. In this case the electron can ”fall down” to the valence band via a very efficient two-steps process, see Figure 8.b. In the **Auger recombination**, Figure 8.c, one electron give up its extra energy to a second electron in the conduction or valence band during recombination thus moving it to a higher energy level. The excited electron collides multiple times with the lattice and gives away its energy, returning to its original state [12].

Resistive losses

These losses are due to the presence of resistances in the solar cell, such as the metal-semiconductor contact at the back surface and on the grid finger, the semiconductor material, the grid finger, collection bus etc.

Other losses

Other losses are, for example, due to reflection from the front surface, shading from the grid and parasitic absorption. These losses are responsible of the difference between $I_L$, which is the maximum current that can be converted from the incident radiation, and $I_{sc}$.

2.1.7 The equivalent circuit

The behavior of a solar cell can be modeled by a so-called equivalent circuit. There are three models which are typically used to characterize a solar cell: the simplified model, the single-diode model or standard model and the two-diode model [13]. In the **simplified model**, shown in Figure 9, the solar cell is modeled by a current source connected in parallel to an ideal diode and the equation that describes the behavior of the solar cell is then composed of two terms, one related to the generated current and the other to the p-n junction (Shockley’s ideal diode equation, see Appendix A).
\[ I = I_{ph} - I_0 \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right] \] (4)

where \( I_{ph} \) is the photocurrent delivered from the current source and the second term accounts for the ideal recombination current from the diffusion and recombination of electrons and holes, according to the Shockley diffusion theory. \( I_0 \) is the dark saturation current of the diode, \( T \) is the temperature and \( k \) is the Boltzmann’s constant. It is common that the term \( \frac{qV}{kT} \) is indicated as \( V_{th} \), thermal voltage. This model, however, does not take into account any losses which are not due to recombination. Hence the one-diode model, also called standard model, is often used and it is shown in Figure 10.

![Figure 9: Simplified model. Taken from [8].](image)

In this model, two resistances are added: a shunt resistance \( R_{sh} \) and a series resistance \( R_s \). \( R_{sh} \) represents the current leakage through the high conductivity shunts across the p-n junction [13] and leak currents at the edges of the solar cell. This resistance is added in parallel to the diode and the current source and it accounts for a possible alternative path for the current, a short circuit between the front and back surface of the cell. \( R_s \) is, on the other hand, added in series and describes especially the ohmic losses in the front contacts of the solar cell and at the metal-semiconductor interface, it also represents the losses in cell solder bonds, interconnection, junction box etc.[13]. Moreover, in this model, an ideality factor \( n \) is added, which takes into account the deviation of the diode from the Shockley diffusion theory [13] and its value is usually between 1 and 2. Hence this model is defined by:

\[ I = I_{ph} - I_0 \left[ \exp \left( \frac{V + IR_s}{nVT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \] (5)

The third model, the two-diode model shown in Figure 11, contains a second diode which accounts for the current from the recombination of electrons and holes in the depletion region, which dominates at lower forward-bias voltages [13]. This model is defined by:

\[ I = I_{ph} - I_{01} \left[ \exp \left( \frac{V + IR_s}{n_1VT} \right) - 1 \right] - I_{02} \left[ \exp \left( \frac{V + IR_s}{n_2VT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \] (6)

where \( I_{01} \) and \( I_{02} \) are the saturation currents of the diodes and \( n_1 \) and \( n_2 \) are the ideality factors of the diodes. It is common to set \( n_1 \approx 1 \) and \( n_2 \approx 2 \). This last method is more complicated to use in the modeling of the behavior of a solar cell since, in fact, 7 parameters have to be determined [13].
The model that is used in this work is the single-diode model.

### 2.1.8 Quantum efficiency (QE)

The quantum efficiency (QE) describes the probability that a photon, which hits the surface of the solar cell, creates an electron which contributes to the photocurrent. The QE is a dimensionless value and it is measured as a function of the wavelength of the incident radiation ($\lambda$). It is expressed as the ratio between the number of contributing electrons and the number of incident photons:

$$QE(\lambda) = \frac{\text{# electrons}}{\text{# photons}} = \frac{A_{\text{gen}}(\lambda)}{f_c(\lambda)}$$

where $A_{\text{gen}}(\lambda)$ is the probability that a photon generates an electron-hole pair and $f_c(\lambda)$ is the wavelength dependent collection probability, i.e. the probability that the generated electron contributes to the photocurrent.

The QE can be used to qualitatively estimate the losses in a solar cell and to calculate the short circuit current ($I_{sc}$):

$$I_{sc} = q \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} QE(\lambda) \Phi(\lambda) d\lambda$$

where $q$ is the electron charge and $\Phi(\lambda)$ is the photon flux of the reference spectrum.

### 2.2 Tandem solar cells

In a single junction solar cell, in order to have a high efficiency device, it is desirable to have a high voltage output and a high current output. The current output is proportional to the number of photons which contribute to the photocurrent, which means that a small band gap is preferable, while the voltage output is related to the band gap of the semiconductor, which means that a higher band gap is preferable. Hence, there has to be a trade-off between efficiency and band gap choice. In this section, an introduction (based on [14]) of the basic principles of operation of the tandem design is given. Tandem solar cells take advantage of different devices connected in series, in order to achieve a high power output. The idea behind tandem solar cells is that different devices are stack on each other and each device works with a specific part of the spectrum (see Figure 12). To successfully achieve a high power output, some requirements have to be taken in consideration. A consequence of the series connection of the junctions is that the output current of the stack is limited by the lower current produced by any of the cells. Hence, every sub-cell should be designed to produce the same current (Current matching). This also means that at the interface between two sub-cells the electrons collected from the bottom cell should efficiently recombine with the holes collected from the top cell, in order to have a continuous current flow through the stack. The current produced is mostly affected by the number of photons whose energy exceeds the bandgap and by the absorptivity of the material. Another aspect that could affects the efficiency of a multi-junction solar cell is the increment of the number of interfaces. A mismatch in the crystal lattice constant at the interface of two junctions gives rise to defects or dislocations that result in an increment of the number of centers of recombination. The consequence is a reduction of the open circuit voltage, short circuit current and fill factor, hence a reduction of the efficiency. A natural consequence of the tandem design is the reduction of the photocurrent of the single junctions, due to a fixed number of
photons being distributed in an increasing number of cell layers. However, the photons used in each layer are subjected to a lower thermalisation loss, since the idea is that more energetic photons are used by high band gap semiconductors. Moreover, the series connection results in a higher output voltage which is the sum of the single voltages of each sub-cell (Figure 12). In addition, the resistive losses, which are proportional to the square of the current, are minimized if the current output is lower. The result of these considerations should be, then, a net gain in efficiency.

Figure 12: Scheme of a triple junction tandem solar cell. The different colors represent the different parts of the spectrum utilized by each cell. The cells are connected in series, so the current that flows through all the cells is the same and the voltage output is the sum of each sub-cell’s voltage.

2.3 Metal-semiconductor contact

As mentioned in Section 2.2, at every sub-cell interface, the holes and the electrons have to efficiently recombine. This means that the so-called recombination interconnect should allow electrons and holes to tunnel through without encountering almost any resistance. In order to understand how to best design such interconnection, it is necessary to first understand the theory behind the metal-semiconductor contact. The interaction between metals and semiconductors is generally complicated and different models have been developed. Among them, the first metal-semiconductor contact model was presented by Schottky and Mott (1938, Figure 13), which gives the barrier height as [15]:

\[
\Phi_{bn} = \Phi_M - \chi_s \tag{9}
\]

\[
\Phi_{bp} = E_g - (\Phi_M - \chi_s) \tag{10}
\]

where \( \Phi_M \) is the metal work function, \( E_g \) is the semiconductor band gap and \( \chi_s \) is the semiconductor electron affinity. Depending on the values of \( \Phi_M \), \( \chi_s \) and the doping type of the semiconductor, one can obtain different types of contacts:

- \( \Phi_M = \chi_s \): neutral contact for both p- and n-type semiconductor;
- \( \Phi_M > \chi_s \): rectifying contact for n-type and ohmic contact for p-type semiconductor;
- \( \Phi_M < \chi_s \): ohmic contact for n-type and rectifying contact for p-type semiconductor;
The Schottky and Mott model predicts that the barrier height is only dependent on the work function of the metal, hence if one would plot the height of the barrier versus the work function of the metal one would obtain a line with a slope equal to 1. It has been experimentally demonstrated that this is not the case and that the barrier height seems to be almost independent from the choice of the metal [16]. The first explanation of this phenomenon was given by Bardeen (1947), who attributed this discrepancy to the effect of surface states. Surface states are energy states available at the surface of a semiconductor which may exist within the fundamental band gap, resulting in a net charge at the surface and an electric field in the semiconductor which causes the bending of the energy bands [16]. The Bardeen model, however, considers the metal and the semiconductor to be "decoupled" by the presence of a thin insulating layer at the interface, which is thin enough to allow the electrons to tunnel through, but thick enough to ensure that the metal does not influence the surface states of the semiconductor. If an intimate contact is made between metal and semiconductor, the interface states will both depend on the surface states of the semiconductor and the metal (Metal induced gap states, MIGS). Moreover, interface defects, doping of the semiconductor at the interface and other factors significantly affect the barrier height.

In a solar cell, the contacts between the semiconductor and the top and back contact are required to be ohmic contact (low $\Phi_b$), with a linear or quasi linear characteristic. In particular, the voltage drop across the contacts should be small enough to ideally not degrade the performance of the device [17]. From the previous paragraph it is evident that the prediction of the barrier height, as a way to make ohmic contacts, is not realistic, due to the multitude of factors which influence it. Hence, if one wants to make a good contact between metal and semiconductor for solar cells, one have to consider a different approach. Before going more into this approach, it is necessary to understand the transport mechanisms for a metal-semiconductor contact. In Figure 14 are shown the three main transport mechanisms for electrons across the metal-semiconductor junction.

The dominant transport mechanism is determined by the doping level of the semiconductor. The

---

2We take as an example the contact between a n-type semiconductor and a metal for which $\Phi_M > \chi_s$ since it is the most common case.
higher the doping level the thinner the barrier that arises at the metal-semiconductor interface. For lowly doped semiconductors \((N_D < 10^{17} \text{ cm}^{-3})\) thermionic emission is dominant, for intermediate doping levels \((10^{17} \text{ cm}^{-3} < N_D < 10^{19} \text{ cm}^{-3})\) thermionic/field emission is dominant and for \(N_D > 10^{19} \text{ cm}^{-3}\) the barrier is thin enough near the conduction band that the electrons can tunnel through it and field emission is the dominant mechanism. Hence, the only practical technique to make a good contact is to deposit the metal on highly doped semiconductor substrates in order for the electrons to tunnel through the barrier \([17]\).

2.3.1 Ag paste contacts

In order to replace the contacts on a BSF Si solar cell it is fundamental to understand how the original contacts are made. In this section is then described the formation mechanism for printed silver-contacts, based on \([4]\). The Ag paste which is used for this kind of contacts consists of Ag particles, organic binders and metal-oxide glass frit, which is usually a PbO-based borosilicate glass. The formation of the contacts proceeds in the following steps:

- Screen printing of the Ag paste;
- Firing, above 500 °C. The frit melts and wets the Ag/SiNx interface;
- Between 500 and 650 °C the PbO reacts with the SiNx (Figure 15.a) which is burn-through by:
  \[2\text{PbO} + \text{SiNx} \rightarrow 2\text{Pb} + \text{SiO}_2 + \frac{x}{2}\text{N}_2\]  
  \((11)\)
- The Pb from the above reaction alloys with Ag (Figure 15.b).
- Above 650 °C, Ag dissolves into the frit and diffuses towards the emitter;
- Near the emitter surface Ag ions are reduced by the redox reaction:
  \[2\text{Ag}_2\text{O} + \text{Si} \rightarrow \text{SiO}_2 + 4\text{Ag}\]  
  \((12)\)
  Si is oxidized and incorporated in the frit and Ag is deposited on the emitter (Figure 15.c).
- During cooling the solubility of Ag decreases and it precipitates in the glass frit (Figure 15.d).
It should be noticed that the Ag diffuses towards the emitter at temperatures above 650 °C, which means that a further heat treatment, for example during the deposition of a top cell, would result in further Ag diffusion and shunt of the p-n junction.

### 2.3.2 Silicides and SALICIDE process

A silicide is defined as a compound that has Silicon with another element which is usually more electropositive (metal). Silicides are used in integrated circuit technology to form ohmic contacts [5][6]. There are two processes used to form a silicide: the polycide process and the SALICIDE process (Self Aligned sILICIDE). The polycide process consists in a codeposition of Si and the metal, while the SALICIDE process consists in a solid-state reaction between Si and the metal. In this work we form Titanium silicide with the SALICIDE process, hence more attention will be given to it. In the SALICIDE process for TiSi$_2$ formation, Ti is sputtered on the Si surface and the two elements are in intimate contact. It follows an annealing step, usually between 600°C and 700°C, in order to allow the reaction and form the silicide and a last etch of the unreacted metal is done. Often, a second annealing follows the last etch step, to lower the resistivity of the silicide (not done in this work), since during the first anneal a higher resistance phase (C49) is formed, while during the second annealing a lower resistance phase is formed (C54). The reason why it is called "self aligned" is because Ti can be sputtered all over the top surface of the solar cell (also on the ARC), but during annealing, only the Ti which is in contact with the pure Si will react. Hence, after the etching of the unreacted Ti, the silicide will be present only in the contact grid, without the use of any additional mask during the sputtering. In Table 1 the silicide formation temperatures and properties of the two TiSi$_2$ phases are given.

---

3The Ti will react only with the Si i.e. where the Ag contacts were placed before. Everywhere else on the surface, Ti will be in contact with the ARC and it will not react with it.
Table 1: TiSi formation temperatures and properties of the two phases. DDS: dominant diffusion species during formation

<table>
<thead>
<tr>
<th></th>
<th>Sintering temperature (°C)</th>
<th>$\rho$ ($\mu\Omega\text{cm}$)</th>
<th>$\Phi_{Bn}$ (eV)</th>
<th>DDS</th>
<th>nm of Si consumed per nm of metal</th>
<th>nm of resulting silicide per nm of metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiSi (C49)</td>
<td>500 - 700</td>
<td>60 - 70</td>
<td></td>
<td>Si</td>
<td>2.27</td>
<td>2.51</td>
</tr>
<tr>
<td>TiSi (C54)</td>
<td>700 - 900</td>
<td>13 - 16</td>
<td>0.58</td>
<td>Si</td>
<td>2.27</td>
<td>2.51</td>
</tr>
</tbody>
</table>

In addition to their low resistivity, Silicides are known to be stable under high temperatures [5].

3 Method

3.1 BSF Silicon solar cells

The cells used in this project are p-type Back Surface Field (BSF) Si solar cells with Ag screen printed top contact and Al screen printed back contact. Two different sizes are used:

(A) 79 x 19 mm$^2$

(B) 52 x 19 mm$^2$

There is no difference between the two solar cells apart from the size, which is different since there were different requirements in size for different instruments. Figure 16 (left) shows a scheme of a commercial BSF silicon solar cell, while Figure 16 (right) shows the two type of cells (A) and (B). The back contact is a screen printed Al paste contact. Al diffuses into the p-type Si bulk and creates a passivation layer, a Back Surface Field (more about this can be found in [18]). On top of the n$^+$ emitter there is an antireflective coating (ARC) made of SiN$_x$. The top contacts are Ag paste screen printed contacts (see Section 2.3.1). The size of the entire cell is usually between 200-500 $\mu$m, with the emitter $<$ 1 $\mu$m [19].

![Scheme of a BSF Si solar cell (left) and type (A) and type (B) Si solar cells used in this project (right).](image)

3.2 IV measurement setup

Figure 17 (left) shows the IV measurement setup. The four-point probes (B) is mounted on a sample stage (A) and is connected to an ampere meter (D) connected to a computer (E), where the data is collected and analyzed. The lamp (C), mounted over the sample stage, is a tungsten halogen lamp with a cold mirror (ELH), i.e. the radiation of the filament is approximated by a black body model and the long wavelengths (> 700 nm) are suppressed (in Figure 17 (right) the photon flux of the ELH lamp compared with the AM 1.5 reference spectrum). The calibration of the setup is made by using a reference cell of which the $I_{sc}$ under the AM 1.5 spectrum is known. The height of the lamp is then adjusted in order to read the known value of the $I_{sc}$. Since the value of the $I_{sc}$ is proportional to the photon flux, this process makes the photon flux of the ELH lamp spectrum equal to the photon flux of the AM 1.5 spectrum.
3.3 IV curve fitting and loss analysis

A MATLAB script is used to fit the I-V curve based on the standard model presented in Section 2.1.5. Different methods have been developed to achieve a good fitting and in this report we base our code on [20] for the fit and [21] for the extraction of the value of \( R_s \). The reason why the value of \( R_s \) is recalculated after the first fit is because \( R_s \) is extracted from the slope of the voltage-current curve at \( V_{oc} \), which is very small and hard to calculate. Moreover, since \( R_s \) is the parameter which takes into account the resistance of the front contact, which is what will be different for the initial and final sample, it has to be calculated as precise as possible. The second calculation is based on the area under the curve, which is more easily controlled. In [20] one can find a detailed theoretical analysis, but here we report only the final equations used for the fit (eq. (13)-(18)) \(^4\).

\[
I = I_L - I_0 \left[ \exp \left( \frac{V + IR_s}{nV_{th}} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (13)
\]

\[
I_L = \frac{R_{sh0}I_{sc}}{R_{sh0} - R_s} \quad (14)
\]

\[
I_0 = \frac{R_{sh0}I_{sc} - V_{oc}}{(R_{sh0} - R_s) \exp \left( \frac{V_{oc}}{nV_{th}} \right)} \quad (15)
\]

\[
R_{sh} = R_{sh0} - R_s \quad (16)
\]

\[
r = \frac{(V_{mp} - I_{mp}R_s)(I_{sc}R_{sh0} - I_{mp}R_{sh0} - V_{mp})}{V_{th}(I_{mp}R_{sh0} - V_{mp})} \quad (17)
\]

\[
R_s = \frac{(A - B)V_{mp}}{(A + B)I_{mp}} + \frac{B}{(A + B)I_{mp}} \quad (18)
\]

where:

\[
A = \left[ V_{mp} + (I_{mp} - I_{sc})R_{sh0} \right] \ln \left[ \frac{V_{mp} + (I_{mp} - I_{sc})R_{sh0}}{V_{oc} - I_{sc}R_{sh0}} \right]
\]

\[
B = V_{mp} - R_{sh0}I_{mp}
\]

The method is supposed to extract the parameters given only the manufacturer information, so the

\(^4\)Two sign conventions exist, one considers \( I_{ph} \) as positive and the other one considers it negative. The different is due to the fact that the solar cell can be considered as a current sink, during characterization when it is connected to an external voltage, or as a current source, during the proper sunlight conversion process. For the fit the second convention is used, while the IV curves in the results appear mirrored.
only known variables are the $V_{mp}$, $I_{mp}$, $V_{oc}$ and the temperature (and consequently $V_{th}$); all the other parameters are expressed as functions of $R_{sh0}$\footnote{This parameter comes from the theoretical analysis done in [20], in this report it does not have any physical meaning and it does not represent a resistance in the equivalent circuit.}. In [20], two methods are presented in order to find $R_{sh0}$:

- The first one is based on another experiment and requires the values of the current and the voltage at a specific point, where the voltage is approximately $0.2 \cdot V_{oc}$ (not used);

- The second one requires the values of the current and the voltage at any operation point, considers

$$I_{op} = I_L - I_0 \left[ \exp \left( \frac{V_{op} + I_{op} R_s}{n V_{th}} \right) - 1 \right] - \frac{V_{op} + I_{op} R_s}{R_{sh}}$$

and defines the function

$$f(R_{sh0}) = |I_L - I_0 \left[ \exp \left( \frac{V_{op} + I_{op} R_s}{n V_{th}} \right) - 1 \right] - \frac{V_{op} + I_{op} R_s}{R_{sh}} - I_{op}|$$

The value of $R_{sh0}$ which minimize the function should be its more realistic value. In order to determine this value, an algorithm which involves a generation and iteration of random populations is used. In our case, since we have the experimental data, we do not use the random population, but we use all the points of the IV curve as operational points and we find the value of $R_{sh0}$ which best minimizes the function at a particular point. Unfortunately, more than one value of $R_{sh0}$ minimizes the function and its value depends also on the choice of the range of $R_{sh0}$ that is tested. For this reason, once the first guess for $R_{sh0}$ is found, it is used to plot the fit curve which is then used to calculate $\frac{dV}{dI}$ at $I_{sc}$ which is a more realistic value of $R_{sh0}$. This two steps are done considering only the data closer to $I_{sc}$, in order to get the best fit of the curve in the points where we calculate the slope. As mentioned previously, this method is used to calculate $R_{sh}$, but no $R_s$, which is calculated considering eq.21 (a more detailed analysis can be found in [21]).

$$R_s = 2 \left[ \frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - n \frac{kT}{q} \frac{1}{I - sc} \right]$$

where

$$A = \int_0^{I_{sc}} V(I) d(I)$$

In Figure 18 an example of experimental data, fit and extracted parameters.
Once the fit is obtained, it is possible to do a loss analysis using the IV curve fit. This can be used to compare the losses before and after the contacts replacement process and to compare the losses in the filtered and unfiltered condition. Although the ELH lamp spectrum looks very different from the AM 1.5 spectrum, the calibration assures that the same number of photons per time per area reaches the cell as if it was measured under the AM 1.5 spectrum. Hence, the loss percentage that will be shown in the results have to be read with respect to the AM 1.5 spectrum. To calculate the generation losses (blue in Figure 19), we just subtract the power generated by the photons with energy larger than the band gap from the total energy available from the spectrum. For the thermalisation losses (yellow in Figure 19), we calculate the “utilization factor” which is defined as the ratio between the band gap and the energy of the photon \( u = \frac{E_g}{E_{ph}} \), then it is possible to calculate the actual power utilized by the solar cell and subtracting this from the power which would be used with an utilization factor of 1 we can find the thermalisation losses. In order to find the recombination losses (green in Figure 19) we calculate the ideal fill factor (red + violet + grey rectangles in Figure 19):

\[
FF_0 = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1}
\]

with the value of \( n \) calculated above and \( v_{oc} = \frac{V_{oc}}{nRT/q} \). Then we calculate the power generated considering \( FF_0 \), \( V_{oc} \) and \( J_L \) and we subtract this power to what was left from before. To find the \( J_L \) losses (grey in Figure 19) we do the same, but we use \( J_{sc} \) to calculate the power and we subtract this power to what was left before. To find the resistive losses (violet in Figure 19) we subtract the actual power generated to what is left.

For the loss analysis under filtered light, the values of the total energy available from the spectrum and \( J_L \) are adjusted considering the part of the spectrum that is filtered. The transmittance of the filter was considered to be 95 %.

Figure 18: Experimental data and fit with extracted values for the single diode model and relative percentage of loss for the different mechanisms.
3.4 QE measurement setup

Figure 20 shows the QE measurement setup. A Xe lamp (A) is coupled to a monochromator (B) and second order reflections, for example from the gratings, are blocked by a filter wheel (C). The beam is then split in two parts: one that goes to a reference cell (D) and one that hits the sample (E). The use of the reference cell makes the instrument less sensitive to variations in the lamp intensity, during calibration and measurement. It is enough to do the calibration once at the beginning of the measurement session. The instrument’s wavelength range goes from 330 nm to 1700 nm. In order to calibrate it for such wide spectrum two calibration cells are used: a Si cell (from 330 nm to 1050 nm) and a InGaAs cell (from 1050 nm to 1700 nm). During the calibration the signal, proportional to the photocurrent, from the calibration cell, $C_{\text{cal}}(\lambda)$, with known QE, $QE_{\text{cal}}(\lambda)$, and the signal from the reference cell, $C_{\text{ref}}(\lambda)$, are recorded simultaneously. During the measurement the signal from the sample, $M_{\text{sample}}(\lambda)$, and the signal from the reference cell, $M_{\text{ref}}(\lambda)$, are recorded and the QE of the sample is calculated according to:

$$QE_{\text{sample}} = \frac{M_{\text{sample}}(\lambda)}{M_{\text{ref}}(\lambda)} \cdot \frac{C_{\text{ref}}(\lambda)}{C_{\text{cal}}(\lambda)} \cdot QE_{\text{cal}}(\lambda)$$

(24)

where in principle $C_{\text{ref}}(\lambda) = M_{\text{ref}}(\lambda)$. 

Figure 19: Representation of the different losses percentages extracted from the IV curve (unfiltered light).
3.5 Behavior of the cells under filtered light (IV and QE)

The behavior of the cells, type (B), in a tandem configuration was simulated using a filter placed between the cell and the lamps for both IV and QE. Figure 21 shows the transmittance of the filter, which cuts all the wavelengths below 695 nm and is, on average, 95 % transparent for the wavelengths above 695 nm.

3.6 SEM (Scanning Electron Microscope)

A Scanning Electron Microscope, as the name suggests, is a microscope that achieve very high resolution images scanning an electron beam over a sample and detecting the emitted signals [22]. In Figure 22 a scheme of a SEM.
Electrons are emitted by an electron gun and accelerated towards the sample, typically by 20 kV. The beam passes through a series of condenser and objective lenses before reaching a aperture. The signal that they produce, interacting with the sample, is then detected by three different detectors. One detector detects the backscattered electrons, which are electrons that are simply scattered by the sample. One detector detects the secondary electrons, which are electrons that originate in the sample. The last detector is an Energy Dispersive X-ray Spectrometer (EDS), which detects the X-rays emitted by the sample. With the electrons signal, the image is reconstructed, while the X-rays give information about the composition of the sample.

### 3.7 Raman spectroscopy

Raman spectroscopy is a technique based on the inelastic scattering of photons on a material and it is used to observe rotational and vibrational modes in a compound. In particular, it can be used to determine the crystalline structure of the sample [22] by comparison with the Raman spectrum of a known sample. Scattering of photons on a molecule can happen in 3 different ways (see Figure 23 left). Most of them are elastically scattered (Rayleigh scattering), which means that the energy of the emitted radiation is the same as the energy of the incident radiation, but a small fraction is scattered inelastically (Stokes-Raman and Anti-Stokes-Raman). In the Stokes-Raman scattering, the molecule is initially in its ground state, it is excited to a so-called virtual energy state, and falls back to a vibrational energy state above the ground level. This results in a positive shift in the emitted radiation wavelength with respect to the incident radiation wavelength. In the Anti-Stokes-Raman scattering, the molecule is initially in a higher vibrational state and after the excitation it falls back to its ground state. This results in a negative shift in the emitted radiation wavelength with respect to the incident radiation wavelength. Since most of the molecule are initially in their ground state, the Stokes-Raman scattering is stronger than the Anti-Stokes-Raman scattering and it is used in Raman spectroscopy.
In Figure 23 right, a scheme of a Raman spectroscopy setup. The light source is a laser with a specific wavelength (range from the ultraviolet to the visible to the near infrared, 785 nm in our case). A mirror directs the beam towards the sample at the right angle. The scattered light is then filtered by the Notch filter, which allows only radiation with wavelength different from the incident radiation wavelength to pass. The radiation is then directed towards a monochromator by mirrors. The monochromator diffracts the radiation into a narrow band of wavelengths. A charged-coupled device turns the measured photocurrent in electric current which is analyzed by a computer. The results are then presented as intensity vs Raman shift (or wavenumber), which is defined as:

$$\Delta w \text{ [cm}^{-1}\text{]} = \left( \frac{1}{\lambda_0} - \frac{1}{\lambda_1} \right)$$

where $\lambda_0$ is the wavelength of the incident radiation and $\lambda_1$ is the wavelength of the emitted radiation.

### 3.8 Replacing the Ag contacts

The work described in this section was done in the cleanroom at the Ångström Microstructure Laboratory at Uppsala University.

**Back contact and edges protection**

The etching of the Ag contacts is done by the *CR-7 (9% (NH₄)₂Ce(NO₃)₆ + 6% HClO₄ + H₂O)* etchant which has an etching rate of 3.8 nm/min for Al and of 450 nm/min for Ag [23]. Since the back contact is made of both Al and Ag, it has to be protected. This is done by spraying a positive photoresist on it. This process covers also the edges of the cell, which prevents the metal to be sputtered there in a subsequent step, avoiding a shunt.

**Etching of the silver contacts**

As previously said the etch of the Ag contacts is done by the *CR-7* etchant. The etching times are between 7 and 11 minutes (until no Ag was visibly left)⁶. A magnetic stirrer (10 Hz) is used during the etching. After the etch the sample is rinsed with water, using a magnetic stirrer for 1 min (5 Hz) This etchant is meant to remove only the Ag, but as explained in Section 2.3.1, the contacts are also made of other materials such as the PbO borosilicate glass. Hence, a second etching is done by 20 H₂O : 1 H₂O₂ : 1 HF (etch time 1 minute), which removes the PbO at the interface between Ag and Si. A last etching step with *CR – 7* (etch time 5 minutes) is done to remove the Ag particles which have been deposited on the Si surface. A final “HF-dip” (50 H₂O : 1 HF) is done to clean the Si surface from possible oxides and prevent oxidation.

---

⁶Different etching times have been tested and no difference regarding the other components of the solar cell has been seen. Hence, we do not report the specific etching time for each sample. All the samples have been etched until no Ag was visibly left.
Formation of the new contacts

After the "HF-dip", 20 nm of Ti are sputtered on the front surface of the cell, the photoresist is then stripped with acetone, followed by Rapid Thermal Processes (RTP). 3 different temperatures have been used on 3 different samples: 500 °C, 650°C and 750°C for 30 s. The unreacted Ti is then selectively etched by NH₄OH : H₂O₂ : 6 H₂O at 30 °C (etching time between 2 and 5 minutes, until the surface appeared "clean").

4 Results

4.1 IV curve fitting and loss analysis

10 samples of type (B) were characterized. In Table 2 average and standard deviation of the solar cell characteristic parameters, extracted parameters form the one-diode model fit and percentage for each loss mechanism. The complete set of values can be found in Appendix B.

<table>
<thead>
<tr>
<th>V_{mp} [V]</th>
<th>J_{mp} [mA/cm²]</th>
<th>V_{oc} [V]</th>
<th>J_{sc} [mA/cm²]</th>
<th>FF [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49 ± 0.01</td>
<td>30.22 ± 0.40</td>
<td>0.603 ± 0.005</td>
<td>33.3 ± 0.4</td>
<td>73.63 ± 1.34</td>
<td>14.81 ± 0.39</td>
</tr>
</tbody>
</table>

Table 2: Average and standard deviation of the solar cell characteristic parameters, extracted parameters form the one-diode model fit and percentage for each loss mechanism.

4.2 Behavior of the cells under filtered light (IV and QE)

2 of the 10 samples characterized in the previous section were also characterized under filtered light (IV and QE). The results of the two measurements were then quantitatively, for the IV, and qualitatively, for the QE, compared with the unfiltered case. In Table 3 and Table 4 the results of the IV measurement and of the loss analysis respectively for both filtered and unfiltered condition. In Figure 24 the results of the QE measurements for both filtered and unfiltered condition.

<table>
<thead>
<tr>
<th>Sample</th>
<th>V_{mp} [V]</th>
<th>J_{mp} [mA/cm²]</th>
<th>V_{oc} [V]</th>
<th>J_{sc} [mA/cm²]</th>
<th>FF [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF2_1</td>
<td>filter</td>
<td>0.465</td>
<td>16.06</td>
<td>0.572</td>
<td>17.62</td>
<td>74.04</td>
</tr>
<tr>
<td></td>
<td>no filter</td>
<td>0.490</td>
<td>30.45</td>
<td>0.603</td>
<td>33.44</td>
<td>73.29</td>
</tr>
<tr>
<td>BSF2_2</td>
<td>filter</td>
<td>0.460</td>
<td>15.68</td>
<td>0.566</td>
<td>17.42</td>
<td>73.21</td>
</tr>
<tr>
<td></td>
<td>no filter</td>
<td>0.490</td>
<td>29.73</td>
<td>0.601</td>
<td>32.94</td>
<td>73.58</td>
</tr>
</tbody>
</table>

Table 3: IV measurement results for filtered and unfiltered condition of two samples of type (B). IV setup calibrated considering the short circuit current extracted from the QE measurement.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gen. (%)</th>
<th>Therm. (%)</th>
<th>Rec. (%)</th>
<th>I_L (%)</th>
<th>Res. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF2_1</td>
<td>filter</td>
<td>38.3</td>
<td>12.3</td>
<td>30.8</td>
<td>3.5</td>
</tr>
<tr>
<td>no filter</td>
<td>20.1</td>
<td>30.6</td>
<td>29.2</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>BSF2_2</td>
<td>filter</td>
<td>38.3</td>
<td>12.3</td>
<td>31.1</td>
<td>3.6</td>
</tr>
<tr>
<td>no filter</td>
<td>20.1</td>
<td>30.6</td>
<td>30.3</td>
<td>2.6</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 4: Loss analysis result for filtered and unfiltered condition for two samples of type (B). IV setup calibrated considering the short circuit current extracted from the QE measurement.
4.3 Replacing the Ag contacts

Here we present the results achieved during the contacts replacement process. The results are presented divided in 3 subsections: results from the SEM, preliminary IV results and Raman results.

**SEM results**

In order to better understand the nature of the Ag-paste contacts and to keep track of the improvements in the etching and silicide formation process, SEM maps have been made. In Figure 25 SEM after the CR−7 etch, in Figure 26 EDS map after the CR−7 + 20 H₂O : 1 H₂O₂ : 1 HF + CR−7 etch and in Figure 27 EDS map after CR−7 + 20 H₂O : 1 H₂O₂ : 1 HF + CR−7 + Ti sputtering + RTP at 500 °C and selective etch of Ti (NH₄OH : H₂O₂ : 6 H₂O).

![Figure 25: EDS map after CR−7 etch.](image)
Between the different etching steps, some cells have been sputtered with Al and the IV curves have been measured. These results allowed us to understand from a physical point of view how the Ag-paste contacts behaves under high temperature treatment.

In Table 5 a summary of the processes occurred for the different cells reported in the results.

**IV measurements**

Figure 26: EDS map after $CR - 7 + 20 \text{H}_2\text{O} : 1 \text{H}_2\text{O}_2 : 1 \text{HF} + CR - 7$ etch.

Figure 27: EDS map after $CR - 7 + 20 \text{H}_2\text{O} : 1 \text{H}_2\text{O}_2 : 1 \text{HF} + CR - 7$ etch + Ti selective etch.
<table>
<thead>
<tr>
<th>Sample</th>
<th>1st CR-7</th>
<th>HF</th>
<th>2nd CR-7</th>
<th>HF dip</th>
<th>Ti sputtered</th>
<th>RTP</th>
<th>Ti etch</th>
<th>Al layer</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF1_2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BSF1_11</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>28</td>
</tr>
<tr>
<td>BSF1_12</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>450</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>BSF1_16</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>BSF2_1</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>30</td>
</tr>
<tr>
<td>BSF2_2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>500</td>
<td>✓</td>
<td>30</td>
</tr>
<tr>
<td>BSF2_3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>650</td>
<td>✓</td>
<td>30</td>
</tr>
<tr>
<td>BSF2_4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>750</td>
<td>✓</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5: Summary of the processes occurred for every cell reported in the results.

Figure 28: Dark IV curve of: BSF1_2 (unprocessed cell), BSF1_11 (1st CR-7, Ti sputtered) and BSF1_12 (1st CR-7, Ti sputtered, RTP at 750 °C).
Figure 29: Dark IV curve of: BSF1, 2 (Al sputtered on unprocessed cell), BSF1, 11 (1st CR-7, Ti sputtered, Al sputtered) and BSF1, 16 (1st CR-7, Ti sputtered, RTP at 450 °C, Al sputtered).

Figure 30: Dark IV curve of: BSF2, 1 (Al evaporated on unprocessed cell), BSF2, 2 (complete etch, Ti sputtered, RTP at 500 °C, Al evaporated) and BSF2, 3 (complete etch, Ti sputtered, RTP at 650 °C, Al evaporated) and BSF2, 4 (complete etch, Ti sputtered, RTP at 750 °C, Al evaporated).
Raman results

Raman scattering was used to support the results of the SEM and the interpretation is based on [24]. In Figure 31 Raman scattering on 3 samples annealed at 500 °C, 650 °C and 750 °C (left) and Raman scattering on a sample annealed at 750 °C in two different parts: grid and ARC (right).

![Figure 31: Raman scattering on 3 samples annealed at 500 °C, 650 °C and 750 °C (left) and Raman scattering on a sample annealed at 750 °C in two different parts: grid and ARC (right).](image)

5 Discussion

5.1 IV curve fitting and loss analysis

Table 2 contains the average values of the results of the IV measurement, extrapolated values from the fit on the one-diode model and loss analysis for 10 different samples that were supposed to be processed and their contacts replaced. One can notice that the standard deviation for the solar cell characteristic parameters is generally small, which means that all the cells showed on average a similar behavior. The fill factor and the efficiency, however, show a higher deviation. This parameters are mostly affected by recombination and shunt losses, which explains the large variation in the values of the shunt resistance, the ideality factor and $I_0$. The value of the series resistance, as expected, do not show a large deviation, which means that the MATLAB script could be used for the specific purpose of the project, which involves the extrapolation and comparison of the series resistance before and after the contacts replacement. Unfortunately, the script only works for light IV curves, while our results are dark IV curves, hence the fitting after contact replacement was not possible. However, a discussion about the contact will be done later in Section 5.3. As mentioned, the idea behind the IV curve fitting and loss analysis was to compare the values of the extrapolated parameters before and after the contacts replacement. What one could expect, according to the metal-semiconductor theory based on the work function of the metal/silicide, is to see a reduction in the values of the series resistance, due to the fact that the barrier height of Ag on n-type Si is 0.75 eV, higher than the one of TiSi$_2$ on Si which is 0.6 eV [17]. However, as explained in Section 2.3, it is not possible to design a metal-semiconductor contact based only on the barrier height value. However, as previously said, silicides are known to make a good contact with Si, hence, we reasonably expected to still obtain a very low value of the series resistance, if the formation process could have been successfully completed. It has to be taken into account that the formation of the silicide requires a very clean Si surface and an intimate contact between Si and Ti, which, as it will be presented later in this report, seems hard to achieve. Hence, it would have not been surprising if the value of the series resistance would have been higher than the initial one. Regarding the other parameters, in the ideal case they would have maintained the original value. However, we expected to see a change in the shunt resistance, both because the metal could have been sputtered on the edges, since the photoresist...
showed some problems in the sputtering chamber \(^7\) and because the etching - silicide formation required a lot of handling that could in principle shunt the cell. Moreover, the high temperatures required for the silicide formation could affect the performance of the cell. For example at temperature higher than 650 °C the Ag on the back contact melted and peeled off from the Al. Hence, we expected to see a decrement in the efficiency of the cell. However, in the case that this process could have been optimized, we could expect an increment in the efficiency, a reduction of the value of the series resistance and a reduction of the resistances losses percentage.

The fit of the IV curve and the loss analysis was however used in the characterization of the cells under filtered light, presented in the next section.

5.2 Behavior of the cells under filtered light (IV and QE)

In this section the results for the behavior of the cells under filtered light are discussed. In particular, the important results of the different measurements are highlighted and explained from a physical point of view. Moreover, based on these result, a discussion on the viability of the development of a tandem solar cell with these particular samples is reported.

The most evident result, from the results of the IV measurements reported in Table 3, is that the efficiency of both cells decreased in the filtered case. This result might not be obvious and expected, since the idea behind the tandem design is to improve the efficiency. However, the efficiency of the bottom cell will inevitably decrease due to a lower open circuit voltage. In fact, for both cells the open circuit voltage decreased as a consequence of the fact that the irradiance and hence the maximum current that can be produced with the respect to the incident spectrum is lower. This can be explained considering the fact that the open circuit voltage is derived from eq.4 considering the current equal to zero:

\[ V_{oc} = \frac{n k T}{q} \ln \left( \frac{I_L}{I_0} + 1 \right) \]  

(26)

The value of \(I_L/\text{area}\) in the two cases is different. For the unfiltered case it is around 431 A/m\(^2\) while in the filtered case it is around 228 A/m\(^2\). The short circuit current naturally decreased, since there are less photons that can contribute to the current, while the fill factor became slightly better. Since the fill factor is an indicator of the recombination losses in the solar cell, one would expect the recombination losses to be less in the filtered case than in the unfiltered case. Moreover, due to a lower number of electron that are promoted to the conduction band, the Auger recombination mechanism would probably become less important. This is however not the result that we got. Looking at Table 4 we can see that the recombination losses are higher in the filtered case. This can be explained considering that the recombination losses are related to the value of the open circuit voltage, lower voltage means more losses. Hence, two factors are affecting the recombination losses at the same time, which results in a net increment of those losses. From Table 4 we can also see that the generation losses increased, while the thermalisation losses decreased. This is a natural consequence of the fact that a different part of the spectrum is used. Since the lower wavelength are cut, there is less power available and wasted due to thermalisation, however, with respect to the total power available, now the photons that do not have enough energy to create an electron-hole pair contribute more in terms of power loss. The resistance losses decreased for the BSF2.1 sample, while they increased for the BSF2.2 sample. According to what was previously said in Section 2.2, we expected to have a reduction of resistive losses, however, they still remain negligible compared to the other mechanisms. The possible reason behind this disagreement between expected and experimental results can be that, as mentioned in Section 3.3, the values of the resistances are very difficult to obtain and since the loss analysis is based on the values calculated from the fit, it is not surprising that there is a disagreement. Regarding the other losses ("I_L" losses), they slightly increased. Since these losses are a collection of many different mechanisms, it is hard to determine exactly the reason why there is an increment.

Regarding the QE measurements, shown in Figure 24, we can see that the cell has, as expected, the same behavior for the filtered and unfiltered case, if one considers that the filter is not 100% transparent above 695 nm. Hence, not much new can be concluded from these measurements. However, these measurements were fundamental for the calibration of the IV setup. As said in Section 2.1.8, from the QE measurement

\(^7\)The photoresist seemed to burn during the sputtering leaving the edges uncovered.
it is possible to obtain the short circuit current. The short circuit current is then used to calibrate the IV setup, in order to obtain the same irradiance from the ELH as for the AM 1.5. In standard calibration condition, a reference cell is used for this purpose, however, it was necessary to calibrate the IV setup in the case of the filtered case, which was not possible to do with the reference cell. Hence, the short circuit current in filtered condition was calculated from the QE measurement (eq.8) for both samples and the height of the ELH lamp was then adjusted in order to obtain the same value for the short circuit current as it was calculated.

With respect to these results and consideration, would it be then possible to have a net gain in efficiency with a tandem design? Which are the requirements? The filter that was used was simulating a cell with a band gap approximately around 1.8 eV, hence the first "requirement", for consistency, would be that the band gap of the top cell is around 1.8 eV. This "forced" requirement represents, however, the best combination of band gaps with a Si solar cell [25]. Regarding the short circuit current and fill factor, the only requirement is that they have to be equal or better than the Si cell ones. This is because the efficiency of the tandem cell is not the sum of the efficiency of the different cells in the stack, but it is limited by the lower short circuit current and fill factor. Hence, in order to have a net gain in efficiency there is a need to develop a top cell with a higher open circuit voltage, to compensate the lower short circuit current and improve the efficiency, characteristics which are expected from a cell with a higher band gap.

5.3 Replacing the Ag contacts

The discussion will focus on the results achieved during the process of understanding how the Ag paste contacts work, if it is possible to remove them, what happens if we do not remove them completely and if it is possible to form the TiSi₂, together with a qualitative discussion about the replaced contacts. The discussion will follow the chronological order of the experiments, even if the results were presented in a different order. It has to be noticed that the IV curves presented are made in dark conditions. However, since the series resistance is related with the slope of the curve at the open circuit voltage and that the curve’s shape remain approximately the same in the dark and light case, it is possible to qualitatively discuss about it even with a dark IV measurement.

In Figure 25, the result of the EDS map on a sample which was only etched with the CR-7 etchant is shown. As we can see, in the grid (central big strip and thin horizontal line) there are Si, O, Pb and still Ag present. This means that even if the first etch removed the Ag, as far as we could see, Ag was still present. We then tried to etch the cell for more time, up until 30 min, to see if the Ag could have been etched, but it could not. This means that the Ag left is "protected", which is in agreement with Figure 15, which shows a layer of PbO on top of some Ag spikes. However, we tested the silicide formation after this first CR-7 etch. The results of this try are several. First, from Figure 28, we can see that the sample that was only etched and sputtered with Ti has a much higher series resistance than the sample which was not processed at all. This is just due to the fact that Ti is not as conductive as Ag, but nothing can be concluded about the difference in the series resistance. Second, the sample which was processed at 750ºC shows a linear behavior, which means that the pn junction is shunted (it behaves like a resistor). This can be explained by the fact that Ag diffuses in Si at temperatures above 650 ºC [4]. Hence, we tried to lower the temperature of the RTP to 450 ºC to see if the formation process could take place even with the interference of Ag. The results are reported in Figure 29. The most obvious result is that the sample which was processed is shunted, but this time it is not completely shunted, since it still shows a diode behavior. The shunt is a consequence of the fact that the Ti was sputtered also on the edges of the cell. A proof of this is the fact that we tried to clean the edges with very thin sand paper and the shunt disappeared. Moreover, what we can see is that the sample which was only sputtered with Ti and Al shows an identical shape as for the one that was not processed. This time it is possible to compare the two samples because they both have an Al film sputtered on top which works as a conductor. It is evident that the Ag which is left at the contact interface is still working as a contact and no silicide was formed. Hence, we tried a different etching approach. After the first CR-7 etch, a second etch with 20 H₂O : 1 H₂O₂ : 1 HF and a second CR-7 etch were done. The EDS results on this sample are shown in Figure
been made according to these previous results. They were etched first with CR-7, then with H
and to prevent oxidation in the time between the last etch and the sputtering. Three samples have then
been made according to these previous results. They were etched first with CR-7, then with H
samples were dipped in HF. This is a standard procedure in Si technology to remove any possible oxide
and to make an intimate contact between Si and Ti and form TiSi
2.
26, which is evident that there is no Ag or Pb left (what we see in the figure is uniform noise). The etch
with this HF solution etched the PbO that was protecting the Ag spikes and the second CR-etch etched
them. Hence, everything belonging to the Ag-paste contacts was removed. This allowed, in principle,
to make an intimate contact between Si and Ti and form TiSi
2. Before the sputtering of the metal the
samples were dipped in HF. This is a standard procedure in Si technology to remove any possible oxide
and to prevent oxidation in the time between the last etch and the sputtering. Three samples have then
been made according to these previous results. They were etched first with CR-7, then with H
2O
2 : 1 HF and again with CR-7. They were dipped in HF and Ti was sputtered on the surface. RTP has
done at 500 °C, 650 °C and 750 °C respectively. All the sample have been etched with NH
4OH : H
2O
2 : 6 H
2O at 30 °C in order to clean the unreacted Ti. This step was quite successful for the sample
made at temperatures lower than 650 °C, but it will have to be optimized for higher temperatures, since
the formation of TiN prevents the surface to be clearly cleaned in an etching time below 5 min (longer
etching time results in the etch of the back contact as well). Two techniques have been used to check if
the formation of the silicide was successful. In Figure 27, the EDS map shows that in the grid there is still
Ti present, while outside the grid it is not. This is a first proof that it might be that a reaction happened
and TiSi
2 was formed. Raman spectroscopy has also been done on the samples, showed in Figure 31
(left). A small peak at 269 cm
−1 indicate that TiSi
2 was indeed formed in this process. Comparing to the
literature [24], we would have expected more obvious silicide growth at the used temperature: in fact, our
results for RTP at 750 °C are similar to the results for [24] at 600 °C. However, the RTP has been done
placing the sample on a Si wafer and the temperature that the tool measured is the wafer temperature,
therefore it is possible that the actual temperature of the sample was lower. However, there is a clear
difference between the Raman done on the TiSi
2 and on the SiN part of the cell, shown in Figure 31
(right). It is evident that in the ARC part the peak at 269 cm
−1 is not present. Al was then evaporated
on the top surface and the results of the IV curves are shown in Figure 30. What we can conclude is that
a contact has been made, since the IV curve shows the typical diode behavior. However, the curves are
shifted, or reduced, with respect to the reference sample. This could be explain considering that during
the silicide formation, the Si of the emitter diffuses in the Ti and it is then "consumed". This reduction
of Si in the emitter should be further investigated to determine if it is the cause of the change in the IV
measurements. Moreover, all the samples look shunted. This could be due to inefficient edges protection
or a consequence of the annealing.

6 Conclusion and outlook

The MATLAB script developed in this project successfully fits the IV curves of BSF Si solar cells and
extrapolates the values of the components of the equivalent circuit. The loss analysis on the cells under
standard illumination shows that the generation losses together with the thermalisation losses account for
~50% of the total power loss as well as the recombination losses. The resistive losses can be considered
almost negligible since on average they account for less than 1% of the total power loss. Other losses
account for ~4-5% of the total power loss. In a tandem configuration, as expected, the thermalisation
losses are reduced. The other losses increased, but one can expect a net gain in efficiency if the top cell
satisfy the discussed requirements. The process of replacement of the original Ag contacts resulted in a
preliminary optimization of the SALICIDE process applied to the particular case of BSF Si solar cells.
In particular, an etching routine has been developed to prepare the Si surface for the silicide formation.
The requirement of multiple etching steps was rationalised by a model for the formation of screen-printed
Ag contacts on Si cells. The formation of TiSi
2 using the SALICIDE process and RTP at 750 °C was
successful and supported by both EDS maps and Raman scattering results. The formation of TiSi
2 at
lower temperatures could not have been supported by Raman scattering, even though the SEM results
show that Ti is left after the selective etching also after RTP at 500 °C. A qualitative characterization
of the cell after the contacts replacement was done, which allows us to conclude that silicides have been
formed, although a deeper understanding of the formed silicide is required to draw conclusions about the
resulted IV curves. A more proper test would involve the use of a transparent conductive oxide (TCO)
to allow a light IV measurement and a quantitative comparison between processed and unprocessed cells.
However, we do not know if the TCO will be conductive enough for the purpose and how it will be possible
to relate the results of the fit with the real tandem configuration, since in the real scenario nothing would
be placed on the silicides, but it will be work as a recombination interconnect. Probably, the best way to test the contacts would be to make a mask in order to sputter Al only on the collection grid. Moreover, different temperatures and RTP times should be tested in order to optimize the SALICIDE process as well as the etching of the unreacted Ti in order to clean the surface and maintain the Al back contact. A deeper understanding of the effect of high temperature treatment on the silicide contacts, in conditions mimicking the deposition of a top cell, should also be done in order to understand if the deposition of a possible solar cell would be possible.

7 Acknowledgements

There are many people that I would like to thank for their help and support during these past months. First of all my supervisor Jonathan Scragg for suggesting this project, sharing with me his many years of experience and answering all my questions. I would also like to thank Uwe Zimmermann and Jörgen Olsson, who managed to make me understand things when I was too stubborn to believe Jonathan, and all the department of engineering sciences for all the useful suggestions. A big thanks goes to Örjan Vallin, for the many hours spent with me in the cleanroom and to the MSL staff for teaching me and helping me with the equipment. Thank you to my mentor Matthias Weiszłog, who always supported me, guided me during these two years in the master programme and convinced me to follow my passion, even if it meant stepping in the dark side of engineering. Thank you to Luciano and Joakim, for sharing with me the experience of doing a thesis and for making me laugh even when there was nothing to laugh about. Thank you to all my friends, to my friend Martina, with whom I could complain in Italian and to my roommate Gabriela, who supported me when nothing was working. A special thanks to my boyfriend Matthias, who supported me and believed in me even if he doesn’t believe in the solar power. Most importantly a big thanks to my parents Mara and Diego for everything that they did for me in these 25 years.
The diode equation

The exponential dependence of the diode equation is derived considering the movement of the minority carriers, for example the holes, in the n-type region, which implies solving:

\[ \frac{d^2 p'}{dx^2} = \frac{p'}{L_p^2} \]  

(27)

where \( p' \) is the holes density in the n-type region and \( L_p \) is the diffusion length of the holes.

The boundary conditions are:

\[ p'(\infty) = 0 \]  

(28)

\[ p'(x_n) = p_{N0}(e^{qV/kT} - 1) \]  

(29)

Equation 29 is known as the quasi equilibrium boundary condition or Shockley boundary condition, where \( p'(X_N) \) is the holes density in the space charge region and \( p_{N0} \) is the holes density at the depletion region edge on the n-side.

The general solution of the equation is given by:

\[ p'(x) = Ae^{x/L_p} + Be^{−x/L_p} \]  

(30)

which, applying the boundary conditions and doing the same for the p-side, becomes:

\[ p'(x) = p_{N0}(e^{qV/kT} - 1)e^{−(x−x_N)/L_p}, \quad x > x_N \]  

(31)

\[ n'(x) = n_{P0}(e^{qV/kT} - 1)e^{−(x−x_P)/L_n}, \quad x < x_P \]  

(32)

From these equations one can derive the equation for the current density of holes, \( J_p \), on the n-side and electrons, \( J_n \), on the p-side:

\[ J_{pN} = -qD_p \frac{dp'(x)}{dx} = q \frac{D_p}{L_p} p_{N0}(e^{qV/kT} - 1)e^{−(x−x_N)/L_p} \]  

(33)

\[ J_{nP} = qD_n \frac{dn'(x)}{dx} = q \frac{D_n}{L_n} n_{P0}(e^{qV/kT} - 1)e^{−(x−x_P)/L_n} \]  

(34)

where \( D_p \) and \( D_n \) are the holes and electrons diffusion coefficients. The total current density at \( x ≃ 0 \) can then be expressed as the sum of the two terms:

\[ J = J_{pN}(x_N) + J_{nP}(x_P) = (q \frac{D_p}{L_p} p_{N0} + q \frac{D_n}{L_n} n_{P0})(e^{qV/kT} - 1) \]  

(35)

which is also the current density at every \( x \), since there is a constant current flow between the p- and n-region. Hence, we find the diode equation multiplying equation 35 by the area \( A \):

\[ I = I_0(e^{qV/kT} - 1) \]  

(36)

where

\[ I_0 = A(q \frac{D_p}{L_p} p_{N0} + q \frac{D_n}{L_n} n_{P0}) \]  

(37)

is the reverse saturation current of the diode.

More about this can be found in [26], on which this section is based.

---

9The space charge region is considered to be very narrow and \( x_N = x_P ≃ 0 \)
B Measured and extracted parameters

In Table 6 the values of the solar cell characteristic parameters, in Table 7 the extracted parameters from the one-diode model fit and in Table 8 the calculated percentage for each loss mechanism.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$V_{mp}$ [V]</th>
<th>$J_{mp}$ [mA/cm$^2$]</th>
<th>$V_{oc}$ [V]</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>FF [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF2_1</td>
<td>0.49</td>
<td>30.45</td>
<td>0.603</td>
<td>33.4</td>
<td>73.29</td>
<td>14.77</td>
</tr>
<tr>
<td>BSF2_2</td>
<td>0.49</td>
<td>29.73</td>
<td>0.601</td>
<td>32.9</td>
<td>73.58</td>
<td>14.57</td>
</tr>
<tr>
<td>BSF2_3</td>
<td>0.47</td>
<td>29.61</td>
<td>0.598</td>
<td>33.0</td>
<td>69.89</td>
<td>13.77</td>
</tr>
<tr>
<td>BSF2_4</td>
<td>0.49</td>
<td>30.31</td>
<td>0.603</td>
<td>33.2</td>
<td>74.15</td>
<td>14.85</td>
</tr>
<tr>
<td>BSF2_5</td>
<td>0.49</td>
<td>30.21</td>
<td>0.595</td>
<td>33.2</td>
<td>74.99</td>
<td>14.80</td>
</tr>
<tr>
<td>BSF2_6</td>
<td>0.50</td>
<td>30.03</td>
<td>0.610</td>
<td>33.2</td>
<td>74.17</td>
<td>15.02</td>
</tr>
<tr>
<td>BSF2_7</td>
<td>0.50</td>
<td>30.47</td>
<td>0.602</td>
<td>33.6</td>
<td>74.66</td>
<td>15.08</td>
</tr>
<tr>
<td>BSF2_8</td>
<td>0.49</td>
<td>30.88</td>
<td>0.603</td>
<td>34.1</td>
<td>73.57</td>
<td>15.13</td>
</tr>
<tr>
<td>BSF2_9</td>
<td>0.50</td>
<td>29.84</td>
<td>0.609</td>
<td>33.0</td>
<td>74.25</td>
<td>14.92</td>
</tr>
<tr>
<td>BSF2_10</td>
<td>0.50</td>
<td>30.71</td>
<td>0.610</td>
<td>33.8</td>
<td>73.78</td>
<td>15.20</td>
</tr>
</tbody>
</table>

Table 6: Values of the solar cell characteristic parameters for 10 different samples. IV setup calibrated with the provided calibration cell.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_{ab}$ [Ω]</th>
<th>$R_s$ [Ω]</th>
<th>$n$</th>
<th>$I_L$ [A]</th>
<th>$I_0$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF2_1</td>
<td>135</td>
<td>0.06</td>
<td>1.6</td>
<td>0.33</td>
<td>1.40E-07</td>
</tr>
<tr>
<td>BSF2_2</td>
<td>65</td>
<td>0.06</td>
<td>1.6</td>
<td>0.33</td>
<td>1.29E-07</td>
</tr>
<tr>
<td>BSF2_3</td>
<td>234</td>
<td>0.08</td>
<td>1.8</td>
<td>0.33</td>
<td>1.03E-06</td>
</tr>
<tr>
<td>BSF2_4</td>
<td>330</td>
<td>0.02</td>
<td>1.7</td>
<td>0.33</td>
<td>5.00E-07</td>
</tr>
<tr>
<td>BSF2_5</td>
<td>64</td>
<td>0.07</td>
<td>1.4</td>
<td>0.33</td>
<td>2.00E-07</td>
</tr>
<tr>
<td>BSF2_6</td>
<td>84</td>
<td>0.03</td>
<td>1.7</td>
<td>0.33</td>
<td>2.20E-07</td>
</tr>
<tr>
<td>BSF2_7</td>
<td>61</td>
<td>0.06</td>
<td>1.5</td>
<td>0.33</td>
<td>3.90E-08</td>
</tr>
<tr>
<td>BSF2_8</td>
<td>125</td>
<td>0.02</td>
<td>1.8</td>
<td>0.34</td>
<td>6.20E-07</td>
</tr>
<tr>
<td>BSF2_9</td>
<td>73</td>
<td>0.04</td>
<td>1.7</td>
<td>0.33</td>
<td>1.90E-07</td>
</tr>
<tr>
<td>BSF2_10</td>
<td>140</td>
<td>0.05</td>
<td>1.7</td>
<td>0.33</td>
<td>3.10E-07</td>
</tr>
</tbody>
</table>

Table 7: Extracted parameters for 10 different samples. IV setup calibrated with the provided calibration cell.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gen. (%)</th>
<th>Therm. (%)</th>
<th>Rec. (%)</th>
<th>$I_L$ (%)</th>
<th>Res. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF2_1</td>
<td>20.2</td>
<td>30.7</td>
<td>29.4</td>
<td>4.4</td>
<td>0.6</td>
</tr>
<tr>
<td>BSF2_2</td>
<td>20.2</td>
<td>30.7</td>
<td>29.5</td>
<td>4.6</td>
<td>0.5</td>
</tr>
<tr>
<td>BSF2_3</td>
<td>20.2</td>
<td>30.7</td>
<td>30.2</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
<td>BSF2_4</td>
<td>20.2</td>
<td>30.7</td>
<td>29.8</td>
<td>4.4</td>
<td>0.1</td>
</tr>
<tr>
<td>BSF2_5</td>
<td>20.2</td>
<td>30.7</td>
<td>29.2</td>
<td>4.6</td>
<td>0.6</td>
</tr>
<tr>
<td>BSF2_6</td>
<td>20.2</td>
<td>30.7</td>
<td>29.3</td>
<td>4.5</td>
<td>0.3</td>
</tr>
<tr>
<td>BSF2_7</td>
<td>20.2</td>
<td>30.7</td>
<td>29.1</td>
<td>4.4</td>
<td>0.6</td>
</tr>
<tr>
<td>BSF2_8</td>
<td>20.2</td>
<td>30.7</td>
<td>29.8</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>BSF2_9</td>
<td>20.2</td>
<td>30.7</td>
<td>29.3</td>
<td>4.6</td>
<td>0.3</td>
</tr>
<tr>
<td>BSF2_10</td>
<td>20.2</td>
<td>30.7</td>
<td>29.4</td>
<td>4.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 8: Loss analysis results for 10 different samples
References


