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**The Development of Bifacial Cells
with
Polysilicon Emitter and BSF Layers**

submitted by Jiang Du, M.Sc.
in partial fulfillment of the requirements
for the degree of Master of Engineering

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for
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Carleton University
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with
Polysilicon Emitter and BSF Layers**

by

Jiang Du

A thesis submitted to
the Faculty of Graduate Studies and Research
in a partial fulfillment of
the requirements for the degree of
Master of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Department of Electronics
Faculty of Engineering
Carleton University
Ottawa, Canada

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Carleton University
September, 1994

To my wife
and
To my parents

Abstract

A bifacial solar cell with poly silicon emitter and poly silicon back surface field (BSF) layer has been developed. This was based on the monofacial poly silicon emitter solar cell developed in our department. The BSF layer and bifacial structure were introduced. The BSF layer was a thin p^+ poly silicon layer deposited in amorphous phase and recrystallized later on. It was shown that the layer improved the open circuit voltage and short circuit current, just like a more conventional diffused back surface field. The relative energy conversion efficiency gain of the cells ranged from ~ 8 -18%, the extent dependent on the cell parameters such as substrate thickness and resistivity. The back metal contact was patterned to implement the bifacial cells. The Al/TiW/Ti structure metal contact was applied in order to keep the BSF layer thin. The total power output improvement due to introducing the bifacial structure was also examined. The maximum output power of the cells with front side illuminated only and back side illuminated only was measured respectively. The maximum output power of the cell with both sides illuminated was estimated. The output power was increased by $\sim 5\%$. The structure and process procedure have also been applied to multicrystalline silicon solar cell. The performance of the multicrystalline cell was close to the single crystal silicon cell with similar parameters. The good performance indicated that the shallow emitter and thin BSF layer worked well with the multicrystalline substrate. A numerical solar cell model was modified to incorporate the feature to calculate the solar cell performance with back illumination. The calculation results were compared with the experimental values and the method was used to simulate the two sides illumination condition which could not be realized experimentally with available equipment.

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I would like to take this opportunity to thank my supervisor Professor Gary Tarr for introducing me to this subject and for his guidance and help during my program. I would also like to thank Mr. Lyall Berndt, Mrs. Carol Adams and Mr. Yasuo Fujimoto for their helpful discussions and for their reliable and crucial technical support in device fabrication; and the Department of Electronics at Carleton University for the financial support in the progress of my work. I owe a lot to my wife and my family for their patience and support, without them the completion of the work would be impossible.

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List of Symbols

Symbol	Description
D	Diffusion coefficient (cm^2/s)
E	Energy (eV)
$F.F.$	Fill factor
G	Generation rate ($\text{cm}^{-3}\text{s}^{-1}$)
I	Current (A)
I_0	Saturation current (A)
I_L	Light-generated current (A)
I_m	Current at maximum power point (A)
I_{sc}	Short circuit current (A)
J	Current density (A/cm^2)
k	Boltzmann constant (J/K)
k_F, k_B	Ration of light entering from front and back
L	Diffusion length (cm)
$\dot{M}$	Photon flux ($\text{cm}^{-2}\text{s}^{-1}$)
N_A	Density of acceptors (cm^{-3})
N_D	Density of donors (cm^{-3})
N_T	Density of total impurities (cm^{-3})
n	Density of free electrons (cm^{-3})
n_i	Intrinsic density (cm^{-3})
P_{in}	Incident solar irradiance density (W/cm^2)
P_m, P_{max}	Maximum output power density (W/cm^2)
p	Density of free holes (cm^{-3})
q	Elementary charge (C)
R	Reflection coefficient
S	Normalized surface recombination velocity

S_F, S_B	Surface recombination velocities at front and back surface (cm/s)
T	Absolute temperature (K)
t	Thickness (cm)
U	Recombination rate (cm ⁻³ s ⁻¹)
V	Voltage (V)
V_m	Voltage at maximum power (V)
V_{oc}	Open circuit voltage (V)
W	Thickness (cm)
W_N	Emitter thickness (cm)
W_P	Base thickness (cm)
x	Distance from front surface (cm)
α	Absorption coefficient (cm ⁻¹)
η	Energy conversion efficiency
λ	Wavelength (μ m)
μ	Minority carrier mobility (cm ² /V-s)
τ	Minority carrier lifetime (s)
ψ	Barrier potential (V)

Chapter 1

Introduction

1.1 Background

Great improvement has been achieved in the performance of the silicon solar cells in the past twenty years.

Several innovations have been introduced into cell design since the early 1970s. The first resulted from the observation that alloying aluminium into the rear of the cell produced improved current and voltage output. The effect was initially attributed to gettering of impurities from the cell bulk by the aluminium [1, 2]. It was subsequently explained in terms of a heavily doped p-type layer produced at the rear surface by the alloyed aluminium [3, 4]. It is now commonly described as a “back surface field (BSF)” effect, although the effect can more usefully be described in terms of a reduction in minority carrier recombination velocity at the rear of the cell. The region with heavily doped aluminium suppresses minority carrier concentrations near the rear of the cell, restricting their flow to the back contact. The gettering effect of rear aluminium treatment has also since been well established [5, 6]. Although the BSF structure is often incorporated in commercial solar cells today, to distinguish the structure of solar cell conveniently, the cells without BSF layer will be called “conventional cells” and the cells with BSF layer will be called “BSF” cells in this thesis.

Further improvement was obtained by applying the photolithographic techniques developed for microelectronics to the definition of the top metal contact [7], using anisotropic etching to produce pyramids structure on the top surfaces [8], and by using thermally grown oxide to passify non-contacted areas of the cell to reduce minority carrier recombination at the front surface [9] and rear surface [10] of the cell. The highest terrestrial silicon cell efficiency confirmed to date has been obtained by the passivated emitter, rear locally diffused (PERL) cell which essentially combines the best features of the previous designs [11].

In the processes of solar cell development, the poly-Si contacts were applied in the mid-1980s. The enhancement in the open circuit voltage of MINP structure solar cells was demonstrated by incorporating polysilicon contacts on the front surface of cells to reduce the front surface recombination velocity [12]. Lindholm [13] used both n^+ and p^+ polysilicon layers followed by a high temperature diffusion as emitter contact and back surface field which gave further enhancements not only in the red spectral response but in the open circuit voltage of solar cells as well.

Polysilicon emitter bipolar transistors have demonstrated very low back-injection currents that resulted in substantial improvements on the performance of such devices [14]. It was the low injection current that played the key role in maximizing the open circuit voltage of a solar cell. This led to the development of a new solar cell structure at Carleton University [15], which employed a thin continuous layer of *in-situ* phosphorus doped polysilicon as the entire emitter region of the cell. This work was aimed at examining whether solar cells with this emitter structure would attain high open circuit voltages by exploiting the low back injection current of the polysilicon emitter structure. A diode quality factor of ~ 1.1 over seven decades of current was observed and a high open circuit voltage of ~ 650 mV was attained. But the fill factor was relatively low due to the high resistivity of the polysilicon.

A bilayer emitter structure was subsequently developed to improve the overall performance of solar cells based on the work mentioned above [16]. A very thin layer of silicon was deposited in the polycrystalline phase which established the desired

interface with single crystal substrate. The interface gave the favorable junction properties. A thicker amorphous layer was deposited and recrystallized on the top to reduce emitter sheet resistance. This was based on early experimental results which showed that the properties of the recrystalline amorphous layer were better than that of a layer deposited in the polycrystalline phase directly [17]. Short circuit current densities of 30 mAcm^{-2} combined with fill factors close to 0.8 were achieved with the structure. Open circuit voltages as high as 669 mV were obtained for cells formed on high-quality float zone substrates. Total-area efficiencies were up to 14%.

On the basis of the work above, a mono-layer emitter structure was established [18]. The very thin layer of polycrystalline silicon was no longer deposited. Instead the emitter was comprised of only 60nm of amorphous n^+ silicon layer recrystallized by annealing at 650°C and rapid thermal processing. The rapid thermal annealing process was to further reduce the sheet resistance of the n^+ layer while preserving good suppression of back injection and maintaining very shallow junctions. The low temperature processing also preserved long minority carrier lifetimes in high-quality substrates. The cells using such emitters have given total-area energy conversion efficiencies of 13.8% under AM1 illumination.

Conventional solar cells only receive sunlight from the front side. Bifacial solar cell structures have been introduced to produce power from light entering both the front and back sides of the cells [19, 20, 21]. In terrestrial applications, these cells can convert sunlight scattered from the ground below and adjacent to them. Thus, the cells can produce additional power from light reflected from the ground. For application in space, the earth's albedo would provide back illumination to boost the cell output. In both applications, the bifacial cells have shown higher total power output than conventional, single-sided cells. The performance of bifacial silicon cells has been reported [22] for space applications. The bifacial cells were found to be advantageous over silicon back-surface reflector cells in a variety of orbits.

In order to further improve the performance of polysilicon emitter solar cells, more work should be done on the cell structure. Although the present emitter structure

resulted in quite high open circuit voltage and fill factor, the structure at the back side still was substrate/metal contact which had very high surface recombination velocity. Therefore, there was room for the enhancement of the open circuit voltage, short circuit current, fill factor, and cell efficiency by applying back surface field technology and bifacial solar cell technology.

1.2 Thesis Objectives

The main purpose of the work described in this thesis was to apply back surface field (BSF) technology and bifacial solar technology to the polysilicon emitter solar cells. It was expected that improved performance of the solar cell in open circuit voltage, short circuit current, fill factor and efficiency would be obtained. The purpose of the work also included the study of the multicrystalline substrate solar cell structure which involved the effort to reduce the cost of solar cells.

The first objective was to apply a back surface field to the solar cells. This required development of a fabrication procedure in which a p^+ polysilicon layer could be deposited on the back side of the substrate while keeping the previously deposited n^+ polysilicon layer intact on the front side. Several new photolithography steps were added to the original polysilicon emitter solar cell process to accomplish this. After deposition, the BSF effect of the back side polysilicon was studied. This was done by measuring the electrical characteristics of the cells under illumination, stripping the back side polysilicon, re-applying a conventional metal back ohmic contact, and then measuring electrical performance again. The results were compared with theoretical predictions and the relation to the properties of silicon substrate was extracted by using various kinds of substrates.

The second objective was to apply polysilicon junctions in a bifacial solar cell structure. This was done using the structure described above, but the back side electrode was patterned to let sunlight enter the cell bulk from the back. The first

obstacle to be overcome in producing useful bifacial cells was the development of a chemical polishing procedure to smooth the backside of conventional single-sided polished starting substrates. The purpose of it was to ensure the successful lithography, which required a relative smooth surface. No attempt was made to texture the back surface to provide light trapping since the main goal was to study BSF effects. Texturizing the surface would expose crystal faces of (111) orientation which might have different properties compared with junction with (100) surface which was well known. Surface texturing should be explored in future work. The next consideration was to align the electrodes on both side of the cell. This was not only to guarantee getting the highest efficiency from the cell, but also to ensure the reliability of the BSF effect measurement. Because of the lack of standard measurement procedures to evaluate the performance of the bifacial solar cells, the cells were measured under front illumination only and back illumination only conditions. The performance of any double illumination condition was then calculated assuming the linear relation with light intensity. The value of open circuit voltage and short circuit current under sun and simulation light source was measured. More comparisons between experimental data and predictions of a numerical model was made.

The last objective was to apply the bifacial BSF solar cell structure to multicrystalline substrates. A similar approach to that used for the single crystalline substrates was applied. Using multicrystalline silicon substrates helps reduce the cost of solar cells. There were two ways to reduce cost: reducing the materials and process cost, and improving the performance of the cells. The former approach was taken when using multicrystalline substrate and the latter approach when applying the BSF layer or bifacial structure as in the first two objectives of the work.

1.3 Thesis Outline

This thesis is divided into 5 chapters. Chapter 1 gives a brief background and the purpose of the work. Chapter 2 introduces various theoretical models applied to

solar cells to predict and explain the performance of different kinds of solar cell structures. A numerical method based on semiconductor equations is presented. The BSF layer effect and bifacial cell performance under front illumination only, under back illumination only and under front and back illumination simultaneously are calculated using the method. Chapter 3 describes the fabrication apparatus briefly and explains the fabrication process of the bifacial BSF solar cells. The chapter also details the methods to remove a BSF layer and then re-fabricate a conventional solar cell on the same substrate. The descriptions emphasize the part of the processes which relates to the back surface field formation and alignment considerations between front and back electrodes. Chapter 4 presents experimental results on the photovoltaic performance of both bifacial BSF cells and conventional cells, including the difference in open circuit voltage, short circuit current, fill factor and efficiency between BSF and conventional cells, under front and back illumination conditions. Performance under different measurement conditions is also compared. The experimental data are compared with the values obtained by theoretical models and numerical calculations. At the end of the chapter, the performance of the multicrystalline silicon substrate solar cell is described and compared with single crystal silicon substrate cells. Finally, Chapter 5 gives the conclusions of the work and outlines the possible future work on the polysilicon emitter solar cells.

Chapter 2

The Structure of Bifacial BSF Cells

2.1 Conventional Cells

The structure of a conventional silicon homojunction solar cell is illustrated in Fig. 2.1 [23]. In the cell, the light is incident through a contact grid on a thin layer of n-type silicon. Various electronic processes occur in the cell. Six domains can be distinguished: (1) the front surface, where surface recombination loss of minority carriers can occur; (2) the metal contact to the n-type silicon, which introduces a contact resistance; (3) the bulk of the n-type region, which contributes mainly a series resistance along with some photocurrent; (4) the junction region itself with the associated depletion regions, where carriers are separated by the junction electric field; (5) the bulk of the p-type region, where most of the electron-hole pairs are generated by absorption of the light and where the minority carriers (electrons) are transported by diffusion and are partially lost by recombination, and (6) the metal contact to the p-type silicon, which introduces a contact resistance. The fundamental principles of solar cell operation are discussed in [23] and [24].

The generation rate for electron-hole pairs in the bulk region (5) is determined by

Figure 2.1: The structure of a conventional silicon homojunction solar cell.

the illumination flux and the optical absorption constant $\alpha(\lambda)$ of the silicon. The diffusion transport process is controlled by the mobility of the photogenerated minority electrons in the p-type region. The recombination loss can be described in terms of a lifetime τ for bulk recombination, as well as by a surface recombination velocity S for recombination of carriers generated near the free surfaces of the device.

The idealized junction current in the dark for the junction region (4) is given by the diode equation

$$I = I_0 \left(e^{qV/kT} - 1 \right) \quad (2.1)$$

where the diode saturation current I_0 can be expressed as [25]

$$I_0 = qn_i^2 \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right) \quad (2.2)$$

where D_n and D_p are electron and hole diffusion coefficient, L_n and L_p are the diffusion length of electrons in base region and diffusion length of holes in the emitter, and N_D and N_A are donor and acceptor concentrations. Eq. 2.1 assumes recombination in the depletion region is negligible. Under illumination, Eq. 2.1 becomes

$$I = I_0 \left(e^{qV/kT} - 1 \right) - I_L \quad (2.3)$$

where I_L is the light-generated current determined largely by the processes in the bulk p-type region (5). Fig. 2.2 shows plots of Eqs. 2.1 and 2.3 for an ideal junction in order to introduce some additional quantities commonly used in describing solar cells. These include the open circuit voltage V_{oc} , the short circuit current I_{sc} , the voltage for maximum power V_m , and the current for maximum power I_m . The efficiency of the cell is defined as the ratio of the maximum power P_m to the sun light power incident on the cell. A quantity called the fill factor $F.F.$ is commonly introduced to relate P_m to the product $V_{oc} I_{sc}$,

$$F.F. = \frac{I_m V_m}{I_{sc} V_{oc}} = \frac{P_m}{I_{sc} V_{oc}} \quad (2.4)$$

Thus the efficiency of a cell can be written as

$$\eta = F.F. \frac{I_{sc} V_{oc}}{P_{in}} = \frac{P_m}{P_{in}} \quad (2.5)$$

Figure 2.2: The typical dark and photo IV curve of solar cell.

where P_{in} is the incident solar power.

Setting I to zero in Eq. 2.3 gives the ideal value for the open circuit voltage

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right) \quad (2.6)$$

i.e., V_{oc} is determined by the properties of the silicon by virtue of its dependence on I_0 . In Eq. 2.2 for I_0 , it is assumed that the cell extends an unlimited distance on either side of the junction. An actual solar cell will have finite dimensions as indicated in Fig. 2.1. This modifies the value of the saturation current, I_0 . The modified value will depend on the surface recombination velocities at the exposed surfaces. It takes the form [26]

$$I_0 = qn_i^2 \left(\frac{D_n}{L_n N_A} F_P + \frac{D_p}{L_p N_D} F_N \right) \quad (2.7)$$

where

$$F_N = \frac{S_F \cosh \frac{W_N}{L_p} + \frac{D_p}{L_p} \sinh \frac{W_N}{L_p}}{\frac{D_p}{L_p} \cosh \frac{W_N}{L_p} + S_F \sinh \frac{W_N}{L_p}} \quad (2.8)$$

$$F_P = \frac{S_B \cosh \frac{W_P}{L_n} + \frac{D_n}{L_n} \sinh \frac{W_P}{L_n}}{\frac{D_n}{L_n} \cosh \frac{W_P}{L_n} + S_B \sinh \frac{W_P}{L_n}} \quad (2.9)$$

where S_F and S_B are the surface recombination velocity (SRV) at the front and back surfaces, and W_N and W_P are the widths of emitter and base regions respectively. If the surface on the p-type side of the device has a high surface recombination velocity, F_P has the form

$$F_P = \coth \left(\frac{W_P}{L_n} \right) \quad (2.10)$$

A corresponding expression will hold for F_N if the corresponding surface is also a high-recombination velocity surface. If it happens to be a low recombination velocity surface, then F_N would be given by

$$F_N = \tanh \left(\frac{W_N}{L_p} \right) \quad (2.11)$$

A similar expression would hold for F_P if the p-type region were also to have a low recombination velocity surface.

Note that the smallest value of I_0 and hence the largest V_{oc} will occur if both surfaces possess low recombination velocities. In fact, the surface recombination velocities at both front contact (n-type region surface) and back contact (p-type region surface) are very high for the conventional cells because the ohmic contact has a surface recombination velocity as high as 10^6 cm/s. Therefore, the expression of I_0 for the conventional cells is

$$I_0 = qn_i^2 \left(\frac{D_n}{L_n N_A} \coth \frac{W_P}{L_n} + \frac{D_p}{L_p N_D} \coth \frac{W_N}{L_p} \right) \quad (2.12)$$

The expression implies that the open voltage of the cell increases as the cell thickness increases.

2.2 Back Surface Field Cells

According to the expression for diode saturation current I_0 (Eq. 2.7) in the last section, low recombination velocity at the surfaces will result in a small I_0 which leads to a high open circuit voltage for the solar cell. Conventional cells have an ohmic metal back surface contact. At the contact, the minority carrier recombination velocity is as high as 10^6 cm/s.

In order to minimize SRV, a back surface field (BSF) layer was introduced into the solar cell [27], as illustrated in Fig. 2.3. The open circuit voltage of the BSF cells was improved considerably (e.g., higher than 580 mV with 10 Ω -cm wafers) and was independent of cell thickness. The measurements indicated that the effective SRV at back was reduced to the order of 1000 cm/s for a diffused Al-BSF [28, 29].

There are several models developed to explain the observed phenomena and give an expression for I_0 in back surface field cells. The three of them, conventional model, drift field model, and low-high junction (LHJ) model will be presented here.

Figure 2.3: The structure of a BSF silicon homojunction solar cell.

2.2.1 Conventional Model

A common view of the conventional n on p solar cell structure (Fig. 2.1) is one in which the p-type base dopant and properties are uniform, the device dimensions are finite, and contact effects are described by SRV. The I_0 for this general case has been derived by McKelvey [26] and has been presented in Eq. 2.7 of the last section. The SRV is represented by S , and L is the bulk diffusion length. This equation reduces to the following approximate forms.

1) *Infinite SRV Case.* When S_F and S_B are very large as would be the case for ohmic contacts, Eq. 2.7 reduces to the hyperbolic cotangent form Eq. 2.12. This case gives a reasonable description of the base region of the conventional cell structure.

2) *Zero SRV Case.* If the SRV's are assumed to be zero, Eq. 2.7 reduces to a second form now containing the hyperbolic tangent geometry factor.

$$I_0 = qn_i^2 \left(\frac{D_p}{N_D L_p} \tanh \frac{W_n}{L_p} + \frac{D_n}{N_A L_n} \tanh \frac{W_p}{L_n} \right) \quad (2.13)$$

where D_n and D_p are diffusion coefficients of electron and hole, and W_n and W_p are width of emitter and base region respectively. This case implies non-ohmic contacts.

3) *Diffusion Velocity Case.* If the SRV for the front and back contacts are equal to the minority carrier diffusion velocities (D/L) in each base region, F_N and F_P reduce to unity. This approximate I_0 is identical to the infinite base case given below.

4) *Infinite Base Case.* When the base region thicknesses are much greater than the bulk diffusion lengths, F_N and F_P again reduce to unity. The resultant I_0 is the well-known expression Eq. 2.2 derived by Shockley [25]. This case and the preceding case predict the I_0 to be independent of base region thickness.

Open circuit voltages calculated for a range of cell thicknesses and p-type base diffusion lengths using the finite width model are shown in Fig. 2.4. The dotted, solid, and dashed lines represent calculations for the infinite SRV, the zero SRV, and the special case where the SRV is equal to the diffusion velocity (D/L), respectively.

Voltages that are independent of cell thickness are predicted only for the last case. For very thick cells and a specified diffusion length, all cases predict voltages that are approaching the limiting values of the infinite width case. This is reasonable since the further away the back contact is from the junction the less it will influence the minority carrier distribution in the base. As the cell becomes thinner, the predicted open circuit voltages trends become very different. It is seen that the zero SRV case predicts open circuit voltages for thin cells that are well in excess of those predicted by the other two cases. In addition only the zero SRV case will predict open circuit voltages above 580mV for 10 Ω cm substrates provided the base diffusion length is substantially greater than 200 μ m

2.2.2 Drift Field Model

Practical solar cells are fabricated by diffusion and alloying processes which usually result in regions having significant nonuniform impurity distributions. It is easily shown that such distributions give rise to an electric field which can significantly influence minority carrier transport in those regions. Wolf [31] used a four layer model to calculate the cell I_{sc} using an expression for the collection efficiency which contains drift field effects. The cell was divided into subregions and exponential impurity distributions were assigned to each region. The important features of this model are that the minority carrier density and the current density are continuous at the subregion boundaries. The I_0 for this structure has been derived [32] and includes not only finite geometry and contact effects, but also the effect of subregion drift fields. The p-type base component of the n on p solar cell containing a drift field only in a thin region in front of the back contact is given by Eq. 2.14. The p-type base subregion nearest the junction is uniformly doped and therefore field free.

$$I_{0p} = \frac{qn_i^2}{N_A} \frac{D_{n1}}{L_{n1}} \left\{ \frac{c-1}{c+1} \right\} \quad (2.14)$$

where

$$c = e^{2\frac{(X-x_2)}{L_{n1}}} \left\{ \frac{-\left(\frac{1}{L_{n1}} - \gamma A_2\right)\left(\frac{R-A_2}{R-B_2}\right)e^{2G_{n2}(W-X)} + \left(\frac{1}{L_{n1}} + \gamma B_2\right)}{\left(\frac{1}{L_{n1}} - \gamma A_2\right)\left(\frac{R-A_2}{R-B_2}\right)e^{2G_{n2}(W-X)} - \left(\frac{1}{L_{n1}} + \gamma B_2\right)} \right\} \quad (2.15)$$

Figure 2.4: The dependence of open circuit voltage on cell thickness for conventional model. [30]

$$A_2 = \frac{qE_2}{2kT} - \left\{ \left(\frac{qE_2}{2kT} \right)^2 + \frac{1}{L_{n2}^2} \right\}^{1/2} \equiv F_{n2} - G_{n2} \quad (2.16)$$

$$B_2 = F_{n2} + G_{n2} \quad (2.17)$$

$$\gamma = \frac{D_{n2}}{D_{n1}} \quad (2.18)$$

$$R = \frac{qE_2}{kT} + \frac{S}{D_{n2}} \quad (2.19)$$

A similar expression is written for the n-type diffused region with the appropriate change in subscripts and by assuming a complementary error function (erfc) donor distribution. The drift field region is nearest the junction for this case. The total diode saturation current can be written

$$I_0 = I_{0n} + I_{0p} \quad (2.20)$$

Equation. 2.14 will reduce to the general SRV case given by Eq. 2.7 if a single layer, field free model is assumed.

The results of the voltage calculations for the drift field model with 10 Ω -cm substrates are shown in Fig. 2.5. A 0.5 μ m thick p⁺ region in which an exponential acceptor concentration profile exists was assumed. The p⁺ region diffusion length was assumed to be 1.0 μ m. It can be seen that the magnitude of the voltage depends on cell thickness and p-type base diffusion length. Below 540mV (i.e., approximately 200 μ m diffusion length) the V_{oc} is nearly independent of cell thickness. Above 540mV the open circuit voltage increases with increasing cell thickness similar to the infinite SRV case.

Fig. 2.6 shows the variations of the open circuit voltage for value of p⁺ region diffusion length between 1 and about 220 μ m. Calculations were made for p region diffusion length of 50, 200, and 600 μ m. The p⁺ region width is again 0.5 μ m. As shown, the diffusion lengths associated with both regions control the magnitude of the voltage and its dependence on thickness. Large values of p⁺ region diffusion lengths are necessary to produce high voltages in thin cells.

Figure 2.5: The dependence of open circuit voltage on cell thickness for drift field model. [30]

Figure 2.6: The effect of p^+ region diffusion length on open circuit voltage for drift field model. [30]

2.2.3 Low-High Junction (LHJ) Model

For the LHJ model in [30], the subregion boundary, unlike the drift field model, represents an abrupt transition between the thick, lightly doped p-type region (i.e., subregion nearest the junction) and the thin heavily doped p^+ region. Both regions are assumed uniform in dopant and materials properties. It has been shown by Gunn that this junction has the unique property of preventing excess minority carriers in the p-type base from entering the p^+ region. Majority carriers pass freely across this junction. The minority carrier concentrations at the space charge region edges depend on the barrier potential (ψ) associated with the low-high junction as shown in Eq. 2.21

$$n_p = n_{p^+} e^{\frac{q\psi}{kT}} \quad (2.21)$$

In addition, the diffusion currents at the p^+ and p region space charge edges are proportional to the gradients of the minority carrier densities there, and given by

$$qD_p \nabla n_p = qD_{p^+} \nabla n_{p^+} \quad (2.22)$$

Eq. 2.21 represents a subregion boundary condition which differs significantly from that assumed in the drift field model. Recombination effects and thickness of the LHJ space charge region are assumed negligible. The I_0 using this model is derived in [30]. The result for the p-side is given by Eq. 2.23:

$$I_{0p} = \frac{qn_i^2 D_n}{N_A L_p} \left\{ \frac{S + \tanh \frac{W_p}{L_p}}{1 + S \tanh \frac{W_p}{L_p}} \right\} \quad (2.23)$$

where

$$S = \frac{N_A}{N_{A^+}} \frac{D_{p^+}}{D_p} \frac{L_p}{L_{p^+}} \left\{ \frac{\frac{S_B L_{p^+}}{D_{p^+}} + \tanh \frac{W_{p^+}}{L_{p^+}}}{1 + \frac{S_B L_{p^+}}{D_{p^+}} \tanh \frac{W_{p^+}}{L_{p^+}}} \right\} \quad (2.24)$$

The parameter S is defined as a normalized surface recombination velocity. It contains the LHJ barrier factor (N_A/N_{A^+}) and the mobility and diffusion length ratios for the p and p^+ region. S also contains geometry factor for the p^+ region, the SRV for the metal- p^+ contact (S_B), and the p^+ region thickness (W_{p^+}). The total I_0 must include the n-type layer component I_{0n} . In the simplest case where n-type layer is viewed as a

uniformly doped region of finite thickness W_{n+} bounded by the space charge layer on the one side and a metal contact of surface recombination velocity S_F on the other, I_{0n} is described by

$$I_{0n} = \frac{qn_i^2 D_p}{N_D L_p} \left\{ \frac{\frac{S_F L_p}{D_n} + \tanh \frac{W_{n+}}{L_n}}{1 + \frac{S_F L_n}{D_n} \tanh \frac{W_{n+}}{L_n}} \right\} \quad (2.25)$$

However the diffused region contribution is always at least three orders of magnitude smaller than that of the p-type base, I_{0p} is always significantly greater than I_{0n} . Therefore I_{0n} is neglected and the total diode saturation current can be approximated by I_{0p} alone:

$$I_0 = I_{0n} + I_{0p} \approx I_{0p} \quad (2.26)$$

The results of voltage calculations using the low-high junction model are shown in Fig. 2.7 for a range of p-type base diffusion lengths. The p^+ region thickness and diffusion length are $0.5\mu\text{m}$ and $1.0\mu\text{m}$ respectively. Contrary to the drift field model, increases in the p^+ region diffusion length up to $200\mu\text{m}$ have no influence on the V_{oc} . The voltages for thick cells asymptotically approach those of the infinite base case since $W/L \gg 1$. For the conditions assumed, the shape and magnitude of the $V_{oc}/\text{thickness}$ curves are identical to those calculated for the zero SRV case. Thus, the zero SRV case, can be used, as an approximation to the LHJ model, to calculate cell V_{oc} with p-region diffusion length as the only variable. As in the previous models, the magnitude of the voltage is determined primarily by the p-type base diffusion length. In the LHJ model the parameter S , which incorporates properties of the LHJ and the p region, assume major importance in determining cell performance.

Fig. 2.8 shows a plot of the open circuit voltage against the magnitude of the normalized surface recombination velocity S . The calculations are made for several values of cell thickness for a p-base diffusion length of $574\mu\text{m}$. The figure shows clearly the influence of S on V_{oc} . For reference, the curve of Fig.2.7 corresponding to the $600\mu\text{m}$ diffusion length has an S equal to about 10^{-3} . For small values of S (less than unity), the voltage asymptotically approaches the values predicted by the zero SRV case shown in Fig.2.4. For large values of S , the V_{oc} approaches that predicted by the infinite SRV case. Thus Fig.2.8 shows graphically the manner in which the

Figure 2.7: The dependence of open circuit voltage on cell thickness for the low-high junction model. [30]

LHJ model reduces to both the zero SRV and infinite SRV models. For intermediate values of S in the range of 0.1 to 10, the voltage varies greatly between the two limiting cases. For S equal to unity, the voltage is independent of cell thickness and equal in magnitude to that predicted by the infinite width case.

2.2.4 BSF Effect Predicted by the Models

Based on the above data, the infinite SRV case can explain the experimental trends of the conventional cell. The trends of the BSF cell are predicted using either the zero SRV case, the drift field model, or the LHJ model. In all cases the fitting is critically dependent on the magnitude of the bulk diffusion length used in the calculations. For a given value of open circuit voltage and thickness, there is a corresponding unique value of the bulk diffusion length. In Fig. 2.4, Fig. 2.6 and Fig. 2.8, all models can predict the high voltages measured in BSF cells when the W/L ratio of the p-base is less than unity. For the drift field model, the voltages will be nearly independent of cell thickness only for a particular value of p⁺-region L which is about 2.5 μm for the 580mV case.

The predictions made by various models on conventional cells and BSF cells were presented above. There are also numerical analysis methods to simulate the performance of the solar cells which can give not only the open circuit voltage but also short circuit current. In the next sections, bifacial structure solar cells will be described and a numerical analysis method and programs [33] will be presented.

2.3 Bifacial Cells

Bifacial cell structures are advantageous in getting more electric power from the sunlight when solar cells are operated in the field where much higher albedo is available. The photovoltaic sensitivity to the light coming from the rear side of the cell enhances the current output. There are basically two kind of bifacial homojunction cell struc-

Figure 2.8: The dependence of open voltage on normalized surface recombination velocity S . [30]

tures. The first consists of an n^+pp^+ structure in which a metal grid is deposited on both sides for contact as illustrated in Fig. 2.9. The second then consists of an n^+pn^+ structure (Fig. 2.10). With this structure, the interdigitated back contact (IBC) [34] is used to make the contact to back n^+ layer and to the p-type substrate. A preliminary experiment [35] indicated that the n^+pp^+ structure cell had higher V_{oc} value and was cheaper to manufacture because of the smaller number of mask alignment steps required. Also, the series resistance was lower, which would give higher fill factor. On the other hand, the n^+pn^+ structure had a higher I_{sc} value and higher $V_{oc} \times I_{sc}$ product. Of course it was expensive to make. In this thesis, only the n^+pp^+ structure bifacial solar cell will be dealt with.

2.4 A Numerical Analysis of Solar Cells

In this section a numerical analysis method developed by Tarr [33] is introduced. The programs will be modified to emulate the back side illumination and both side illumination situations. The programs will be used to simulate the performance of the bifacial BSF solar cells in this thesis.

2.4.1 The Basic Semiconductor Equations

The operation of any solar cell is governed by the five basic equations of semiconductor physics: the continuity equations, the current equations, and Poisson's equation. Normally, only steady-state operation is of interest for solar cells. Further, only one-dimensional devices will be considered. The basic equations are listed below in their steady-state, one-dimensional form.

Continuity Equations:

$$\frac{1}{q} \frac{dJ_n}{dx} + G - U = 0 \quad (2.27)$$

$$-\frac{1}{q} \frac{dJ_p}{dx} + G - U = 0 \quad (2.28)$$

Figure 2.9: The structure of a bifacial n^+pp^+ solar cell.

Figure 2.10: The structure of a bifacial n^+pn^+ solar cell.

Current Equations:

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx} \quad (2.29)$$

$$J_p = q\mu_p pE - qD_p \frac{dp}{dx} \quad (2.30)$$

Poisson's Equation:

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\epsilon}[N_D - n_p - N_A] \quad (2.31)$$

where J_n and J_p are electron and hole current densities, μ_n and μ_p are electron and hole mobilities, n and p are electron and hole densities, G is the net generation rate by external process such as illumination, U is net recombination rate, E is electric field.

Before any progress can be made in solving the basic equations, boundary conditions must be imposed on n , p and ψ at the front and back surfaces of the cell. It is conventionally assumed that at the front surface the electron concentration is fixed at its thermal equilibrium value and the electron quasi-Fermi level coincides with the Fermi level in the metal contact to the emitter. Analogous boundary conditions are applied to the hole concentration and quasi-Fermi level at the back surface. These two conditions automatically determine the electrostatic potential drop across the cell for any applied bias V . Further boundary conditions are imposed by specifying surface recombination velocities for minority carriers. At the front surface,

$$-J_p(x_F) = qS_F \frac{d}{dx} p_n(x_F) \quad (2.32)$$

while at the back surfaces

$$-J_n(x_B) = qS_B \frac{d}{dx} n_p(x_B) \quad (2.33)$$

2.4.2 Numerical Solution of the Basic Semiconductor Equations

The Seidman and Choo algorithm [36] is applied to the modelling of silicon homojunction solar cells in this thesis. The algorithm considers only the recombination

through trapping centers and assumes that the dependence of U on n and p could be accurately described by a Shockley-Read-Hall model [37] with a single trapping level at midgap. In this case,

$$U = \frac{np - n_i^2}{\tau_p(n + n_i) + \tau_n(p + n_i)} \quad (2.34)$$

The basic equations are linearized and the variables in the equations are normalized. The linearized basic equations are then solved by iteration.

2.4.3 Photogeneration

The photogeneration distributions contributed by front illumination and back illumination were calculated separately and were added together to give the total distribution. For the front illumination

$$G_F(x_j) = \sum_i e^{-\alpha(\lambda_i)x_j} M(\lambda_i) \Delta\lambda_i \quad (2.35)$$

and for the back illumination

$$G_B(x_j) = \sum_i e^{-\alpha(\lambda_i)(t-x_j)} M(\lambda_i) \Delta\lambda_i \quad (2.36)$$

where G_F and G_B were the photogenerations caused by front illumination and back illumination, α was absorption coefficient, M was photon flux, t was the thickness of the cell, and x was the distance from the front surface of the cell. For both cases, the reflectance at the surface of the cell was taken as zero, i.e., $R(\lambda) = 0$. The total distribution of photogeneration therefore was the sum

$$G(x_j) = k_F G_F(x_j) + k_B G_B(x_j) \quad (2.37)$$

where k_F and k_B were the ratios of incident sunlight intensities to AM1 intensity at front and back side respectively. It was assumed that the spectrum of the sunlight incident on both sides was the same as AM1. Fifteen wavelength intervals $\Delta\lambda_i$ were used to span the solar spectrum from the wavelength corresponding to the silicon bandgap to the ultraviolet; λ_i is the central wavelength of the i th interval. The

Wavelength Interval $\Delta\lambda_i$ (μm)	α (cm^{-1})	M ($\text{m}^{-2}\text{s}^{-1}$)
0.28 - 0.32	1.8×10^8	7.52×10^{18}
0.32 - 0.36	1.2×10^8	4.48×10^{19}
0.36 - 0.40	1.2×10^7	6.87×10^{19}
0.40 - 0.44	4.4×10^6	1.18×10^{20}
0.44 - 0.48	2.3×10^6	1.69×10^{20}
0.48 - 0.52	1.4×10^6	1.79×10^{20}
0.52 - 0.56	9.0×10^5	1.76×10^{20}
0.56 - 0.60	6.3×10^5	1.75×10^{20}
0.60 - 0.64	4.0×10^5	1.90×10^{20}
0.64 - 0.68	3.0×10^5	1.83×10^{20}
0.68 - 0.72	2.0×10^5	1.83×10^{20}
0.72 - 0.76	1.6×10^5	1.71×10^{20}
0.76 - 0.80	1.0×10^5	1.61×10^{20}
0.80 - 1.00	4.1×10^4	7.00×10^{20}
1.00 - 1.20	5.0×10^2	5.91×10^{20}

Table 2.1: Data used to compute photogeneration distribution.

absorption coefficient $\alpha(\lambda_i)$ was extracted from the graphical data presented by Sze [23], while the total photon flux $M(\lambda_i)\Delta\lambda_i$ in the interval was computed from the AM1 spectral composition specified in [38]. These data are summarized in Table 2.1.

2.4.4 The Selection of Parameters

The empirical relations between the electron and hole mobilities and the substrate doping level (Equ. 2.38 and 2.39) were used in the programs. These expressions provide an approximation to the mobility data collected by Sze [23].

$$\mu_n = \frac{\mu_{n0}}{\left(1 + \frac{N_T}{N_{0\mu n}}\right)^{a_{\mu n}}} \quad (2.38)$$

where $\mu_{n0} = 1350 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, $N_{0\mu n} = 5.0 \times 10^{16} \text{ cm}^{-3}$ and $a_{\mu n} = 0.45$

$$\mu_p = \frac{\mu_{p0}}{\left(1 + \frac{N_T}{N_{0\mu p}}\right)^{a_{\mu p}}} \quad (2.39)$$

where $\mu_{p0} = 480 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, $N_{0\mu p} = 1.0 \times 10^{17} \text{ cm}^{-3}$ and $a_{\mu p} = 0.40$ The electron and hole lifetime were related to the doping level through the formulas

$$\tau_n = \frac{\tau_{0n}}{1 + \frac{N_T}{N_{0n}}} \quad (2.40)$$

and

$$\tau_p = \frac{\tau_{0p}}{1 + \frac{N_T}{N_{0p}}} \quad (2.41)$$

as suggested by Fossum [39]. Following [39], τ_{0n} and τ_{0p} were set equal to $1.7 \times 10^{-5} \text{ s}$ and $3.5 \times 10^{-7} \text{ s}$ respectively, while N_{0n} and N_{0p} were both set equal to $7.1 \times 10^{15} \text{ cm}^{-3}$.

The front n^+/p junction is simulated as a Gaussian doping profile, while the back surface conditions are represented by back surface recombination velocity S_B . The value of S_B is taken as 10^6 cm/s for the ohmic contact of the conventional cells and 1000 cm/s for p/p^+ interface of the BSF cells. As can be seen in last few sections, the former assumption is close to the infinite SRV case in conventional model and large S case in LHJ model at the back surface. The latter assumption on the other hand is close to the zero SRV case in conventional model and small S case in LHJ model at the back surface. The assumptions are based on the cells having an abrupt interface between uniform doped p and p^+ layers rather than nonuniform doped layers in the drift field model.

The behaviour of the voltage predicted by the numerical methods therefore is expected to be similar to the results given by the conventional model and LHJ model. Furthermore, the numerical methods can also predict both voltage and current behaviours in the different cell thicknesses, wafer resistivities, and illumination conditions.

2.5 Bifacial BSF Cells Characteristics Predicted by Numerical Method

The behaviours of open circuit voltage and short circuit current of bifacial n^+pp^+ BSF solar cells were calculated using the numerical analysis method described in the last section. For comparison, the voltage and current of conventional n^+p bifacial cells were also calculated.

First, the dependence of cell performance on cell thickness was examined. The doping concentration of the p-base was chosen as $5 \times 10^{16} \text{ cm}^{-3}$, and the depth of the front junction was $0.5 \mu\text{m}$. The light intensity was assumed as AM1 when illuminated by front side only and back side only. In the situation of illumination from both sides, the intensity of front side was chosen as AM1 and of the back side was 30% of the front side with the same spectrum. Setting the back light intensity at 30% of that of the front was done because the albedo is 30 to 50% of the sunlight in the practical operation [40]. The results are shown in Table 2.2.

As expected, the open circuit voltage of the conventional cells increases with the increase of the cell thickness and the open circuit voltage of BSF cells decreases with the increase of cell thickness when illuminated from front side. When illuminated from the back side only, the open circuit voltage of both conventional and BSF cells are decreased.

The short circuit current of both kind of cells increases when illuminated from the front side and the short circuit current decreases when illuminated from the back side as the thickness increases. This is because with the thicker cell, more carriers are collected by the junction when the cell is illuminated from the front side. Although light is absorbed when the cell is illuminated from the back side, the number of collected carriers decreases rapidly because the junction is farther away from the back surface where most carriers are created. The total current of the cell with both sides illuminated, as calculation indicates, is decreasing when the thickness increased

Cell Thickness (μm)			100	200	300
Open Circuit Voltage (mV)	Front Side Illuminated	Conventional Cells	542	555	559
		BSF Cells	566	563	562
	Back Side Illuminated	Conventional Cells	484	480	474
		BSF Cells	560	545	531
	Both Sides Illuminated	Conventional Cells	543	555	559
		BSF Cells	571	567	564
Short Circuit Current Density (mA cm^{-2})	Front Side Illuminated	Conventional Cells	34.0	35.6	36.1
		BSF Cells	36.2	36.3	36.4
	Back Side Illuminated	Conventional Cells	3.61	1.97	1.37
		BSF Cells	28.5	18.0	10.9
	Both Sides Illuminated	Conventional Cells	35.1	36.2	36.5
		BSF Cells	44.8	41.8	39.8

Table 2.2: Open circuit voltage and short circuit current density as the function of cell thickness with different illumination modes. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode

since the decrease of the current relating to back illumination is much faster than the increase of the current relating to front illumination.

The BSF effect is more effective for thinner cells, i.e., a greater increase in open circuit voltage and short circuit current is observed. The most striking effect is the great boost of the current in thinner cells with back side illumination. For the 100 μm cells, the current density increases from 3.61 mA cm^{-2} to 28.5 mA cm^{-2} with back side illumination and therefore boosts from 35.1 mA cm^{-2} to 44.8 mA cm^{-2} , i.e., increased by 28%, with both sides illuminated.

The results suggest that better cell performance can be achieved when the BSF structure is used on the thinner substrate and the cell is working with both sides illuminated. But the use of thinner, 100 μm thick for example, substrates has its drawback: the cell will become very fragile.

The cell performance as a function of junction depth was investigated. The thickness of the cells was fixed at 200 μm and the substrate doping concentration was

Junction Depth (μm)			0.5	0.06
Open Circuit Voltage (mV)	Front Side Illuminated	Conventional Cells	555	555
		BSF Cells	563	563
	Back Side Illuminated	Conventional Cells	480	479
		BSF Cells	545	543
Short Circuit Current Density (mA cm^{-2})	Front Side Illuminated	Conventional Cells	35.6	38.3
		BSF Cells	36.3	39.1
	Back Side Illuminated	Conventional Cells	1.97	1.97
		BSF Cells	18.0	18.1

Table 2.3: Open circuit voltage and short circuit current density as the function of junction depth of the cells under different illumination modes. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode

still at 5×10^{16} . Two junction depths were chosen: $0.5 \mu\text{m}$ and a much shallower $0.06 \mu\text{m}$. The results are demonstrated in Table 2.3. The results show that the open circuit voltage behaviours of both conventional and BSF cells, front and back illuminated, are same regardless of the depth of the junction. The current for illumination from the back side is also almost independent of junction depth. The only difference happens in the situation when the cell is illuminated from the front side. The short circuit current of both the conventional and BSF cells increases with the use of a shallow junction. This can be explained by the reduction of the carrier loss in the n^+ layer in which minority carriers are most likely to recombine before crossing the junction because of the short diffusion length.

Finally, the cell performance as a function of substrate resistivity was calculated. The thickness of the cell was $200 \mu\text{m}$ and the depth of the junction was $0.5 \mu\text{m}$. Two resistivity values were used, $2.5 \Omega\text{-cm}$ and $10 \Omega\text{-cm}$. The corresponding doping concentrations are $5 \times 10^{16} \text{ cm}^{-3}$ and 1.5×10^{16} respectively. The results are presented in Table 2.4. The clear result is that, with increasing substrate resistivity, the open circuit voltage drops and the short circuit current rises regardless of the cell structures and illumination conditions. That is because the high resistivity, i.e., the low doping concentration, means the smaller junction potential barrier and larger minority carrier

Substrate Resistivity ($\Omega\text{-cm}$)			2.5	10
Open Circuit Voltage (mV)	Front Side Illuminated	Conventional Cells	555	525
		BSF Cells	563	538
	Back Side Illuminated	Conventional Cells	480	453
		BSF Cells	545	524
Short Circuit Current Density (mA cm ⁻²)	Front Side Illuminated	Conventional Cells	35.6	36.1
		BSF Cells	36.3	36.9
	Back Side Illuminated	Conventional Cells	1.97	2.08
		BSF Cells	18.0	20.3

Table 2.4: Open circuit voltage and short circuit current density as the function of substrate resistivity under different illumination modes. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode

diffusion length. The former results in the lower voltage output and latter gives the higher photo-current of the cell. Therefore, there is tradeoff between the open circuit voltage and the short circuit voltage in choosing the resistivity of the substrate. Comparing the drop of voltage and rise of current, the low resistivity substrate is favorable because it has the larger voltage current product which implies the higher conversion efficiency.

In summary, considering the results of the simulation described above, solar cells will have better performance when they are made in bifacial BSF structure with shallow front junction using thinner, low resistivity silicon wafers.

Chapter 3

The Preparation of the Cells

In this chapter, the considerations in designing bifacial back surface field (BSF) solar cells are presented. The experimental procedures used in fabricating the bifacial conventional and BSF cells are described respectively next.

3.1 Design Considerations

The bifacial BSF solar cells investigated in this thesis were developed based upon the polysilicon emitter solar cells described by Tarr et al [18]. The cross section view of the cell is illustrated in Fig. 3.1. The structure of the cell utilized the property of suppression of hole back injection observed in npn polysilicon emitter BJTs to provide high open-circuit voltages [15, 16]. It also kept the processing temperature low enough to make a shallow emitter junction possible and preserve long minority carrier lifetimes in high-quality substrates. This approach has been shown to give an emitter of near ideal characteristics [41] while at the same time giving higher current by letting more incoming light enter the cell.

In order to further enhance the open circuit voltage and utilize the albedo light, the BSF layer and bifacial structure were introduced into the above cells.

Figure 3.1: The structure of a conventional polysilicon emitter solar cell.

From the analysis results at the end of the last chapter, the favoured structure was the cell with shallow front junction and thin, low resistivity substrate. For the same reason that a shallow front junction is desirable, it is best if the BSF layer is kept thin. In other words, the thin BSF layer minimized the number of the minority carriers which recombined in the highly doped layer and let more carriers contribute to the total current. To get a thin BSF layer, the production of the BSF used low temperature processes only to prevent the dopant atoms diffusing into the wafer. It would not damage the shallow front junction and preserved all the merits the shallow junction cells had. Furthermore, it had advantages of using the same technology to produce both the emitter and BSF layer. Taking these considerations into account, polysilicon deposited by LPCVD was used to form the BSF layer.

For the bifacial cell structure, the back metal contact was to be patterned to allow albedo light penetration from back side of the cell. In order to carry out this patterning by photolithography, the back surface had to be relatively smooth. A backside polishing step was therefore carried out before any other processing was done. The other advantage of the process was that the thickness of the wafers was reduced. The performance of the cells based on these wafers was expected to be improved.

The structure of the metal contact was modified to correspond to the new cell design structures. The original metal contact at front side was patterned Al/TiW/Ti, with thick Al and thin TiW/Ti. The purpose of TiW/Ti was to prevent the aluminum diffusion through the thin emitter layer. The metal contact at the back side was a simple thick unpatterned Al layer.

For the bifacial cells, the same structure used for the front metal contact was applied to the back side of the cell. That was done because the BSF layer was thin and the aluminum-only conventional back metal contact would allow the aluminum to penetrate through the BSF layer, possibly destroying the BSF effect. The added layers of metals prevented damage to the BSF layer and kept the BSF fully effective. The cross section view of a bifacial BSF solar cell is shown in Fig. 3.2.

Figure 3.2: The structure of a bifacial BSF solar cell.

A specific technical problem faced in fabricating the bifacial cells was the alignment of the back electrode to the device well and electrode on the front side. This would not be critical for cells occupying an entire wafer. But it was necessary for the cells described in this thesis since only part of each 5 cm diameter starting wafer was used to form a solar cell. The metal contact mask was therefore modified to allow for alignment of the grid pattern to the wafer's edge. The mask patterns are shown in Fig. 3.3. As can be seen, five scale arms were added to the pattern. The arms could be used to help measure the distance of the pattern from the wafer edges, and the double arms at the bottom then used for determining the orientation of the pattern to the major flat. Alignment of the back electrode to the front is important to minimize cell series resistance.

The effect of the BSF layer was examined by comparing the conventional and BSF cells. The conventional cell was obtained by removing the BSF layer and making a new back metal contact. The change of the cell performance reflected the effect of the BSF layer because the measurements were carried out on the same cell with the only difference being the presence or absence of a BSF layer. The reliability of the measurements were also helped by the modified mask pattern due to good alignment between front and back contacts before and after the removal of the BSF layer.

The complete process was also applied to the multicrystalline silicon substrate bifacial solar cell. The wafer was smoothed and became thinner. There was no high temperature process involved which was essential because grain boundary diffusion in the multicrystalline silicon wafer had to be avoided. The highest temperature long time process was the recrystallization step which was at 650°C for 60 minutes. The other relatively high temperature process was the rapid thermal annealing step at 850°C for 5 seconds. Hartiti [42] pointed out that the diffusion depth of the dopant atoms into a multicrystalline silicon substrate was less than 0.15 μm with a RTA process at 850°C for 25 seconds. Therefore, the thin emitter and BSF were not affected by the RTA process for which the increase in the thickness of both emitter and BSF layers on the multicrystalline silicon substrate was very small. This was

Figure 3.3: The original (top) and modified (bottom) patterns of the metal contact mask. The size of the cell is $2\text{cm} \times 2\text{cm}$, the width of fingers is $19.5\mu\text{m}$ and the distance between fingers is $711\mu\text{m}$. The grid finger shading is 3%.

also true for the single crystalline silicon substrate, for which diffusion was expected to be even smaller than in the multicrystalline silicon case.

The fabrication of bifacial BSF and conventional solar cells, with both single and multicrystalline silicon substrates, is explained step by step in the following sections. The run sheet for the cell fabrication is given in Appendix A and B.

3.2 Fabrication of the Bifacial BSF Solar Cells

3.2.1 Pretreatment of the Wafers

Solar cells were fabricated on 5cm diameter p-type single crystal silicon wafers of $\langle 100 \rangle$ orientation. One additional cell was fabricated on a multicrystalline silicon wafer. The doping levels of the single crystal silicon substrates were in the range of $10^{15} - 10^{16} \text{ cm}^{-3}$, and their initial thickness were in the range of 250 - 320 μm . Different bulk resistivities was selected from those available in the silicon wafer inventory of the Department of Electronics. To concentrate the study on BSF effect, relatively lightly doped wafers were selected. 1.8-2.5 $\Omega\text{-cm}$ Czochralski (CZ) single side polished, 3.2-4.3 $\Omega\text{-cm}$ CZ single side polished, 8-10 $\Omega\text{-cm}$ CZ single side polished, and 1-10 $\Omega\text{-cm}$ CZ double side polished wafers were used as starting substrates. The one multicrystalline wafer was Wacker SILSO material of 1.5 $\Omega\text{-cm}$ resistivity.

As the first step, the resistivity and thickness of each wafer was measured and the results are listed in Table 3.1.

Because both front and back metal contacts of bifacial cells were going to be patterned by lithography, both surfaces of the wafer were required to be relatively smooth. Therefore, the rough side of the single side polished wafers and both sides of the multicrystalline silicon wafer needed to be chemically polished.

Before carrying out the process, the polished side of the wafer was covered by

Wafer #	Type	Polished Side(s)	Resistivity (Ω -cm)	Thickness (μ m)	
				Before Etching	After Etching
#1	p type Cz single	single	2.26	310	220
#2	p type Cz single	single	2.36	320	260
#3	p type Cz single	single	3.69	270	210
#4	p type Cz single	single	3.41	270	220
#5	p type Cz single	single	7.23	280	230
#6	p type Cz single	single	7.65	270	220
#7	p type Cz single	double	6.99	260	
#8	p type Cz single	double	8.39	260	
#9	p type Cz single	double	13.08	250	
#10	p type Cz single	double	10.59	260	
#20	p type multicrystal	none	1.44		270

Table 3.1: The resistivity and thickness of wafers.

a layer of wax which protected this surface from the etching solution. The wafers were first immersed in HF solution to remove the oxide layer on the surface to be smoothed. The wafers were then etched using HNO_3 : CH_3COOH : HF solution in the ratio of 5:3:3. The etch rate was about $16 \mu\text{m}/\text{min}$ [43]. The etch time was 5 minutes. After etching was completed, each wafer was rinsed in DI water and blown dry with compressed N_2 . The wax was removed in warm trichloroethylene followed by a rinse in acetone and DI water. Shining mirror-like surfaces were obtained. The thickness of the wafers was reduced and measured again. The results are also listed in Table 3.1.

3.2.2 Fabrication of the Emitter and BSF Layers

The wafers were initially RCA cleaned to remove any organic and metal contaminants from the surface as well as any residual oxide. A Lotox deposition of $\sim 300\text{nm}$ of SiO_2 followed in order to provide some degree of surface passivation. The actual thickness of the oxide was measured using an AME-500 Ellipsometer after the deposition.

The device wells then were opened on the front side. The mask used was CU-106-01-0B as shown in Fig. 3.4. Because the next step would be to deposit the n^+ layer on the front side of the wafer and the n doped layer simultaneously deposited on the back side needed to be removed, the SiO_2 on the back was left in place to separate the n doped layer from the wafer. Therefore the back side was protected by photoresist while the device wells were opened. After device wells were opened, the wafers were RCA cleaned, flash dipped in 10% hydrofluoric acid (HF) until windows turned hydrophobic, and then spun dry and loaded as quickly as possible into a Low Pressure Chemical Vapour Deposition (LPCVD) reactor in order to minimize growth of an interfacial native oxide between n^+ emitter and p wafer base.

The LPCVD system consisted of a horizontal quartz tube reactor in a conventional three zone furnace. Wafers were loaded back-to-back vertically in a quartz boat so that the wafers were perpendicular to the tube axis. Silane and phosphine source gases supplied to the reactor were controlled independently by mass flow controllers, allowing the phosphine/silane flow ratio to be easily adjusted. The pressure was determined by the pumping speed of the unthrottled vacuum pump. The deposition temperature was monitored by a thermocouple which extended into the reactor just below the wafers. Since the structure of the deposited silicon is critically dependent on the deposition temperature, particularly at temperatures close to the amorphous/polycrystalline transition, the temperature profile was maintained as flat as possible ($\pm 2^\circ\text{C}$) over the length of the wafer load.

The emitter layer was deposited in amorphous phase from a 160/1 silane to phosphine mixture for 85 minutes at a temperature of 560°C and a pressure of 0.4 Torr. The thickness of the layer was 60nm. The emitter then was patterned using Mask CU-106-02 (Fig. 3.5). The solution used to pattern the amorphous layer was $\text{HF}/\text{HNO}_3/\text{H}_3\text{PO}_4/\text{DI}$ and the temperature was 20°C . The n doped layer on back side of the wafer was removed at same time while the front side layer was patterned.

In order to protect the patterned front side n^+ type emitter during BSF deposition, an oxide layer was deposited to separate the p^+ BSF layer from the n^+ emitter layer.

Figure 3.4: The pattern of mask CU-106-01-0B.

Figure 3.5: The pattern of mask CU-106-02.

After the RCA cleaning of the wafers, a 300 nm thick layer of SiO_2 was deposited by the LOTOX technique. The oxide layer was removed from the wafer back side by etching in buffered hydrofluoric acid while the front side was protected by photoresist.

The wafers once again were RCA cleaned, flash dipped in 10% hydrofluoric acid (HF) until the back side surface turned hydrophobic, and then spun dry and loaded rapidly into the above mentioned LPCVD reactor. The BSF layer was deposited in amorphous phase using an 80/1 silane to diborane mixture gas at a temperature of 475°C and a pressure of 0.4 Torr. The deposition time was set at 30 minutes to give a p^+ layer thickness of 60nm. At this temperature, the p^+ layer was deposited in the amorphous phase. The BSF layer at the back side then was protected with photoresist. The p doped layer at the front side was wet etched away using $\text{HF}/\text{HNO}_3/\text{H}_3\text{PO}_4/\text{DI}$ (10:300:100:150) solution at 20°C .

The initially amorphous emitter and BSF layers were next recrystallized into the polycrystalline phase by annealing for 60 minutes at 650°C in a nitrogen ambient.

Most wafers were then rapid thermal annealed in flowing N_2 in an AG Associates Heatpulse 210 system. It consisted of a quartz tube chamber heated by two rows of tungsten halogen lamps, one above and the other below. The wafer was transported to the chamber through a flat quartz stand attached to the chamber door. After loading each wafer, the chamber was purged with N_2 gas to expel any air present, the constituents of which were likely to contaminate the wafer, i.e., cause unwanted oxidation. The wafer was then heated by the radiant energy of the lamps. The wafer temperature was monitored through a chromel alumel thermocouple embedded in a T-shaped silicon piece and pre-calibrated to gauge the temperature of the wafer being processed. As the chamber was quite small, the ambient condition could be controlled very efficiently. The operating temperature was controlled at 850°C . The heating rate is of the order of $100 - 150^\circ\text{C}$ per second. The annealing time during which the temperature maintained at 850°C was 5 seconds.

After recrystallization and RTA processes, the oxide layer on the top of the device

wells at the front side was etched away. The emitter and BSF layers were then exposed and the wafers were ready for contact formation.

3.2.3 Preparation of the Front and Back Contacts

A Ti/TiW/Al structure was used to form both front and back metal contacts. The Ti/TiW layers acted as a barrier to prevent aluminum penetrating through the thin emitter and BSF layers. The Ti and TiW were RF sputtered and Al was e-beam evaporated. A dilute hydrofluoric etch was performed for 10 to 15 seconds immediately before putting wafers into sputtering system chamber to remove native oxide. The back contact was formed first.

A multitarget sputtering system (MRC SEM-8620) having both sputter etch and RF bias capabilities was used. The titanium-tungsten target used in this work had a 10:90wt% Ti:W composition while both the $\text{Ti}_{0.1}\text{W}_{0.9}$ and Ti targets were of 99.99% purity. The targets were located 7 cm from the substrate. The deposition chamber was evacuated to a base pressure of $\sim 5 \times 10^{-7}$ Torr prior to the introduction 60 sccm of high purity (99.999%) argon flow to a partial pressure of about 8×10^{-3} Torr. Both the $\text{Ti}_{0.1}\text{W}_{0.9}$ and Ti targets were sputter cleaned for one minute at 1.4kV RF peak voltage prior to each corresponding deposition, while 100W RF power was used throughout the sputtering process. The front surface of the wafers was sputter etched for 30 seconds at 950V RF peak voltage in order to remove native oxide, and then the Ti and $\text{Ti}_{0.1}\text{W}_{0.9}$ films were sputter-deposited sequentially on the wafers without breaking vacuum. Both the Ti and $\text{Ti}_{0.1}\text{W}_{0.9}$ were sputtered at 1.4kV RF peak voltage for 2 minutes and 20 minutes respectively, depositing a $\sim 0.01\mu\text{m}$ thick Ti film and a $\sim 0.2\mu\text{m}$ $\text{Ti}_{0.1}\text{W}_{0.9}$ film on sample wafers.

The aluminum film was then deposited on top of the Ti/TiW films by e-beam evaporation using a Balzer Evaporator. The chamber was cryopumped to a base pressure of 10^{-6} Torr. The aluminum film was deposited at a rate of $15\text{\AA}/\text{sec}$ to a thickness of $4\mu\text{m}$. The pressure during deposition was $1-2 \times 10^{-6}$ Torr and the

thickness of Al was measured by monitoring the change in frequency of a quartz-crystal oscillator exposed to the evaporation.

The Ti/TiW/Al metal on the back side was patterned using Mask CU-106-03-0B (Fig. 3.6). The alignment between the front and back electrodes was critical. The scale arms on each side of the pattern were used. The distances of the back electrode to the wafer edges were easily measured with the help of the arms. The orientation of the back electrode to the wafer was then measured using double arms at one side of the pattern. The proper orientation and position of the front electrode were determined by adjusting the distances marked by the five arms. The error of the readings was within few tenth of millimeters and the front and back electrodes were satisfactorily aligned with each other.

To avoiding undercutting while etching the $5\mu\text{m}$ thick aluminum, a two step etch process was used. The etch solution was H_3PO_4 heated to 60°C . The wafers were initially put into the solution for four minutes. The wafers were then pulled out of the solution, rinsed in deionized water to stop the reaction and baked for 10 minutes at 130°C to reharden the predefined photoresist pattern. The wafers were then put back into the etching solution to finish the patterning of the aluminum film.

The TiW layer was patterned using water/ammonium-hydroxide/hydrogen-peroxide ($\text{DI}:\text{NH}_4\text{OH}:\text{H}_2\text{O}_2$) solution at the ratio of 5:1:1 for about two minutes. The remaining Ti film was then quickly patterned using 5% HF solution for 10 seconds.

The front metal contact was made using essentially the same procedures. After the deposition of Ti/TiW/Al layers, the Mask CU-106-03-0B (Fig. 3.6) was used to pattern the front metal. After the photoresist used to pattern the front metal was exposed, developed and hardened, a layer of photoresist was painted on the top of the back electrode to protect it. The front metal was then patterned by etching the unwanted Ti/TiW/Al using the same solutions as in patterning the back metal contact.

Finally, the devices were given a 20 minute heat treatment at 400°C in a hydrogen

Figure 3.6: The pattern of mask CU-106-03-0B.

ambient in order to anneal the radiation damage introduced on both surfaces during the sputtering and evaporation processes.

3.3 BSF Removal and Cell Re-Fabrication

Following electrical characterization, the BSF bifacial cells were reprocessed into bifacial cells without BSF layers. The back metal contact and BSF layer were removed, and the back metal contact was then re-formed to give bifacial conventional cells which had same front structure as the bifacial BSF cells. This process gave a reliable basis for the comparison of the conventional and BSF cells, even with only a limited number of samples.

The back metal contact was first removed. The aluminum, titanium tungsten and titanium layers were etched in H_3PO_4 at 60°C , $\text{DI}/\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$ solution and HF respectively, while the front electrode was protected by painting on a layer of photoresist.

The p^+ BSF layer was then plasma etched away using a Technics PELIA planar Plasma Etcher. The chamber was pumped to $\sim 10^{-3}$ Torr and conditioned at the power of 300W under 0.5 Torr O_2 ambient followed by another conditioning process at the power of 100W under 0.3 Torr CF_4/O_2 ambient. The wafer was then placed into the chamber with the BSF layer facing up. The etching was performed using a power of 100W in 0.3 Torr CF_4/O_2 ambient for a duration of 5 minutes. As the etching rate of boron doped polysilicon was $\sim 1000\text{\AA}/\text{min}$ and the thickness of BSF layer was $600\text{\AA}$, this ensured that the BSF layer was totally removed from back side of the cell.

The back metal contact of the conventional cell was made of aluminum only because the barrier layer was no longer needed. A $4\mu\text{m}$ aluminum layer was deposited by e-beam evaporation. The cells were then given a 20 minute heat treatment at 400°C in a hydrogen ambient. The electrical characteristics of the cells were then

measured. At this stage the cells were functioning as conventional monoface devices.

After the measurements, the back contact grid was finally patterned using the double etching process described in the last section. The bifacial conventional cells were then tested. The measurement results of bifacial n^+pp^+ BSF cells, monofacial n^+p conventional cells, and bifacial n^+p conventional cells were compared.

Chapter 4

Cell Performance

The photo characteristics, i.e., short circuit current I_{sc} , open circuit voltage V_{oc} , fill factor $F.F.$, and energy conversion efficiency η , of the solar cells are presented in this chapter. The measurements were taken at three stages of cell refabrication. Measurements were first performed on complete bifacial BSF cells with the back surface field layer and patterned back metal contact in place. The second measurement was carried out after the BSF layer was removed and a new back metal contact was produced, but before the back metal was patterned. The cell structure at this stage was monofacial conventional cell. The last measurement was taken after the back metal contact was patterned. The structure was then a bifacial conventional cell. Comparison was made between BSF cells and conventional cells, front illumination and back illumination condition, as well as before and after back metal patterning. The back surface field effect contributed by the p^+ polysilicon layer was evaluated. The efficiency improvement of the BSF cell over the conventional cell, and bifacial cell over monofacial cell, was calculated and estimated.

4.1 The Measurement Setups

Energy distribution of the illumination spectrum is an important parameter in the evaluation of the photovoltaic performance of a solar cell. Two kinds of light sources are usually used to measure the photo characteristics of cells: natural sunlight and simulated sunlight. The advantage in using natural sunlight is that it gives results without the error introduced by the spectral deviation from the desired solar energy distribution. This is especially important in measuring the parameters which are sensitive to the spectrum of light, e.g., measuring the short circuit current. In fact, the photocurrent varies with the choice of the simulated illumination spectrum because the spectrum varies considerably among different solar simulators [44, 45]. The disadvantage of using natural sunlight is the irradiance variations due to changes in atmospheric conditions. Solar simulators avoid this problems and usually give more reproducible results.

In the experiments described in the thesis, both natural sunlight and light from a solar simulator were used to measure the photo characteristics of solar cells. The former was used to obtain the true photocurrent while the latter was used to compare the performance of different cell structures.

The experimental test setup is shown in Figure 4.1. The solar cells were positioned on a portable vacuum chuck to receive light at normal incidence. The operating temperature of the solar cell was monitored by a temperature sensor attached on the chuck, and was adjusted by a temperature control unit so as to maintain an operating cell temperature at $25 \pm 1^\circ\text{C}$. The illuminated I-V characteristics of the solar cells were obtained with the aid of an HP4145A semiconductor parameter analyzer, by applying and varying a forward bias voltage on the cell from zero to one volts. A calibrated cell provided by ASEC (Applied Solar Energy Corporation) with a AM1 rated photocurrent of 83.2mA was used as standard reference cell for indirect indication of the level of the total incident light intensity. The reference cell reading was taken just prior to and after I-V characteristics measurements in order to check and, in the

case of the halogen light source, if necessary adjust the intensity of the incident light. The measurements in natural sunlight were carried out in Ottawa during the months of July and August, only on clear days and between 1 pm to 3 pm daylight savings time. When the halogen lamp was used as the light source, the intensity of light was controlled at a fixed level at which the current reading of the standard cell was $83.2 \pm 2 \text{ mA}$. The intensity was equivalent to incident sunlight of $100 \text{ mW cm}^{-2} \pm 2.5\%$ if the spectrum difference was not taken into consideration.

4.2 The Back Surface Field Cell Measurements

The measurement results which exhibit BSF effect are presented in this section. The BSF effect on cell performance with front illumination under natural sunlight or halogen lamp light is listed in Tables 4.1 to 4.4 and the BSF effect on cell performance with back illumination is listed in Tables 4.5 to 4.8. Note that all the data for cell #4 in conventional structure were obtained with the back metal contact unpatterned.

4.2.1 The BSF Effect with Front Illumination

Table 4.1 shows the BSF effect on the open circuit voltage of the cells. The results of natural sunlight and halogen lamp illumination are quite consistent. They all show improvement in open circuit voltage for all kind of wafers examined, with resistivity varying from $2 \Omega \text{ cm}$ to $13 \Omega \text{ cm}$. The results indicate that the polysilicon p^+ layer at the back side of the cell does act as a back surface field layer. The p^+ layer suppresses the recombination of minority carriers, i.e., electrons, at the back surface of the p type wafer and results in an increase of open circuit voltage in the cells.

Because of the good repeatability of measurements, the results obtained with halogen lamp illumination are used to evaluate the effect of the BSF. The increase of open circuit voltage due to the p^+ layer is in the range of 7 to 14 mV. Generally speaking, higher increase is observed in cells which have higher voltage in a conventional struc-

Figure 4.1: Experimental test set-up for photo I-V characteristics measurement.

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	V_{oc} (mV)	Conventional Cells	563	547	540	551	552
		BSF Cells	576	562	549	558	564
	ΔV_{oc} (mV)		13	15	9	7	12
	$\Delta V_{oc}/V_{oc}$		2.3%	2.7%	1.7%	1.3%	2.2%
Halogen Light Illuminated	V_{oc} (mV)	Conventional Cells	566	554	543	554	552
		BSF Cells	577	564	550	567	566
	ΔV_{oc} (mV)		11	10	7	13	14
	$\Delta V_{oc}/V_{oc}$		1.9%	1.8%	1.3%	2.3%	2.5%

Table 4.1: Back surface field effect on open circuit voltage with 1 sun at front side. All cells, except #4, have their back metal contact patterned.

ture. For example, the percentage increase of cells #8 and #9 are $\sim 2.4\%$ and cell #6 is only 1.3% .

The open circuit voltage of conventional cells changes with substrate resistivity and cell thickness. The trend is consistent with the prediction made by the conventional and LHJ models as well as the numerical calculations in Chapter 2: lower resistivity and thicker substrate give higher open circuit voltage. The models and calculations predict that the voltage gain due to BSF is large for thinner substrate and, to a lesser extent, for higher resistivity substrate. The experimental results show that the voltage gain due to BSF is larger for thicker substrates, and no obvious conclusion can be drawn regarding its resistivity dependence.

The BSF effect on short circuit current density is shown in Table 4.2. It is obvious that the results of halogen lamp illumination are more consistent than that of the natural sunlight illumination. Therefore the current values obtained by halogen illumination are used to analyze the BSF effect. The results once again support the conclusion that the p^+ polysilicon BSF structure used is effective and boosts the short circuit current. Table 4.2 shows that, with the BSF structure, the current density

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	J_{sc} (mAcm^{-2})	Conventional Cells	22.0	20.7	22.6	23.6	22.4
		BSF Cells	21.7	22.4	22.9	23.2	22.6
	ΔJ_{sc} (mAcm^{-2})		-0.3	1.7	0.3	-0.4	0.2
	$\Delta J_{sc}/J_{sc}$		-1.4%	8.2%	1.3%	-1.7%	0.9%
Halogen Light Illuminated	J_{sc} (mAcm^{-2})	Conventional Cells	19.7	21.2	21.9	22.6	21.3
		BSF Cells	22.0	21.6	22.7	24.0	22.5
	ΔJ_{sc} (mAcm^{-2})		2.3	0.4	0.8	1.4	1.2
	$\Delta J_{sc}/J_{sc}$		11.7%	1.9%	3.7%	6.2%	5.6%

Table 4.2: Back surface field effect on short circuit current density with 1 sun at front side. All cells, except #4, have their back metal contact patterned.

increase is in the range from 0.4 to 2.3mAcm^{-2} . The percentage increase is between 1.9% and 11.7%.

The trend observed for open circuit voltage still holds for short circuit current. In general, more current gain is obtained when the substrate is thick. Once again, this is not what the conventional, LHJ models and numerical calculations predict. The models indicate that the current gain will decrease when the thickness of the cell increases if the minority carrier diffusion length in the base region is constant.

The BSF effect on fill factor is presented in Table 4.3. Essentially the fill factor is between 65% and 72% and the BSF cells have slightly higher fill factor. The much higher fill factor of conventional cells than that of BSF cell #4 is due to the structure of the back metal contact rather than the BSF effect and will be discussed in Section 4.4.

Finally, the overall effect of the presence of a BSF on a cell is reflected in the energy conversion efficiency. The results are shown in Table 4.4. It is known that the efficiency is determined by the three factors mentioned above, i.e., it is the product

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	<i>F.F.</i> (%)	Conventional Cells	64.3	71.1	70.0	68.2	61.6
		BSF Cells	64.3	64.3	71.2	71.5	66.6
	$\Delta F.F.$ (%)		0	-6.8	1.2	3.3	5.0
	$\Delta F.F./F.F.$		0%	-9.6%	1.7%	4.8%	8.1%
Halogen Light Illuminated	<i>F.F.</i> (%)	Conventional Cells	65.7	71.2	70.0	68.3	60.5
		BSF Cells	64.3	65.3	72.2	71.5	65.7
	$\Delta F.F.$ (%)		-1.4	-5.9	2.2	3.2	5.2
	$\Delta F.F./F.F.$		-2.1%	-8.3%	3.1%	4.7%	8.6%

Table 4.3: Back surface field effect on fill factor with 1 sun at front side. All cells, except #4, have their back metal contact patterned.

of short circuit current, open circuit voltage and fill factor. Therefore, the behaviour of efficiency can be deduced from the behaviour of the three factors.

From the table it can be seen that the efficiency gain is from as low as 8.2% for the thin cell #6 to 17.7% for the thicker cell #9. Note that these efficiencies were measured without antireflection coating on the cells. The efficiency will be greatly improved when antireflection coating is applied to the cells. The photo I-V curves of two typical conventional and BSF cells under front illumination are illustrated in Figures 4.2 and 4.3.

4.2.2 The BSF Effect with Back Illumination

Tables 4.5 to 4.8 display the BSF effect on cell performance with back illumination. All the parameters except fill factor show a large discrepancy between the measurement results obtained by natural sunlight illumination and by halogen lamp illumination. This is because of the spectral difference between natural sunlight and halogen lamp light. Since the spectrum of the halogen lamp is richer in red light

Figure 4.2: Photo I-V curves of conventional and BSF cells with front side illuminated (Cell #2).

Figure 4.3: Photo I-V curves of conventional and BSF cells with front side illuminated (Cell #8).

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	η (%)	Conventional Cells	7.96	8.05	8.54	8.87	7.62
		BSF Cells	8.04	8.10	8.95	9.25	8.49
	$\Delta\eta$ (%)		0.08	0.05	0.41	0.38	0.87
	$\Delta\eta/\eta$		1.0%	0.6%	4.8%	4.3%	11.4%
Halogen Light Illuminated	η (%)	Conventional Cells	7.33	8.36	8.33	8.55	7.11
		BSF Cells	8.16	7.95	9.01	9.73	8.37
	$\Delta\eta$ (%)		0.83	-0.41	0.68	1.18	1.26
	$\Delta\eta/\eta$		11.3%	-4.9%	8.2%	13.8%	17.7%

Table 4.4: Back surface field effect on energy conversion efficiency with 1 sun at front side. All cells, except #4, have their back metal contact patterned.

which can penetrate deeper into the cell, the voltage and current of the cell with back illumination using the halogen lamp is much larger than that using natural sunlight and gives incorrect results. Therefore the results with natural sunlight illumination will be used to analyze the performance of the cells with back illumination.

Table 4.5 shows the BSF effect on the open circuit voltage of the cells for backside illumination. It shows improvement in open circuit voltage for all types of wafers used here. The results confirm the fact that the polysilicon p^+ layer at the rear of the cell acts as a back surface field layer. The increase of the open circuit voltage due to the p^+ layer is in the range of 35mV to 73mV, much larger than the improvement of the open circuit voltage seen with front side illumination. The open circuit voltage is close to that observed with front illumination, especially for the cells #8 and #9 with thicker and high resistivity substrates.

The BSF effect on short circuit current density for backside illumination is shown in Table 4.6. The results essentially follow the same pattern as the open circuit voltage and once again support the conclusion that the BSF structure used is effective. The p^+ polysilicon back layer boosts the short circuit current in the range from 1.5 to 6.3

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	V_{oc} (mV)	Conventional Cells	427		494	485	492
		BSF Cells	500	527	529	530	541
	ΔV_{oc} (mV)		73		35	45	49
	$\Delta V_{oc}/V_{oc}$		17.1%		7.1%	9.3%	10.0%
Halogen Light Illuminated	V_{oc} (mV)	Conventional Cells	489		511	511	507
		BSF Cells	537	535	535	543	547
	ΔV_{oc} (mV)		48		24	32	40
	$\Delta V_{oc}/V_{oc}$		9.8%		4.7%	6.3%	7.9%

Table 4.5: Back surface field effect on open circuit voltage with 1 sun at back side. All cells, except #4, have their back metal contact patterned.

mAcm^{-2} . The percentage increase is between 109% to 225% which is a significant improvement for bifacial applications. The most significant improvement happens in the case of cell #9 which has thicker and high resistivity substrate, just like the situation of open circuit voltage.

The BSF effect on fill factor under backside illumination is presented in Table 4.7. Generally the fill factor is between 65% and 73% and the BSF cell has slightly higher fill factor. This is the same as the fill factor of the cells measured with front illumination. The only exception is the fill factor of cell #2, with low resistivity and relatively thicker substrate, which has a very low value for the conventional structure and is improved by almost 30% for the BSF structure.

The overall effect of the BSF on cell performance is reflected in the energy conversion efficiency which is shown in Table 4.8. The efficiency of the cells with back illumination is improved greatly due to the increase of the open circuit voltage and short circuit current, especially the latter. The percentage increase of the efficiency is between 150% and 275% and the efficiency of most cells is increased to the range of 3 to 4% from only $\sim 1\%$. The I-V curves of two typical conventional and BSF cells

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	J_{sc} (mAcm^{-2})	Conventional	1.37		4.26	3.18	2.78
		BSF Cells	2.86	6.88	10.3	8.63	9.03
	ΔJ_{sc} (mAcm^{-2})		1.49		6.04	5.45	6.25
	$\Delta J_{sc}/J_{sc}$		108.8%		141.8%	171.4%	224.8%
Halogen Light Illuminated	J_{sc} (mAcm^{-2})	Conventional	3.13		6.83	5.71	5.05
		BSF Cells	5.03	9.09	12.2	11.1	10.8
	ΔJ_{sc} (mAcm^{-2})		1.9		5.4	5.4	5.8
	$\Delta J_{sc}/J_{sc}$		60.7%		78.6%	94.4%	113.9%

Table 4.6: Back surface field effect on short circuit current density with 1 sun at back side. All cells, except #4, have their back metal contact patterned.

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	$F.F.$ (%)	Conventional Cells	52.1		72.7	65.5	70.3
		BSF Cells	67.6	68.7	71.4	69.3	73.5
	$\Delta F.F.$ (%)		15.5		-1.3	3.8	3.2
	$\Delta F.F./F.F.$		29.8%		-1.8%	5.8%	4.6%
Halogen Light Illuminated	$F.F.$ (%)	Conventional Cells	60.1		73.6	68.5	69.9
		BSF Cells	67.2	67.2	73.5	70.5	73.1
	$\Delta F.F.$ (%)		7.1		-0.1	2.0	3.2
	$\Delta F.F./F.F.$		11.8%		-0.1%	2.9%	4.6%

Table 4.7: Back surface field effect on fill factor with 1 sun at back side. All cells, except #4, have their back metal contact patterned.

Cell Number			#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	3.41	7.65	8.39	13.08
Thickness (μm)			260	220	220	260	250
Natural Sunlight Illuminated	η (%)	Conventional Cells	0.31		1.53	1.01	0.96
		BSF Cells	0.97	2.49	3.89	3.17	3.59
	$\Delta\eta$ (%)		0.66		2.36	2.16	2.63
	$\Delta\eta/\eta$		212.9%		154.2%	213.9%	274%
Halogen Light Illuminated	η (%)	Conventional Cells	0.92		2.57	2.00	1.79
		BSF Cells	1.82	3.27	4.80	4.25	4.32
	$\Delta\eta$ (%)		0.90		2.23	2.25	2.53
	$\Delta\eta/\eta$		97.8%		86.8%	112.5%	141.3%

Table 4.8: Back surface field effect on energy conversion efficiency with 1 sun at back side. All cells, except #4, have their back metal contact patterned.

under back illumination are illustrated in Figs. 4.4 and 4.5.

In the Tables 4.5 to 4.8 it can be observed that, for the conventional cells, both the open circuit voltage and the short circuit current decrease as cell thickness increases. This agrees with the prediction of conventional and LHJ model as well as numerical calculations. The number of electron hole pairs separated by the front junction decreases when the front junction is farther away from the back of the cell where most electron hole pairs are created when the cell is illuminated from the back side.

The great improvement of voltage and current with back illumination due to the BSF layer is also predicted. The low surface recombination velocity of minority carriers makes the carriers more likely to be collected by the front junction to provide voltage and, especially, current gain. But by examining the thickness dependency of both voltage and current gain, it is found that the trend deviates from what the models predict if the same value of minority carrier diffusion length is used in all thickness situations. That is, the amount of voltage and current improvement increase with the thickness of the cells, while the models predict less improvement for thicker cells.

Figure 4.4: Photo I-V curves of conventional and BSF cells with back side illuminated (Cell #2).

Figure 4.5: Photo I-V curves of conventional and BSF cells with back side illuminated (Cell #8).

4.3 The Bifacial Cell Measurements

The measurement results related to the bifacial cell structure are presented in this section. The performance of bifacial conventional cells is listed in Tables 4.9 to 4.12 and that of the bifacial BSF cells is listed in Tables 4.13 to 4.16. In the tables the values of open circuit voltage, short circuit current, fill factor and maximum output power measured with front and back illumination, using natural sunlight and halogen lamp light, are listed. For the short circuit current, the value is estimated for the situation of being illuminated from both sides simultaneously. The condition of the illumination is assumed to be 1 sun at the front side and 0.3 sun at the back side. Therefore the estimated value of the current is the value for front illumination only plus the 30% of the value for back illumination only. In order to estimate the value of the power output with both sides illuminated, the voltage and fill factor values are estimated first. It is simply assumed that the open circuit voltage and fill factor are the same as in the case of front illumination only. The value of the power output with bifacial illumination is then calculated using these open circuit voltage, short circuit current and fill factor values. The natural sunlight illumination results are used in the calculations and comparisons in this section.

This choice of the short circuit current and open circuit voltage is based on the numerical calculation of Chapter 2. For simplicity, it is assumed that the open circuit voltage for BSF cells with both sides illuminated is the same as that with front side illuminated only although the calculation indicated that the former is a few millivolts higher, the exact value depending on the cell thickness and substrate resistivity.

4.3.1 The Conventional Bifacial Cells

The bifacial conventional cells are investigated first. The open circuit voltage, short circuit current, fill factor and maximum output power are shown in Tables 4.9 to 4.12 respectively. The open circuit voltage for back illumination is around 90% of that

Cell Number			#2	#6	#8	#9
Resistivity (Ω -cm)			2.36	7.65	8.39	13.08
Thickness (μ m)			260	220	260	250
V_{oc} (mV)	Natural Sunlight	Front Illuminated	563	540	551	552
		Back Illuminated	427	494	485	492
	Halogen Lamp Light	Front Illuminated	566	543	554	552
		Back Illuminated	489	511	511	507
$V_{oc,back}/V_{oc,front}$			75.8%	91.5%	88.0%	89.1%
Estimated $V_{oc,both}$ (mV)			563	540	551	552

Table 4.9: Open circuit voltage for conventional cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

for front illumination and the current for back illumination is less than 20% of that for front illumination. Therefore, the estimated power output of conventional bifacial cells with both sides illuminated is only a few percent higher than that of conventional monofacial cells in relative terms, providing the thickness and resistivity of the wafer are in the mentioned range. Note that the values for comparison and calculations come from experimental data and/or other calculation results. Figures 4.6 and 4.7 present the experimental I-V curves of two typical cells with front and back illuminations and estimated I-V curves of cells with both sides illuminated.

4.3.2 The BSF Bifacial Cells

One of the main purposes of the thesis is to explore how much improvement can be achieved with the introduction of a bifacial structure into the polysilicon emitter and BSF layer solar cell. The voltage, current, fill factor and maximum output power of the various kind of cells under front and back illumination are listed in Tables 4.13 to 4.16. The total power output values with both sides illuminated are estimated

Cell Number			#2	#6	#8	#9
Resistivity (Ω -cm)			2.36	7.65	8.39	13.08
Thickness (μ m)			260	220	260	250
J_{sc} (mAcm ⁻²)	Natural Sunlight	Front Illuminated	22.0	22.6	23.6	22.4
		Back Illuminated	1.37	4.26	3.18	2.78
	Halogen Lamp Light	Front Illuminated	19.7	21.9	22.6	21.3
		Back Illuminated	3.13	6.83	5.71	5.05
$J_{sc,back}/J_{sc,front}$			6.2%	18.8%	13.5%	12.6%
Estimated $J_{sc,both}$ (mAcm ⁻²)			22.4	23.9	24.6	23.9

Table 4.10: Short circuit current density for conventional cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

Cell Number			#2	#6	#8	#9
Resistivity (Ω -cm)			2.36	7.65	8.39	13.08
Thickness (μ m)			260	220	260	250
F.F. (%)	Natural Sunlight	Front Illuminated	64.3	70.0	68.2	61.6
		Back Illuminated	52.1	72.7	65.5	70.3
	Halogen Lamp Light	Front Illuminated	65.7	70.0	68.3	60.5
		Back Illuminated	60.1	73.6	68.5	69.9
$F.F_{back}/F.F_{front}$			81.0%	103.9%	96.0%	114.1%
Estimated $F.F_{both}$ (%)			64.3	70.0	68.2	61.6

Table 4.11: Fill factor for conventional cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

Figure 4.6: Photo I-V curves of conventional cells with front side illuminated only, back side illuminated only, and both sides illuminated (Cell #2).

Figure 4.7: Photo I-V curves of conventional cells with front side illuminated only, back side illuminated only, and both sides illuminated (Cell #8).

Cell Number			#2	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	7.65	8.39	13.08
Thickness (μm)			260	220	260	250
P_{max} (mWcm^{-2})	Natural Sunlight	Front Illuminated	7.96	8.54	8.87	7.62
		Back Illuminated	0.31	1.53	1.01	0.96
	Halogen Lamp Light	Front Illuminated	7.33	8.33	8.55	7.11
		Back Illuminated	1.82	4.80	4.25	4.32
$P_{max,back}/P_{max,front}$			3.9%	17.9%	11.4%	12.6%
Estimated $P_{max,both}$ (mWcm^{-2})			8.05	9.00	9.17	7.91
$\Delta P_{max,both}/P_{max,front}$			1.1%	5.4%	3.4%	3.8%

Table 4.12: Maximum output power per unit area of cell for conventional cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

based on the experimental data and numerical calculations, in the same manner as that in the last section, and listed in the tables also.

The open circuit voltage of the cells with back illumination is above 90% of that for front illumination for most cells. For a few cells the difference is within 5%, i.e., the open circuit voltage for back illumination is nearly equal to that for front illumination. The short circuit current for back illumination varied from 13% to as high as 45% of that under front illumination, depending on the substrate. The estimated relative improvement in maximum power output is over 10%, the largest improvement is 12.8%. The I-V curves of two typical cells are illustrated in Figures 4.8 and 4.9 which include the estimated I-V curves of cells with both sides illuminated.

The results found here are similar to these obtained for n^+pp^+ cells with diffused emitter and BSF layers formed using normal processing procedures [46] which gave the back illumination performance with 95% voltage, 40% current and about 38% efficiency compared to front illumination performance, providing an estimated 11.4% improvement in maximum output power with both sides illuminated.

Cell Number			#1	#2	#4	#6	#8	#9
Resistivity (Ω -cm)			2.26	2.36	3.41	7.65	8.39	13.08
Thickness (μm)			220	260	220	220	260	250
V_{oc} (mV)	Natural Sunlight	Front	577	576	562	549	558	564
		Back	527	500	527	529	530	541
	Halogen Lamp Light	Front	577	577	564	550	567	566
		Back	535	537	535	535	543	547
$V_{oc,back}/V_{oc,front}$			91.3%	86.7%	93.8%	96.2%	95.0%	95.9%
Estimated $V_{oc,both}$ (mV)			577	576	562	549	558	564

Table 4.13: Open circuit voltage for BSF cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

Cell Number			#1	#2	#4	#6	#8	#9
Resistivity (Ω -cm)			2.26	2.36	3.41	7.65	8.39	13.08
Thickness (μm)			220	260	220	220	260	250
J_{sc} (mAcm ⁻²)	Natural Sunlight	Front	23.0	21.7	22.4	22.9	23.2	22.6
		Back	5.28	2.86	6.88	10.3	8.63	9.03
	Halogen Lamp Light	Front	22.0	22.0	21.6	22.7	24.0	22.5
		Back	6.65	5.03	9.09	12.2	11.1	10.8
$J_{sc,back}/J_{sc,front}$			23.0%	13.2%	30.7%	45.0%	37.2%	40.0%
Estimated $J_{sc,both}$ (mAcm ⁻²)			24.6	22.6	24.5	26.0	25.8	25.3

Table 4.14: Short circuit current density for BSF cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

Cell Number			#1	#2	#4	#6	#8	#9
Resistivity (Ω -cm)			2.26	2.36	3.41	7.65	8.39	13.08
Thickness (μ m)			220	260	220	220	260	250
F.F. (%)	Natural Sunlight	Front	64.0	64.3	64.3	71.2	71.5	66.6
		Back	65.0	67.6	68.7	71.4	69.3	73.5
	Halogen Lamp Light	Front	64.0	64.3	65.3	72.2	71.5	65.7
		Back	62.4	67.2	67.2	73.5	70.5	73.1
F.F. _{back} /F.F. _{front}			101.6%	105.2%	106.9%	100.3%	96.9%	110.4
F.F. _{both} (%)			64.0	64.3	64.3	71.2	71.5	66.6

Table 4.15: Fill factor for BSF cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

Cell Number			#1	#2	#4	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.26	2.36	3.41	7.65	8.39	13.08
Thickness (μm)			220	260	220	220	260	250
P_{max} (mWcm^{-2})	Natural Sunlight	Front	8.54	8.04	8.10	8.95	9.25	8.49
		Back	1.81	0.97	2.49	3.89	3.17	3.59
	Halogen Lamp Light	Front	8.13	8.16	7.95	9.01	9.73	8.37
		Back	2.22	1.82	3.27	4.80	4.25	4.32
$P_{max,back}/P_{max,front}$			21.2%	12.1%	30.7%	43.5%	34.3%	39.5%
Estimated $P_{max,both}$ (mWcm^{-2})			9.08	8.33	8.85	10.12	10.20	9.50
$\Delta P_{max,both}/P_{max,front}$			6.3%	3.6%	9.3%	12.8%	10.3%	11.9%

Table 4.16: Maximum output power per unit area of cell for BSF cells as a function of illumination mode. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode. All cells have their back metal contact patterned.

Figure 4.8: Photo I-V curves of BSF cells with front side illuminated only, back side illuminated only, and both sides illuminated (Cell #2).

Figure 4.9. Photo I-V curves of BSF cells with front side illuminated only, back side illuminated only, and both sides illuminated (Cell #8).

Although the improvement of bifacial solar cells is predicted by the models and numerical calculations described in Chapter 2, the behavior of the cells does not follow the predictions in all aspects. For example, the open circuit voltage with back illumination is predicted to decrease when the thickness and resistivity increases. The short circuit current is also predicted to decrease when thickness rises and increase slightly when resistivity increases. But both the largest voltage and largest current with back illumination are obtained from cell with the thickest and most resistive substrate. This particular result cannot be explained by the models and numerical calculations. This may be due to wafer-to-wafer variations in minority carrier lifetime amongst the small group of substrate processed here.

4.4 The Effect of Back Metal Contact on Cell Performance

In the last section, the conclusion was reached that the maximum output power of bifacial solar cells is larger than that of monofacial solar cells. This result was concluded by not considering the structural change of the back metal contact. But the back contact will influence the performance of the cells because the back electrode of monofacial solar cells does not need to be patterned while the electrode of the bifacial cells must be patterned. The series resistance introduced by the patterning of the back metal will change the performance of the cells.

In order to investigate the effect of the back metal contact structure, measurements on cells with both monofacial and bifacial back metal contact structure were conducted. This was done by measuring performance before and after patterning the back metal on conventional cells. The measurement results are listed in Table 4.17. Note that the measurements were made with natural sunlight illumination.

The table indicates that the open circuit voltage and short circuit current are essentially the same for the two cases. The most profound difference is seen in the

Cell Number		#2	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)		2.36	7.65	8.39	13.08
Thickness (μm)		260	220	260	250
V_{oc} (mV)	Monofacial Cells	566	540	554	550
	Bifacial Cells	563	540	551	552
J_{sc} (mAcm^{-2})	Monofacial Cells	20.9	21.6	23.4	21.7
	Bifacial Cells	22.0	22.6	23.6	22.4
$F.F.$ (%)	Monofacial Cells	71.1	74.7	73.3	65.8
	Bifacial Cells	64.3	70.0	68.3	61.6
η (%)	Monofacial Cells	8.41	8.71	9.50	7.85
	Bifacial Cells	7.96	8.54	8.87	7.62
$\eta_{bifacial}/\eta_{monofacial}$		94.6%	98.0%	93.4%	97.1%

Table 4.17: Performance for monofacial cells (back metal without patterning) and bifacial cells (back metal patterned), with front side illuminated with 1 sun.

fill factor. The fill factor of the cells with patterned back contact is less than that of cells without a patterned back contact by about 5 percent consistently for all cells. Therefore the maximum output power of the patterned cells is about 95% of that of the cells without patterning. The I-V curves of two typical cells with different back metal contact structures are illustrated in Figures 4.10 and 4.11.

Using the results, the maximum output powers of the monofacial BSF cells are estimated and the values are presented in Table 4.18. In the table, the maximum output powers of the bifacial conventional cells and bifacial BSF cells are chosen from Tables 4.12 and 4.16 respectively. The maximum output power of monofacial conventional cells is from Table 4.17. The maximum output power of monofacial BSF cells is then estimated by using the data of bifacial BSF cells with front illumination only in Tables 4.13 to 4.15. The voltage and current are taken as the same with that of bifacial cells and the fill factor is then adjusted by adding 5% to that of the bifacial cells.

The table shows that the maximum output power of the bifacial conventional solar

Figure 4.10: Photo I-V curves of cells with patterned back metal contact (solid lines) and cell without patterned (dashed line) (Cell #2)

Figure 4.11: Photo I-V curves of cells with patterned back metal contact (solid lines) and cell without patterned (dashed line) (Cell #8)

2 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISION^{SM} RESOLUTION TARGETS

Cell Number			#2	#6	#8	#9
Resistivity ($\Omega\text{-cm}$)			2.36	7.65	8.39	13.08
Thickness (μm)			260	220	260	250
Conventional Cells	P_{max} (mWcm^{-2})	Monofacial	8.58	9.15	9.52	8.23
		Bifacial	8.06	9.03	9.24	8.13
	$P_{max,bifacial}/P_{max,monofacial}$		93.2%	98.7%	97.1%	98.8%
BSF Cells	P_{max} (mWcm^{-2})	Monofacial	8.66	9.58	9.90	9.13
		Bifacial	8.37	10.16	10.29	9.13
	$P_{max,bifacial}/P_{max,monofacial}$		96.7%	106.1%	103.9%	104.1%

Table 4.18: Estimated maximum output power for conventional and BSF cells with monofacial and bifacial structures illuminated from both sides. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode.

cells is less than that of the monofacial conventional solar cells. This is due to the fact that the current resulting from back illumination in bifacial conventional cells is very small. Therefore the power gain of bifacial cells utilizing light from the back side is less than the loss due to patterning of the back metal contact.

On the other hand, the maximum output power of the bifacial BSF solar cells is larger than that of the monofacial BSF solar cells. The reason is the current of the bifacial cells with back illumination is greatly enhanced by the back surface effect. The power output gain of the BSF bifacial cells resulting from back side illumination surpasses the resistive loss due to the patterning of the back metal contact.

The relative maximum output power improvement of bifacial BSF cells generally is about 5%. Further improvement is expected by optimizing the pattern of the back metal contact. Many studies have been made towards optimizing the front metal grid structure [47, 48, 49, 50, 51, 52, 53, 54] under various constraints, and a variety of grid patterns have been developed [24]. Papadopoulos [55] also investigated the front contact pattern on which the cells described in this thesis were based.

The same structure and pattern of metal contact was used on both sides of the bifacial BSF cells. But they were optimized for the front side polysilicon emitter of the cell [55]. Since there are different structures on two sides of the cell, an n^+ polysilicon layer on the front side and p^+ polysilicon layer on the back side, the metal structure and pattern may not suited to the back side. In order to get best results, the metal structure and pattern need to be studied and optimized according to the properties of the p^+ layer, especially its sheet resistance.

4.5 Comparison with Theory and Discussion

In the last few sections the performance of the cells fabricated here was compared with the prediction of the theoretical models and numerical calculations. Only general trends were discussed, the absolute values were not compared with the models and numerical calculations. In this section, the comparison will be made between the absolute values and numerical calculations for the cell #8, which shows the best performance in all these cells.

Table 4.19 shows the experimental data for the cell and the calculated values using the numerical method described in Chapter 2. The simulation procedure is as follows.

The bifacial conventional cell is analyzed first. The values of the doping concentration in n^+ emitter and p base, the thickness of the cell, the depth of the junction are determined by the actual cell parameters. The back surface recombination velocity is taken as 10^5 cm/sec, a reasonable value for semiconductor-metal contact. The simulation begins by choosing the minority carrier lifetime in the base region to fit the open circuit voltage with front illumination. The value of the lifetime is then fixed in the rest of the calculations. The short circuit current with front illumination, the open circuit voltage and short circuit current with back illumination are calculated for this lifetime value.

The bifacial BSF cell is analyzed next. All the parameters of the cell but back

Cell #8			Experimental Data	Numerical Calculation
Resistivity ($\Omega\text{-cm}$)			8.39	
Thickness (μm)			260	
Conventional Cells	Front Side Illuminated	$V_{oc} (mV)$	551	554
		$J_{sc} (mAcm^{-2})$	23.6	38.5
	Back Side Illuminated	$V_{oc} (mV)$	485	476
		$J_{sc} (mAcm^{-2})$	3.18	1.83
BSF Cells	Front Side Illuminated	$V_{oc} (mV)$	558	558
		$J_{sc} (mAcm^{-2})$	23.2	38.8
	Back Side Illuminated	$V_{oc} (mV)$	530	530
		$J_{sc} (mAcm^{-2})$	8.63	12.8

Table 4.19: The comparison between experimental data and numerical calculations.

surface recombination velocity are kept unchanged. The back surface recombination velocity is taken as 10^3 cm/sec which is the value for a good p-p⁺ interface. The open circuit voltage and short circuit current with both front and back illumination are calculated, with the same minority carrier lifetime value. After all the parameters are calculated, the minority carrier lifetime in base region is adjusted again to bring the calculated values, especially the open circuit voltages, as close to the measured one as possible.

The comparison between calculated value and measurement results is made. The final value of minority carrier lifetime in base region giving best agreement is $14\mu\text{s}$. For the conventional cells, the measured open circuit voltage is higher than the one calculated. The experimental current value is 61% of that calculated. The current loss is mainly due to the reflection at the surface. The surface without antireflection coating, just like the cell described, reflects over 30% of the incident light. A lesser loss happens at the metal contact on the side of the cell which blocks 5 to 15% of the incoming light [24]. If these factors are taken into account, the calculated value of current is quite close to the experimental value. The experimental values of the voltage and current with back illumination are both much higher than the calculated values. A possible reason for this is that the back surface recombination velocity may

not as high as the one used in the calculation due to the passivation effect of the thin native oxide layer.

For the BSF cell, the experimental values of open circuit voltage with both front illumination and back illumination are the same as the calculated value. The current with front illumination is 60% of the calculated value, and the current with back illumination is 67% of the calculated value. Both of them are very close to the value after the reflection loss correction. The results show that the actual effect of the back surface field on the performance of the solar cell with back illumination agrees well with the prediction of the numerical calculations. But the actual improvement on open circuit voltage due to BSF (7mV) is much higher than the calculated value (4mV). The reason for the unexpectedly large improvement on voltage is not clear and it needs to be investigated further.

4.6 The Performance of the Multicrystalline Silicon Solar Cell

The Multicrystalline silicon solar cell is considered to be one of the most promising in terms of achieving both high efficiency and low cost [56]. On the other hand multicrystalline silicon substrates contain many kinds of defects and impurities, so the efficiency of solar cells built on these substrates has been inferior to that of single crystal cells. In recent years, the quality of multicrystalline silicon substrate has been considerably improved since the casting method [57] was developed. High efficiency cells using multicrystalline silicon substrate have been developed with various structures [58, 59, 60, 61, 62, 63]. These cells have been obtained by high temperature diffusion to form emitter and BSF layers and by using relatively complicated technologies such as texturizing and grooving techniques.

In this thesis, a method using more simple technology to produce a multicrystalline silicon solar cell is described. It is essentially the same technology which is used

Cell #20		V_{oc} (mV)	J_{sc} (mAcm ⁻²)	$F.F.$ (%)	P_{max} (mWcm ⁻²)
Natural Sunlight	Front Illumination	573	22.6	66.4	8.60
	Back Illumination	492	4.94	59.2	1.44
Halogen Lamp Light	Front Illumination	579	22.2	66.1	8.49
	Back Illumination	513	6.99	58.3	2.09
Back : Front		85.9%	21.9%	89.2%	16.7%
Both Sides (Estimated)		573	24.1	66.4	9.17
Both Sids : Front					106.6%

Table 4.20: The performance of the multicrystalline substrate solar cell. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode

to fabricate single crystal cells as presented in Chapter 3. The structure of the cell is the same as that of the single crystal cell, i.e., n^+pp^+ bifacial BSF cell with shallow, polysilicon emitter and thin back surface field layer. The whole procedure does not involve long duration of high temperature processing. The only relatively high temperature step is the rapid thermal annealing process which performs efficient gettering [64, 65, 66, 67, 68] to remove the impurities in substrate while the shallow junction of the cell is maintained [42].

The measurement results of a multicrystalline silicon solar cell are listed in Table 4.20. The parameters of the multicrystalline silicon cell are also listed in Table 4.21 to compare with the single crystal cells. The single crystal cells for comparison are cell #1 and #2 which have the closest substrate resistivity. The cell #2 also has comparable thickness. Therefore cell #2 is the best selection for comparison.

As indicated in the Table 4.21, the performance of the multicrystalline solar cell with front illumination is close to that of the single crystal comparison cell. The open circuit voltage is slightly lower, and both the short circuit current and the fill factor are slightly higher. The maximum power output is higher than that of single crystal cell #2.

Cell Number		#1	#2	#20
Resistivity ($\Omega\text{-cm}$)		2.26	2.36	1.44
Thickness (μm)		220	260	270
V_{oc} (mV)	Front Illumination	577	576	573
	Back Illumination	527	500	492
J_{sc} (mAcm^{-2})	Front Illumination	23.0	21.7	22.6
	Back Illumination	5.28	2.86	4.94
$F.F.$ (%)	Front Illumination	64.0	64.3	66.4
	Back Illumination	65.0	67.6	59.2
P_{max} (mWcm^{-2})	Front Illumination	8.54	8.04	8.60
	Back Illumination	1.81	0.97	1.44
	Both Sides (Estimated)	9.08	8.33	9.17

Table 4.21: Comparison between single crystal substrate cells and multicrystalline silicon substrate cell. 1 sun was used in front illuminated only, back illuminated only mode. 1 sun at front and 0.3 sun at back were used in both sides illuminated simultaneously mode

The performance of the multicrystalline solar cell with back illumination is much better compared to single crystal cell #2. The open circuit voltage is little bit smaller, the short circuit current is much larger, almost twice as large, and the fill factor is considerably smaller. The maximum output power with back illumination is then larger than that of cell #2 since the much larger current overcomes the effect of smaller voltage and fill factor. The surface texture of multicrystalline substrate relative to single crystal substrate may also contribute to the larger short circuit current here.

The good performance of the multicrystalline silicon solar cell indicates that the shallow emitter and thin BSF layer work well with the multicrystalline substrate. The rather simple technology used is successful in fabricating the cell and the rapid thermal annealing process helps to produce shallow junctions and performs effective gettering to remove impurities in substrate. The performance of the cell is expected to be improved by using a thinner substrate, like the results of cell #1 and #2 show. The I-V curves of multicrystalline cell with front and back illumination are illustrated

in Figure 4.12. For the comparison, the I-V curves of the single crystal cell #2 are also illustrated in the figure.

In summary, the results of the multicrystalline silicon solar cell are very encouraging.

Figure 4.12: Photo I-V curves of multicrystalline solar cell (Cell #20, solid lines) and single crystal solar cell (Cell #2, dashed lines)

Chapter 5

Conclusions

5.1 Conclusions

Solar cells with poly silicon emitters and back surface field regions have been made on various substrates with different thickness and doping concentration. The range of thickness is from $220\mu\text{m}$ to $260\mu\text{m}$ and the range of the resistivity of the substrates is from about $2\Omega\text{cm}$ to $13\Omega\text{cm}$. Most substrates were microelectronic grade single crystal wafers, but some multicrystalline substrates were also examined.

It was shown that the thin layer of p^+ polysilicon on the back of the cells improves the performance in the same manner as a more conventional diffused back surface field. Both the open circuit voltage and short circuit current have been improved, to an extent dependent on parameters such as substrate thickness and resistivity. The results indicate the reduction of the minority surface recombination velocity at the pp^+ interface at the back of the cells.

The improvement of open circuit voltage of solar cell with front illumination due to the BSF effect is about 10mV. The improvement of short circuit current is $\sim 2\text{mAcm}^{-2}$. The fill factor is essentially unchanged. The relative energy conversion efficiency gain of the cells ranges from $\sim 8\%$ to $\sim 18\%$.

The improvement of performance of cells with back illumination is much greater than that with front illumination. The voltage is close to the value with front illumination and the current increases by 100% to over 200%. The absolute value of efficiency of the cells is raised from $\sim 1\%$ to 3-4%, two to three times as high as for a cell without BSF layer.

The larger improvement of performance of cells, both with front illumination and with back illumination, happens on the cells with higher resistivity substrate. The best performance is obtained with the cell #8 with a thickness of $260\mu\text{m}$ and resistivity of $8.4\ \Omega\text{cm}$.

The improvement of maximum output power due to introducing the bifacial structure is estimated. The gain of utilizing the back illumination light competes with the loss due to patterning the back metal contact. With 1 sun on the front side and 0.3 sun on the back side, the total power output of the bifacial conventional cell is less than that of monofacial cell since the contribution from back side illumination is too small. With the same condition, the total power output of the bifacial BSF cells is larger than that of monofacial cells because of the great improvement of back illumination performance. The improvement is $\sim 5\%$ and further improvement is expected by optimizing the pattern of the back metal contact.

A multicrystalline silicon solar cell was produced using basically the same procedures. Its performance is close to the single crystal silicon cell which has similar parameters such as thickness and substrate resistivity. The good performance indicates that the shallow emitter and thin BSF layer work well with the multicrystalline substrate.

A numerical solar cell model has been modified to incorporate the feature to calculate the solar cell performance with back illumination. The open circuit voltage and short circuit current are calculated with various cell parameters such as thickness, substrate resistivity, and emitter junction depth. The results have been used to compare with the experimental values. The method has also been used to sim-

ulate the condition under which the front and back side of the cell are illuminated simultaneously, which could not be realized experimentally with available equipment.

5.2 Future Work

Two original contributions were made in this work: first use of polysilicon for both emitter and BSF layers in a solar cell, allowing very low thermal budget processing, and first use of this structure in a bifacial cell.

To further improve the performance of the cells, several structures can be introduced:

1. Texturizing both front and back side of the cell to form V-groove structure;
2. Utilizing the antireflection layers on both side of the cells;
3. Redesigning and optimizing the back metal contact pattern of the cell;
4. Implementing the local p^+ BSF poly silicon structure at the back of the cell;
5. Growing thermal oxide layers on both sides of the cell to passivate the surfaces.

A cross section view of the cell which incorporates these features is illustrated in Figure 5.1. These efforts are expected to improve the performance of the solar cells.

Figure 5.1: The structure of the cell incorporating the proposed features.

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Appendix A

Run Sheet for Bifacial BSF Solar Cells

Starting Material:

p-type <100> 1.8-2.5 Ωcm single crystal Cz wafer

p-type <100> 3.2-4.3 Ωcm single crystal Cz wafer

p-type <100> 8-10 Ωcm single crystal Cz wafer

p-type <100> 1-10 Ωcm single crystal Cz wafer

Wacker SILSO p-type 1.5 Ωcm multicrystal wafer

1. Smooth the Non-polished Side of Wafers

- Cover polished side of wafers with wax
- Etch natural oxide layer with HF
- Etch with HNO_3 : CH_3COOH : HF (5:3:3)
  - Etching time: 5 min.
  - Etch rate: 16 $\mu\text{m}/\text{min}$.
- Rinse in DI water
- Blow dry with N_2
- Remove wax in warm trichloroethylene
- Rinse in acetone
- Rinse in DI water
- Blow dry with N_2

2. RCA Clean

3. Lotox Deposition

- Deposition temperature: 410°C
- Pressure: 0.3 Torr
- SiH₄ flow setting: 25%
- O₂ flow setting: 27.5%
- Deposition time: 18 min.
- Expected thickness: 300 nm

4. Open Device Wells (Front)

Mask: CU-106-01-0B (dark field)

- Apply HMDS and POSITIVE PR on front surface
- Spin at 4,000 rpm for 30 sec.
- Prebake at 85°C for 20 min.
- Expose in UV light for
- Develop in Positive Developer : H₂O (1:1) for 60 sec.
- Rinse in DI water
- Blow dry with N₂
- Probake at 120°C for 15 min.

Protect backside with PR

Etch SiO₂ in Silox etchant at 20°C until hydrophobia

- Expected etch time: 2 min. 30 sec.
- Rinse in DI water
- Blow dry in N₂

Strip PR in Caro's acid at 110°C for 10 min.

- Rinse in DI water
- Blow dry with N₂

5. Emitter n⁺ Amorphous Silicon Deposition

RCA Clean

immediately prior to deposition, etch in DI:HF (100:1) for 3 min.

- surface must be hydrophobic
- n⁺ Amorphous Silicon Deposition**
- Deposition temperature: 560°C
  - Pressure: 0.4 Torr
  - SiH₄ flow setting: 53.8%
  - PH₃ flow setting: 33.9%
  - Target ratio: 160:1
  - Deposition time: 85 min.
  - Expected thickness: 0.06 μm

6. Pattern Emitter

Mask: CU-106-02

- Apply HMDS and POSITIVE PR on front surface
- Spin at 4,000 rpm for 30 sec.
- Prebake at 85°C for 20 min.
- Expose in UV light for
- Develop in Positive Developer : H₂O (1:1) for 60 sec.
- Rinse in DI water
- Blow dry with N₂
- Probake at 120°C for 15 min.

Etch amorphous Si in HF/HNO₃/H₃PO₄/DI water (1:30:10:15) at 20°C

- Expected etch time: 10 sec.
- Rinse in DI water
- Blow dry by N₂

Strip PR in Caro's acid at 110°C for 10 min.

- Rinse in DI water
- Blow dry by N₂

7. Lotox Deposition

RCA Clean

Lotox Deposition

- Deposition temperature: 410°C
- Pressure: 0.3 Torr
- SiH₄ flow setting: 25%
- O₂ flow setting: 27.5%
- Deposition time: 18 min.
- Expected thickness: 300 nm

8. Blanket Removal of Oxide from Backside

Protect front with positive PR

Etch in Siloxide Etchant at 20°C until hydrophobia

- Expect etch time: 5 min.

Strip PR in Caro's acid at 110°C for 10 min.

- Rinse in DI water
- Blow dry with N₂

9. Backside p⁺ Amorphous Silicon Deposition

RCA Clean

immediately prior to deposition, etch in DI:HF (100:1) for 3 min.

- surface must be hydrophobic

p⁺ Amorphous Silicon Deposition

- Deposition temperature: 475°C
- Pressure: 0.4 Torr
- SiH₄ flow setting: 35.9%
- PH₃ flow setting: 30.8%
- Target ratio: 80:1
- Deposition time: 30 min.
- Expected thickness: 0.06 μm

10. Removal of p⁺ Si from Front Side

Protect back side with PR

Etch amorphous Si in HF/HNO₃/H₃PO₄/DI water (1:30:10:15) at 20°C

- Expected etch time: 10 sec.
  - Rinse in DI water
  - Blow dry by N₂
- Strip PR in Caro's acid at 110°C for 10 min.
- Rinse in DI water
  - Blow dry by N₂

11. Emitter and BSF Layer Recrystallization Anneal

RCA Clean

Anneal at 650°C for 60 min.

12. Emitter and BSF RTA

Anneal at 850° for 5 sec.

13. Removal Lotox from Front Side

Etch in Siloxide Etchant at 20°C until poly emitter exposed

- Central area should be hydrophobic
- Expect etch time: 2 min. 30 sec.

14. Back Contact Metallization Ti/TiW/Al

RF Sputtering of Ti and TiW

- Distance of target from substrate: 2.5 inch
- Base pressure: 5×10^{-7} Torr
- Ar partial pressure: 8×10^{-3} Torr
- Presputtering Ti target for 1 min.
- RF power: 100W
- RF peak voltage: 1.4kV
- Sputter etch back surface for 30 sec. to remove native oxide
- RF power: 100W
- RF peak voltage: 950V
- Sputter 0.01 μ m Ti

- RF power: 100W
- RF peak voltage: 1.4kV
- Sputtering time: 2 min.
- Presputtering TiW target for 1 min.
- RF power: 100W
- RF peak voltage: 1.4kV
- Sputter $0.2\mu\text{m Ti}_{0.1}\text{W}_{0.9}$
- RF power: 100W
- RF peak voltage: 1.4kV
- Sputtering time: 20 min. E-beam Depositing Al
- Base pressure: 1×10^{-6} Torr
- Pressure during deposition: $1-2 \times 10^{-6}$ Torr
- Deposition rate: $0.0015\mu\text{m/sec}$.
- Al thickness: $4\mu\text{m}$
- Expected time: 45 min.

15. Pattern Back Metal Contact

Mask: CU-106-03-0B

- Apply HMDS and POSITIVE PR on back surface
  - Spin at 4,000 rpm for 30 sec.
  - Prebake at 85°C for 20 min.
  - Expose in UV light for 4 sec.
  - Develop in Positive Developer : H_2O (1:1) for 60 sec.
  - Rinse in DI water
  - Blow dry with N_2
  - Probake at 120°C for 15 min.
- Etch Al in H_3PO_4 at 60°C for 2 min.
- Rinse in DI water
  - Bake at 120°C for 10 min.
  - Repeat the etch, rinse and bake cycle until Al patterned
  - Expected total etch time: 5 min.

Etch TiW in DI:NH₄OH:H₂O₂ (5:1:1)

- Expected etch time: 2 min.
- Rinse in DI water
- Blow dry with N₂
- Bake at 120°C for 10 min.

Etch Ti in 5% HF for 10 sec.

- Rinse in DI water
- Blow dry with N₂

Strip PR in Microstrip 2001 at 90°C for 10 min.

- Rinse in DI water
- Blow dry with N₂

16. Front Contact Metallization Ti/TiW/Al

RF Sputtering of Ti and TiW

- Distance of target from substrate: 2.5 inch
- Base pressure: 5×10^{-7} Torr
- Ar partial pressure: 8×10^{-3} Torr
- Presputtering Ti target for 1 min.
- RF power: 100W
- RF peak voltage: 1.4kV
- Sputter etch front surface for 30 sec. to remove native oxide
- RF power: 100W
- RF peak voltage: 950V
- Sputter 0.01 μ m Ti
- RF power: 100W
- RF peak voltage: 1.4kV
- Sputtering time: 2 min.
- Presputtering TiW target for 1 min.
- RF power: 100W
- RF peak voltage: 1.4kV
- Sputter 0.2 μ m Ti_{0.1}W_{0.9}

- RF power: 100W
- RF peak voltage: 1.4kV
- Sputtering time: 20 min. E-beam Depositing Al
- Base pressure: 1×10^{-6} Torr
- Pressure during deposition: $1-2 \times 10^{-6}$ Torr
- Deposition rate: $0.0015 \mu\text{m}/\text{sec}$.
- Al thickness: $4 \mu\text{m}$
- Expected time: 45 min.

17. Pattern Front Metal Contact

Mask: CU-106-03-0B

- Apply HMDS and POSITIVE PR on front surface
- Spin at 4,000 rpm for 30 sec.
- Prebake at 85°C for 20 min.
- Expose in UV light for 4 sec.
- Develop in Positive Developer : H_2O (1:1) for 60 sec.
- Rinse in DI water
- Blow dry with N_2
- Probake at 120°C for 15 min.

Protect Back with Positive PR

Etch Al in H_3PO_4 at 60°C for 2 min.

- Rinse in DI water
- Bake at 120°C for 10 min.
- Repeat the etch, rinse and bake cycle until Al patterned
- Expected total etch time: 5 min.

Etch TiW in $\text{DI}:\text{NH}_4\text{OH}:\text{H}_2\text{O}_2$ (5:1:1)

- Expected etch time: 2 min.
- Rinse in DI water
- Blow dry with N_2
- Bake at 120°C for 10 min.

Etch Ti in 5% HF for 10 sec.

- Rinse in DI water

- Blow dry with N₂

Strip PR in Microstrip 2001 at 90°C for 10 min.

- Rinse in DI water

- Blow dry with N₂

18. Anneal to Remove the Radiation Damage

- Furnace temperature: 400°C

- Load wafers in quartz boat

5 min. preheat in N₂

5 min. preheat in H₂

20 sec. push in H₂

20 min. anneal in H₂

20 sec. pull in H₂

5 min. cool in H₂

5 min. cool in N₂

- Unload

Appendix B

Run Sheet for Cell Re-Fabrication

Starting Material:

Bifacial BSF Solar Cells

1. Removal of Back Metal Contact

Protect Front Metal Contact with Positive PR

Etch Al in H_3PO_4 at 60°C

- Expected etch time: 5 min.
- Rinse in DI water
- Bake at 120°C for 10 min.

Etch TiW in $\text{DI}:\text{NH}_4\text{OH}:\text{H}_2\text{O}_2$ (5:1:1)

- Expected etch time: 2 min.
- Rinse in DI water
- Blow dry with N_2
- Bake at 120°C for 10 min.

Etch Ti in 5% HF for 10 sec.

- Rinse in DI water
- Blow dry with N_2

2. Removal of p^+ BSF Layer by Plasma Etcher

- Back pressure: 1×10^{-3} Torr

Conditioning Chamber under O_2 ambient

- O₂ partial pressure: 0.5 Torr
- RF power: 300W
- Time: 5 min.

Conditioning Chamber under CF₄/O₂ ambient

- CF₄/O₂ partial pressure: 0.3 Torr
- RF power: 100W
- Time: 5 min.

Etching BSF Layer

- CF₄/O₂ partial pressure: 0.3 Torr
- RF power: 100W
- Etch rate: 0.1 μ m/min.
- Etch time: 5 min.

Strip PR in Microstrip 2001 at 90°C for 10 min.

- Rinse in DI water
- Blow dry with N₂

3. Back Contact Metallization Al

E-beam Depositing Al

- Base pressure: 1×10^{-6} Torr
- Pressure during deposition: $1-2 \times 10^{-6}$ Torr
- Deposition rate: 0.0015 μ m/sec.
- Al thickness: 4 μ m
- Expected time: 45 min.

4. Pattern Back Metal Contact

Mask: CU-106-03-0B

- Apply HMDS and POSITIVE PR on back surface
- Spin at 4,000 rpm for 30 sec.
- Prebake at 85°C for 20 min.
- Expose in UV light for 4 sec.
- Develop in Positive Developer : H₂O (1:1) for 60 sec.

- Rinse in DI water
- Blow dry with N₂
- Probake at 120°C for 15 min.

Protect Front with Positive PR

Etch Al in H₃PO₄ at 60°C for 2 min.

- Rinse in DI water
- Bake at 120°C for 10 min.
- Repeat the etch, rinse and bake cycle until Al patterned
- Expected total etch time: 5 min.

Strip PR in Microstrip 2001 at 90°C for 10 min.

- Rinse in DI water
- Blow dry with N₂

5. Anneal to Remove the Radiation Damage

- Furnace temperature: 400°C
- Load wafers in quartz boat
  - 5 min. preheat in N₂
  - 5 min. preheat in H₂
  - 20 sec. push in H₂
  - 20 min. anneal in H₂
  - 20 sec. pull in H₂
  - 5 min. cool in H₂
  - 5 min. cool in N₂
- Unload

END

3 1 - 0 5 - 9 5

FIN