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High-Efficiency Concentrator Silicon Solar Cells

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1	Introduction	436
2	The Family of Backside Contact Silicon Solar Cells	437
2.1	IBC Solar Cells	437
2.2	Front-Surface-Field, Tandem-Junction and Point-Contact Solar Cells	438
3	Modelling of Backside Contact Solar Cells	442
4	Perimeter and Edge Recombination	445
5	Manufacturing Process for Backside Contact Solar Cells	446
6	Stability of Backside Contact Cells	446
7	Toward 30% Efficiency Silicon Cells	448
8	How to Improve the Efficiency of Backside Contact Solar Cells	459
8.1	Reduce Emitter Saturation Current Density	450
8.2	Demonstrate Low Contact Resistance	451
8.3	Reduce the Cell Thickness	451
8.4	Improve Light Trapping	452
8.5	Shrink Geometries	452
8.6	Reduce Series Resistance	452
8.7	Target Performance	453
9	Conclusions	453
	Acknowledgements	453
	References	454

1 Introduction

Concentrating sunlight for photovoltaic conversion has always been a very attractive solution. Since one can easily acknowledge that the cost of photovoltaic energy conversion is driven by the fabrication cost of the solar cells, and particularly the cost of the semiconductor material, it becomes obvious that much less expensive concentrating lenses or mirrors can replace the expensive solar cells area. The concentration ratio can be increased several hundred fold, to the point where the cost of fabricating the solar cells becomes insignificant in the overall PV system cost. However, this benefit does not come without cost. Concentrating PV systems need solar trackers with a tracking precision that increases with the concentration ratio, and a more expensive module design with a well-engineered and low-cost cooling system for the solar cells.

Concentration not only increases the energy productivity of the solar cell material and device, but also increases its efficiency, since both current and voltage increase with the light intensity. However, in order to compare efficiencies of concentrator PV systems with flat plate PV systems, we have to remember that concentrator systems only use direct sunlight, about 85% of the incident power density on a clear sunny day. Therefore, a 20% efficient concentrator system would produce about the same amount of energy as a 17% efficient flat plate system, if they are both mounted on the same tracking system.

The series resistance of the cell limits the concentration ratio to which the solar cells can be used and the efficiency advantage of concentration systems over flat plates. To collect a current that is, for example at $500\times$ concentration, almost 20 A/cm^2 from a solar cell that has an open-circuit voltage of 0.800 V requires a series resistance that is less than $0.001\ \Omega\text{ cm}^2$. To achieve such low series resistance, the concentrator solar cell requires a well-engineered double-level, solderable metallisation scheme [4, 5] (see Figure 1).

The carrier recombination in commercial one-sun solar cells for flat-plate application is usually dominated by bulk Shockley-Read-Hall (SRH) or surface recombination. In high-efficiency ($>18\%$) solar cells or when medium-concentration ($<100\times$) is applied, the carrier recombination is usually

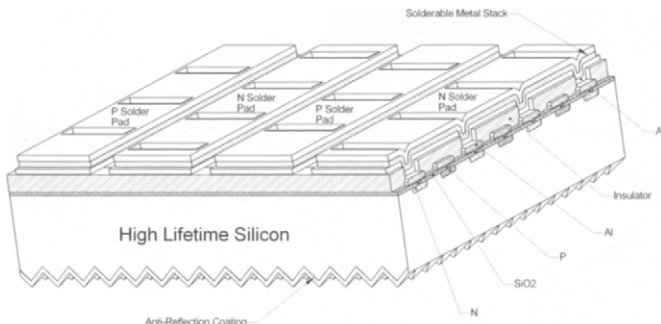


Figure 1 Structure of IBC silicon solar cell.

dominated by junction recombination. Auger recombination usually dominates in high-concentration silicon solar cells. Auger recombination occurs when an electron from the conduction band recombines with a hole from the valence band giving its energy to another electron. This is the opposite mechanism of impact ionisation. The Auger recombination rate increases as the cube of the carrier density, and is generally the dominant recombination mechanism when the carrier concentration exceeds 10^{17} cm^{-3} . In order to reduce the Auger recombination rate, concentrator solar cells must be as thin as possible (typically $120 \mu\text{m}$ or less) and, therefore, require a good light trapping.

Because the solar cell cost represents only around 10% of the total concentrator PV system cost, a high efficiency solar cell provides a great leverage for reducing the cost of solar electricity; the higher the concentration ratio the greater the leverage. The most efficient silicon solar cell, both for laboratory cells and for production scale, is currently the interdigitated back contact (IBC) and, in particular, the point-contact (PC) solar cell [5–9]. The structure of such a cell is shown in Figure 1. It has attained a conversion efficiency of 28.3% [2, 3] in the laboratory, and 26.8% at $100\times$ (AM1.5D, 10 W/cm^2 , 25°C) at the production scale [1]. It is, at the present time, the only high-intensity silicon solar cell commercially available. Figures 2 and 3 show examples of concentrator silicon solar cells manufactured by SunPower Corporation of Sunnyvale, California. Two examples of a reflective concentrator dish, built by Solar Systems Pty Ltd of Hawthorn, Australia and using high-efficiency concentrator silicon solar cells, are shown in Figures 4 and 5. The 20 m^2 concentrator system represented in Figure 5 was the first silicon-based concentrator system to reach an overall system efficiency of 20% under normal operating conditions [6]. Figure 6 shows a picture of the receiver of such concentrator system in operation.

2 The Family of Backside Contact Silicon Solar Cells

2.1 IBC Solar Cells

Schwartz et al. [7, 8] introduced the IBC design in 1975. The main reason that the IBC solar cell design is particularly suitable for high concentration is that both metal contacts are made on the backside of the cell (Figure 1). Therefore, there is no shadowing effect on the front side. The trade-off between the shadowing effect and the series resistance is eliminated, which is particularly interesting for concentration applications. Furthermore, the design of the front side (optical side) and the backside (electrical side) can easily be optimised separately. In a conventional solar cell, the doping of the front side emitter is a trade-off between series resistance and efficiency: a lighter doped front side emitter would improve the quantum efficiency and reduce the emitter saturation current density, but it would increase the series resistance of the cell. On the other hand, in IBC solar cells, the front side could be optimised for maximum

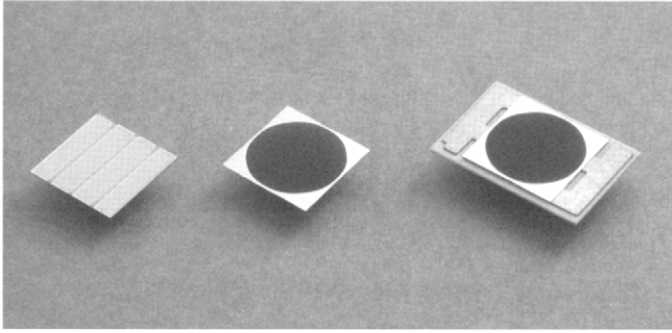


Figure 2 A point-contact silicon solar cell for Fresnel concentrator application. (Courtesy of SunPower Corporation.)

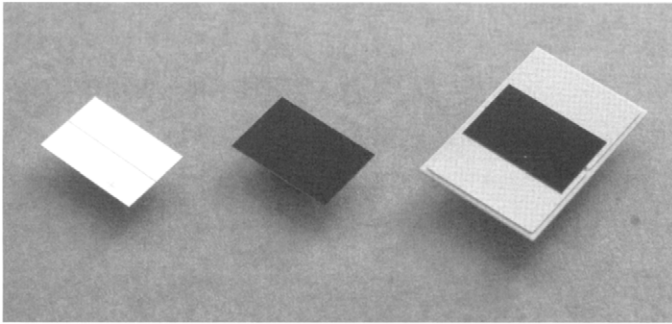


Figure 3 A point-contact silicon solar cell for dense array concentrator application. (Courtesy of SunPower Corporation.)

quantum efficiency, reduced recombination and reduced sub-linearity, without compromising the series resistance of the cell.

The main requirements for obtaining a high efficiency with IBC cells are:

- Long recombination lifetime in the bulk. After the solar cell fabrication the diffusion length must be at least 5 times longer than the solar cell thickness. For this reason, Float-Zone (FZ), high-resistivity, n-type substrates with carrier lifetime greater than 1 ms are generally preferred. The typical solar cell thickness is 100–150 μm .
- Low front surface recombination velocity. The front surface must be passivated with a thin, thermally grown, silicon dioxide layer, grown in a very clean environment.

2.2 Front-Surface-Field, Tandem-Junction and Point-Contact Solar Cells

Over the years, several variants in the IBC design have been introduced. The front-surface-field (FSF) solar cell has a high-low (n+/n or p+/p) junction on the

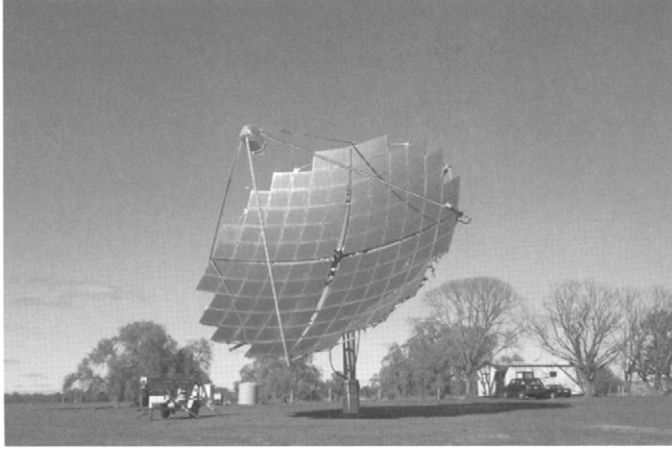


Figure 4 Picture of a 25 kW dish concentrating PV system with point-contact silicon solar cells. (Courtesy of Solar Systems Pty Ltd.)

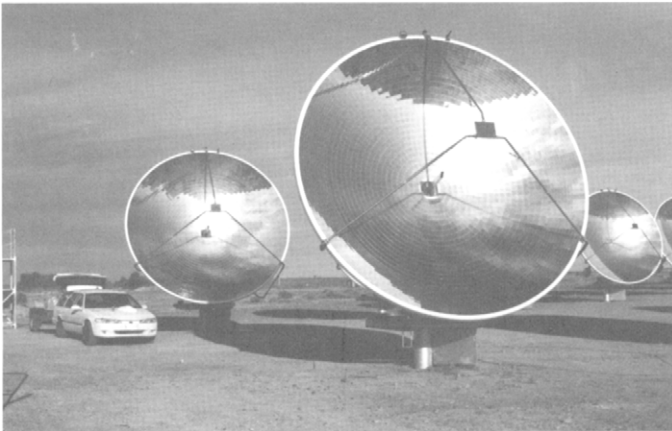


Figure 5 A dish concentrating PV system with point-contact silicon solar cells. This PV system, installed in White Cliff, Australia, demonstrated 20% overall efficiency under normal operating conditions [6]. (Courtesy of Solar Systems Pty Ltd.)

front side of the IBC solar cell (Figure 7(a)). The function of the front surface field is to reduce the effective front-surface recombination velocity for the carriers in the bulk of the device. It behaves the same way as a back surface field (BSF) in a conventional $n^+/p/p^+$ solar cell. However, since the high-low junction is now applied on the front side of the cell and since the solar cell is operating under high injection, the effective recombination velocity increases as the injection level increases and the effect of the FSF decreases. In high injection, the front-surface recombination current density, $J_{fs,rec}$, can be expressed as a function of the

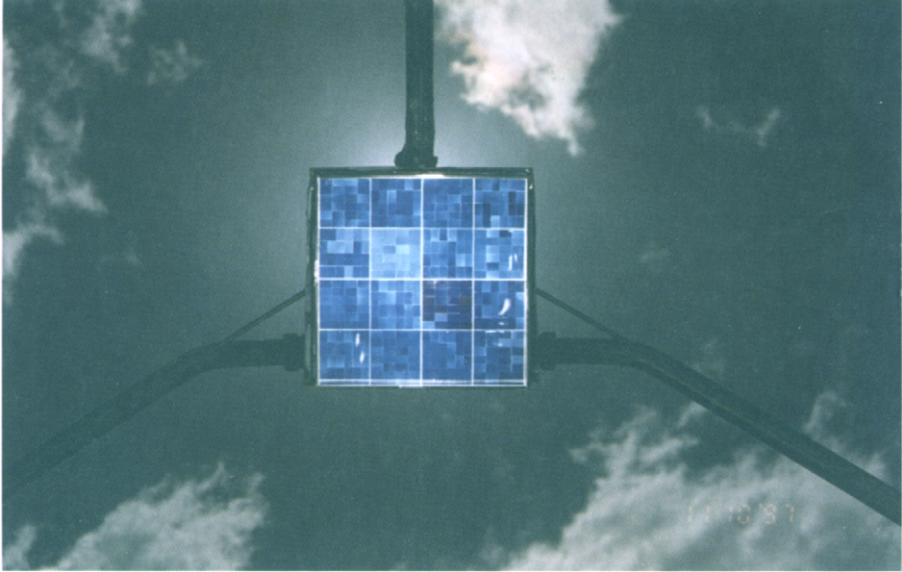


Figure 6 A dense array receiver with point-contact silicon solar cells. (Courtesy of Solar Systems Ltd Pty.)

saturation current density of the high-low junction, J_{0+} , or as a function of an effective surface recombination velocity, S_{eff} :

$$J_{fs,rec} = \frac{n^2}{n_i^2} J_{0+} = qnS_{eff} \quad (1)$$

where n is the carrier concentration (note that, in high-injection, the electron and hole concentrations are equal, $n = p$) at the front surface of the cell and n_i is the intrinsic carrier concentration.

Tandem-junction (TJ) solar cells are identical to FSF solar cell, except that a floating p-n junction replaces the high-low junction at the front side of the cell (Figure 7b). The front surface recombination current density, $J_{fs,rec}$, is determined by Equation (1) in the same way as in the FSF solar cell, and there is practically no difference between a TJ and a FSF solar cell (the only difference resides in the space charge recombination current at a very low intensity). The designer choice between a TJ and a FSF solar cell is fully determined by the ability to make a front side emitter with the lowest emitter saturation current density, J_{0+} , as possible. For this reason, n-type (phosphorous doped) emitters are usually preferred.

As we can see from Equation (1), the front surface recombination current increases as n^2 and the effective surface recombination velocity increases as the injection level increases:

$$S_{eff} = \frac{n}{qn_i^2} J_{0+} \quad (2)$$

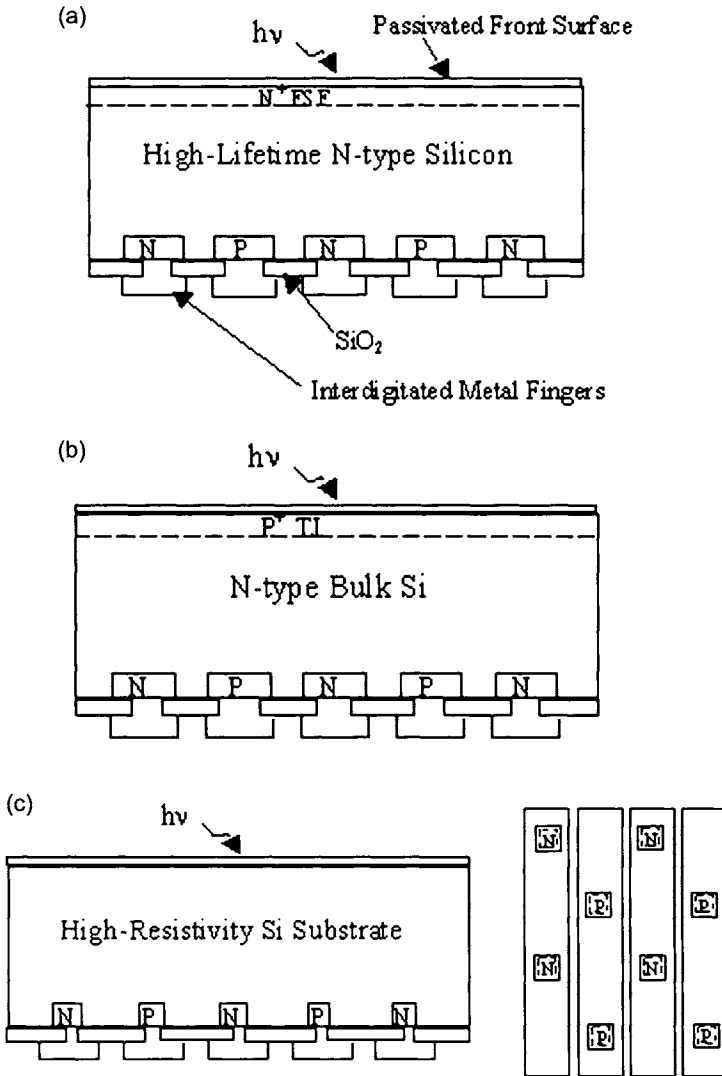


Figure 7 (a) Structure of a front-surface-field silicon solar cell. (b) Structure of a tandem junction silicon solar cell. (c) Structure of a point-contact silicon solar cell.

These characteristics result in a significant sub-linearity of the responsivity of the cell. The responsivity of a solar cell is, for a given spectrum, the total photo-generated current per unit of incident power. The responsivity has the dimension of amp/watt. The typical value of responsivity for high-efficiency concentrator solar cells is 0.395 A/W. If it varies with the concentration ratio, the solar cell is called sub-linear or super-linear. Therefore, a doped front side surface (TJ or FSF) is usually reserved to low-concentration applications ($< 10\times$).

Point-contact solar cells are IBC cells with a reduced emitter area and reduced metal contact area on the backside of the cell (Figure 7(c)) in order to decrease as

much as possible the emitter recombination. For one-sun or low-concentration applications ($< 5\times$), the backside emitter coverage fraction could be kept at almost 100% since the dominant recombination mechanisms are SRH and surface recombinations, and a simple IBC design is preferred. However, the metal contact area is kept very low, typically less than 1%, depending on the metal-Si contact resistance. For concentration ratios between $5\times$ and $200\times$, the backside emitter coverage fraction could be reduced to typically around 10%, whereas the metal contact area is typically 5% of the backside of the cell.

3 Modelling of Backside Contact Solar Cells

The simplest way to model IBC solar cells is to consider the integral approach as proposed by R.M. Swanson [9, 10] and, for a precise simulation of an IBC or PC solar cell, we refer the reader to the model developed in these papers which includes 3D effects close to the backside contacts. However, we will give below a simple formulation.

The current, I , at the terminals of a solar cell can be written in the form:

$$I = I_{ph} - I_{b,rec} - I_{s,rec} - I_{em,rec} \quad (3)$$

where I_{ph} is the photogenerated current (the maximum photogenerated current within the silicon material with a defined thickness, including reflection losses and light trapping), $I_{b,rec}$ is the sum of all the bulk recombination currents (including SRH and Auger recombination), $I_{s,rec}$ is the sum of all the surface recombination currents (including front side, backside and edge surface recombination) and $I_{em,rec}$ is the sum of all the emitter recombination currents (including backside emitters, the front TJ or FSF emitter if it exists, and also including recombination at the contacts). The recombination currents increase as the carrier concentration increases and, therefore, increase as the terminal voltage increases. Eventually, at the open-circuit condition, the sum of all the recombination currents will be equal to the photocurrent, I_{ph} , and the terminal current will be equal to zero. Therefore, at V_{oc}

$$I_{ph} = I_{b,rec} + I_{s,rec} + I_{em,rec} \quad (4)$$

Calculating the different components of the recombination current is the most interesting and the most powerful approach to simulate, optimise or analyse the performance of solar cells. Table 1 gives a summary of the different relevant recombination mechanisms in silicon, their controlling parameters, typical values in high-efficiency concentrator silicon solar cells and the corresponding recombination currents under high-level injection.

If an IBC solar cell is to be modelled, in a simple manner, as a backside illuminated conventional solar cell, one has to realise that:

- in most of the device, the electron and holes are flowing in the same direction, from the front side of the cell toward the backside where the collecting n-type and p-type junctions are;

Table 1 Recombination mechanism and the corresponding recombination current in highly injected silicon solar cells.

Carrier recombination mechanism	Controlling parameter	Unit	Typical values	Recombination current density (A/cm ²)
Bulk (SRH, trap assisted)	τ_B	s	1–10 ms	$\frac{qnW}{\tau_B}$
Surface (trap assisted)	S	cm/s	1–4 cm/s	qnS
Emitter	J_o	A/cm ²	50–200 fA/cm ²	$\frac{n_i^2}{n_i} J_o$
Auger	C_A	cm ⁶ /s	1.66×10^{-30}	$qn^3 C_A W$

The ambipolar Auger coefficient value is from Sinton [11, 12]. In this chapter, τ_B represents the bulk lifetime and, since we are considering high-injection conditions only, we have assumed that $\tau_n = \tau_p = \tau_B$, where τ_n and τ_p are the electron and hole lifetimes.

- since the cell is under high injection, and to maintain electrical neutrality in the device, the electron and hole concentrations are equal throughout the device;
- for the same reasons as above, electrons and holes are flowing with the same ambipolar diffusion constant, $D_a = 2D_n D_p / (D_n + D_p)$, where D_n and D_p are the electron and hole diffusion constants;
- in most of the device, from the front-side to very close to the emitter area where 3D current flow starts to appear, the current flow is almost unidirectional, perpendicular to the surface:

$$J_n = -J_p = qD_a \frac{dn}{dx} = qD_a \frac{dp}{dx} \quad (5)$$

where J_n and J_p are the electron and hole current densities, and, therefore, the total current along the wafer J_T is negligible:

$$J_T \approx 0 \quad (6)$$

Since the backside carrier concentration is determined by the terminal voltage of the solar cell

$$n_{back} = n_i \exp\left(\frac{qV}{2k_B T}\right) \quad (7)$$

we can use Equation (3) and the expression of recombination currents in Table 1 to calculate the cell current at any bias voltage. We can take, as a simple example, a high-efficiency IBC or PC solar cell under high injection, with long carrier lifetime ($\tau_n = \tau_p \gg W^2/D_a$, where W is the thickness of the cell) and low surface recombination velocity ($S_0 \ll D_a/W$, where S_0 is the surface recombination velocity at the front surface).

In short-circuit condition, we can consider that, in the first approximation:

- $n_{back} = 0$,

- the emitter and surface recombination currents at the back of the cell can be neglected, as well as Auger recombination,
- the electron and hole concentrations linearly decrease from front to back.

Equation (3) then becomes:

$$J_{sc} = J_{ph} - \frac{qn_0W}{2\tau_B} - qn_0S_0 = qD_a \frac{n_0}{W} \quad (8)$$

where J_{sc} is the short circuit current density, n_0 is the front-surface electron concentration and currents were replaced by current densities in view of the effectively planar geometry of the cell as a result of the perpendicular direction of the current. A few iterations are necessary to determine the short-circuit current and the front-surface carrier concentration.

It becomes immediately apparent that, if the thickness of the cell, W , increases, the front-surface carrier concentration, n_0 , increases, which, in turn, results in an increased bulk and front-surface recombination current.

In open-circuit condition, we can consider that the electron and hole concentrations are constant throughout the device. The open-circuit voltage is given by:

$$V_{oc} = 2 \frac{k_B T}{q} \ln\left(\frac{n}{n_i}\right) \quad (9)$$

after solving the following equation:

$$J_{ph} = \frac{qnW}{\tau_B} + qn^3 C_a W + qnS_0 + qnS_{back}(1 - A_n - A_p) + \frac{n^2}{n_i^2} (A_n J_{on} + A_p J_{op}) \quad (10)$$

where J_{on} and J_{op} are the saturation current densities at the n and p junctions, A_n and A_p are the n-type and p-type emitter coverage fractions respectively, and S_{back} is the backside surface recombination velocity.

The maximum power point and efficiency of the solar cell can be determined the same way, considering that the backside carrier concentration is given by Equation (7) and that the carrier concentration is still linearly distributed from front to back. Equation (3) becomes:

$$\begin{aligned} J_{mp} = J_{ph} - \frac{qn_{avg}W}{\tau_B} - q \int_0^W n(x)^3 C_a dx - qn_0S_0 \\ - qn_{back}S_{back}(1 - A_n - A_p) - \frac{n_{back}^2}{n_i^2} (A_n J_{op} + A_p J_{on}) = qD_a \frac{n_0 - n_{back}}{W} \end{aligned} \quad (11)$$

where $n_{avg} = (n_0 + n_{back})/2$ is the average carrier concentration and

$$n(x) = n_{back} + (n_0 - n_{back})\left(1 - \frac{x}{W}\right) \quad (12)$$

Several iterations are necessary to reach the solution.

This is a very simple way to analyse the IBC or PC solar cells. It allows a quick determination of the carrier concentration in the device and an analysis of the different recombination mechanisms. Note that Equation (1) must be used for the front-side recombination current expression in FSF or TJ solar cells. For a more precise modelling, including 3D effects at the backside of the solar cell, the reader is referred to the Swanson model [9, 10].

4 Perimeter and Edge Recombination

So far, we have not considered the edge recombination. It has been recently demonstrated that, in most high-efficiency silicon solar cells, the dominant recombination mechanism is a recombination current at the unpassivated surface at the edge of the silicon die [13]. Two cases need to be considered here:

- aperture illuminated solar cells (e.g. cells for Fresnel lens modules, Figure 2),
- totally illuminated solar cells (e.g. cells for dense array receivers, dish and thermo-photovoltaic (TPV) applications, Figure 3).

In order to reduced the edge recombination, the aperture illuminated IBC solar cells must have its active area as far as possible from the edge of the silicon die, in theory at a distance of least three times the ambipolar diffusion length at the considered carrier concentration. In practice, economical considerations prevent manufacturers to increase this distance too much and a typical distance between the edge of the silicon die and the nearest emitter at the backside of the cell is 500 μm . For totally illuminated solar cells, there is an optimal distance that can be calculated as explained in [13]. The width of the border region is optimal when the illuminated border region generates just enough current to supply the recombination current at the edge of the silicon die. A wider or narrower border region than the optimal width would result in a lower efficiency. If d is the width of the border region, P the cell perimeter, and n the average carrier density at the middle of the cell, at the maximum power point (V_m , I_m) and at the considered concentration ration, the current generated by the border region is:

$$I_{border} = dPJ_{sc}$$

and the edge recombination current is:

$$I_{edge} = qPWD_a n/d$$

The border width is optimal when:

$$I_{border} = I_{edge}$$

and

$$d = \sqrt{\frac{qWD_a n}{J_{sc}}} \quad (13)$$

For a fixed geometry and cell thickness, the carrier concentration and short-circuit current are more or less proportional to the concentration ratio. Therefore, the optimal border width is generally independent of the concentration ratio. However, since the average carrier concentration increases with the thickness of the cell, the optimal border width is roughly proportional to the thickness of the cell. For a typical IBC solar cell for dense array application at $400\times$ and with a thickness of $100\text{ }\mu\text{m}$ ($n \approx 10^{17}\text{cm}^{-3}$), the optimal border width is about $135\text{ }\mu\text{m}$.

Equation (13) is valid if the edge is unpassivated such as in silicon solar cells diced with a dicing saw. New techniques to passivate the edges of solar cells are needed but, so far, there has been no satisfactory development in low-temperature passivation of silicon surfaces.

5 Manufacturing Process for Backside Contact Solar Cells

The typical process flow to manufacture IBC solar cells is presented in Figure 8 although actual processes may significantly differ in practice. A typical process requires 6 photolithography steps. Additional photolithography steps are required for:

- inverted pyramid texturisation instead of random texture,
- local thinning instead of uniform wafer thinning.

6 Stability of Backside Contact Cells

In the same way as many other high-efficiency silicon solar cells, the IBC cells are subject to efficiency degradation. If float-zone (FZ) wafers are used, the degradation is limited to the silicon-silicon dioxide interface [1, 14–16]. The degradation of the interface could be due to the loss of hydrogen atoms passivating the dangling bonds at the silicon-silicon dioxide interface, or the creation of new interface states. The degradation of the interface is manifested by:

- an increase of the surface recombination velocity, which, in turn, results in a reduction of the short-circuit current over the entire range of concentration ratio or,
- by an increase of the front emitter current J_0 which results in an increase of the sub-linearity (the cell responsivity decreases as the concentration ratio increases) if the front surface is lightly doped or inverted due to charges in the dielectric layer.

Both mechanisms will result in a significant decrease in efficiency. The degradation has been observed so far due to the following individual or combined conditions:

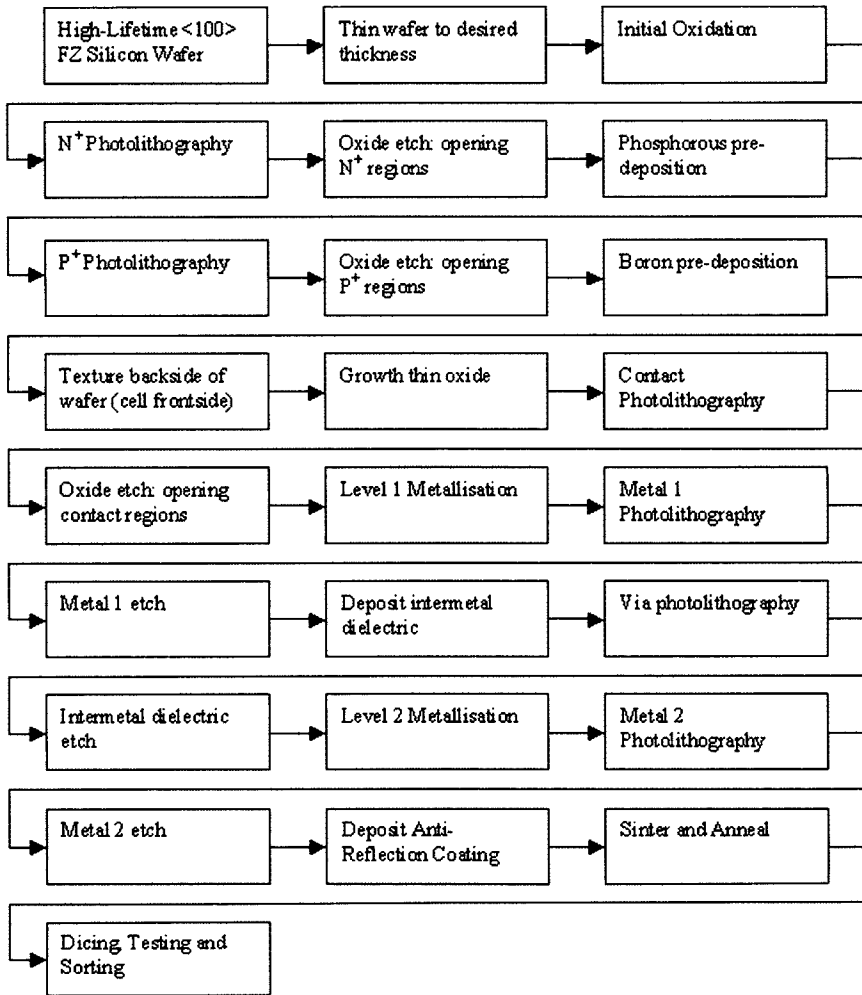


Figure 8 Process flow of manufacturing IBC solar cells.

- UV light, which creates hot electrons that can overcome the potential barrier at the silicon-silicon dioxide interface and create new interface states,
- elevated temperature ($> 100^{\circ}\text{C}$), which allows hydrogen atoms to escape from the interface,
- mechanical stress.

It is also assumed that the following conditions enhance the degradation:

- highly concentrated sunlight which creates a large concentration of carriers at the surface of the solar cell;

- the presence of moisture;
- the presence of atomic hydrogen which could break an existing Si-H bond to form a hydrogen molecule H_2 .

There is still much research to be done to understand the degradation mechanisms and to find a solution to this issue.

The easiest way to prevent the strong influence of the degradation of the surface recombination velocity to solar cell efficiency is to isolate the surface from the rest of the cell with FSF or a floating tandem junction. Unfortunately, although it makes the cell more stable, the front side emitter has a significant impact on the sub-linearity of the solar cell [1, 15], which makes this solution unsuitable for concentration application. In any case, the front emitter must be lightly doped in such way that the front emitter J_o is kept as low as possible. Indeed, we can see from Equation (1) that the greater the front emitter J_o , the more significant the sub-linearity of the solar cell will be.

There are other ways to ensure stability of the IBC solar cells:

- It is very important that, during the solar cell fabrication, the front passivating oxide layer is grown with the smallest interface state density. 1,1,1-Trichloroethane (TCA), dichloroethane (DCA), trichloroethylene (TCE) or HCl oxide growth, as well as an aluminium anneal, should be avoided as they have been recognised as giving very unstable Si-SiO₂ interfaces [16, 17].
- UV light with wavelength below 400 nm should be filtered from the solar spectrum, either at the solar cell level or at the concentrator module level. For example, the anti-reflection coating (ARC) can include a UV filter such as TiO₂ or a very thin polysilicon layer [14, 16].
- The front surface of the solar cell should be coated with a thin layer of silicon nitride (as part of the ARC), or another material, hopefully compatible with the ARC, forming a great hydrogen and moisture diffusion barrier (for example, a very thin amorphous silicon or polysilicon layer) [16].

7 Toward 30% Efficiency Silicon Cells

In 1985, Gray and Schwartz presented a paper entitled ‘Why don’t we have a 30% efficient silicon solar cell?’ [18]. At that time, the highest reported efficiency for silicon solar cell was 22% under concentrated sunlight. In that paper, the authors concluded that 30% efficiency would be attainable with a silicon solar cell if:

- good light trapping was developed which does not degrade the open-circuit voltage of the solar cell,
- the contact and grid series resistance could be reduced enough to allow for high concentration ratio,
- the current crowding effects are reduced by a judicious design,

- a novel heterojunction or heteroface contact with small contact resistance and low emitter saturation current was developed.

A few years later, the first three steps to attain the 30% efficiency target had been addressed and resolved: the PC solar cell with a thin substrate and long carrier lifetime, with a textured and passivated front surface, proved to be the best design for high efficiency concentrator solar cell [19, 20]. In 1989, the highest reported efficiency for silicon PC solar cell was 28.3% [21]. The same year, Swanson responded to Gray's paper in a publication entitled "Why we will have a 30% efficient silicon solar cell" [22] where he demonstrates that all the pieces are now in place to fabricate a 30% efficient silicon solar cell. The last milestone to reach the 30% breakthrough, namely the development of polysilicon emitters with a low contact resistance, and low emitter saturation currents had just been demonstrated at Stanford [23, 24]. Swanson announced: Within one year, cells will be reported with efficiency in excess of 30% [22].

We believe that 30% efficient silicon solar cells are possible in a manufacturing environment. In order to achieve this goal, polysilicon or heterojunction emitter technology needs to be implemented, along with several other improvements to the existing technology (thinner cells, improved light trapping, and reduced dimension geometries).

8 How to Improve the Efficiency of Backside Contact Solar Cells

Campbell and Green [25] discussed the efficiency limit of silicon solar cells under concentrated sunlight. They showed that the limit of efficiency for a silicon cell is between 30 and 35%. These very high efficiencies have never been demonstrated so far with a single-junction silicon solar cell. Commercially available PC concentrator cells have efficiencies around 26.5%. In order to reach such high efficiencies, the recombination mechanisms such as trap-assisted SRH recombination, in the bulk or at the surface, and emitter recombination must be negligible compared to Auger recombination. The Auger recombination is intrinsic to the material and, for example, cannot be improved by using a purer starting material or a cleaner fabrication process. Therefore, the only way to

Table 2 Strategy for 30% efficient backside contact solar cells.

Step	Parameter	Target value	Acceptable value	Unit
1	Emitter J_0	3×10^{-14}	5×10^{-14}	A/cm ²
2	Emitter contact resistance	10^{-6}	10^{-4}	Ω cm ²
3	Cell thickness with manufacturable yield	30	80	μ m
4	Light trapping: number of passes for long wavelengths	50	35	passes
5	Unit cell geometry	25	40	μ m
6	Total series resistance	5×10^{-4}	10^{-3}	Ω cm ²

reduce the Auger recombination rate inside the cell is to reduce its thickness. However, using a very thin silicon solar cell requires the use of a very effective scheme for light trapping. For example, Campbell and Green [25] suggest that the optimum cell would be less than $1\ \mu\text{m}$ thick and could reach 36–37% under concentration.

By comparison, the recombination in the PC solar cell at $250\times (25\ \text{W}/\text{cm}^2)$ is almost equally dominated by emitter (40%) and Auger (40%) recombination. The surface and bulk SRH recombination represents less than 20% of the overall recombination rate. In the PC design, the emitter coverage fraction has already been reduced to the minimum acceptable, and the only way to further reduce the emitter recombination rate is to reduce the emitter saturation current density J_o . Therefore, in order to reach 30% or greater efficiency, the following strategy needs to be used:

1. Reduce the emitter recombination by reducing the emitter saturation current density from 2×10^{-13} to $5 \times 10^{-14}\ \text{A}/\text{cm}^2$. Polysilicon heterojunction emitters with less than $5 \times 10^{-14}\ \text{A}/\text{cm}^2$ as saturation current density have already been demonstrated [23, 24].
2. Demonstrate low contact resistance between the bulk and the emitters. A desired value for the contact resistance between bulk and emitter is less than $10^{-5}\ \Omega\ \text{cm}^2$.
3. Reduce the cell thickness in order to reduce the Auger recombination rate. For a practical concentrator for which the angle of incidence of the light to the cell is between 0 and 30 degrees, the optimal thickness is about $30\ \mu\text{m}$ [25]. This is very difficult to achieve in a manufacturing environment. Manufacturing techniques, such as local thinning, need to be implemented.
4. Improve light trapping by designing new textured surfaces on both sides of the cell.
5. Reduce the unit cell geometry down to a dimension equal or smaller than the thickness of the cell.
6. Reduce the external series resistance (metal and interconnect).

8.1 Reduce Emitter Saturation Current Density

The saturation current density of an emitter J_o represents the sum of all the recombination mechanisms inside the emitter. It includes the SRH, surface, contact and Auger recombination mechanisms, as well as heavy doping effects such as band gap narrowing. The best diffused emitter J_o that can be achieved is around $2 \times 10^{-14}\ \text{A}/\text{cm}^2$. However, such an emitter is very transparent which means that, if a metal contacts it, its saturation current density dramatically increases about 100 fold. For contacting PC solar cell, the emitter must be opaque and the best saturation current density of such emitter is around $2 \times 10^{-13}\ \text{A}/\text{cm}^2$.

An ideal emitter for silicon should be transparent to majority carriers and a mirror for minority carriers. Therefore, it should have a wide band gap such that

an additional potential barrier will appear in the minority band when it is doped (see Figure 9). Although there are many semiconductors with a larger band gap than silicon, so far none of the large band gap materials have proven to be ideal for contacting silicon. Indeed, the potential barrier at the emitter heterojunction blocks the minority carriers, they still can recombine at the interface due to the presence of interface traps.

There are only two materials that were reported to have low J_o : polysilicon emitters and semi-insulating polysilicon emitters (SIPOS), both used with an interfacial thin oxide layer [23, 24, 26, 27]. However, some very promising results have recently been reported on non-concentrator solar cells with amorphous silicon emitters [28] that do not require an interfacial thin oxide to block the minority carriers.

8.2 Demonstrate Low Contact Resistance

The growth of a thin (10 to 20 Å) interfacial layer of silicon dioxide is critical to obtain low emitter saturation current density with polysilicon. However, in order to achieve a low contact resistance, it is necessary to anneal the polysilicon emitter to break up the oxide layer on about 1% of the contact area [23]. The trade-off between J_o and a high contact resistance is highly dependent on the oxide thickness and the anneal (or breakup) step.

8.3 Reduce the Cell Thickness

Once the emitter recombination mechanism has been reduced, it is possible to reduce the Auger recombination rate by using a thinner substrate for the solar cell. Solar cells made on 100 μm thick wafers are can be manufactured in large volumes but thinner cells present a real challenge for manufacturing. Since both sides of the cells must be processed for texturing, passivation and anti-reflection coating, the thinning of the wafers cannot just be done by lapping the wafers at the end of the process. Solar cells of 30–80 μm thickness must be fabricated on locally thinned substrates.

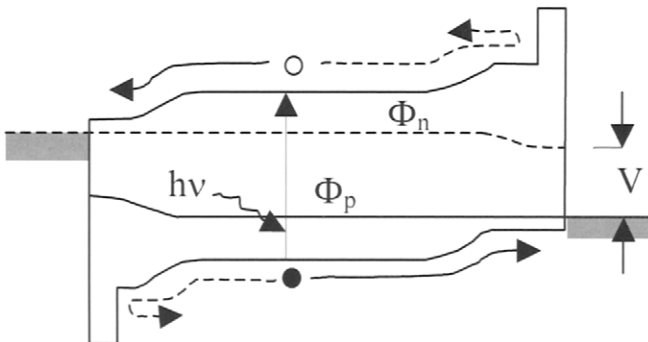


Figure 9 Band diagram of a p-i-n solar cell with heterojunction emitters.

8.4 Improve Light Trapping

When very thin silicon solar cells are designed, the light trapping property of the cells becomes a significant factor for the efficiency. Present cells have only one-side texturisation. Unfortunately, this is not enough for cells thinner than 100 μm . In this case, a double side texturisation or perpendicular grooving must be designed in order to insure good light trapping. In current PC solar cells, the analysis of the internal quantum efficiency near the edge of the band gap shows that the effective number of passes for long wavelength light is greater than 30 [1]. The light trapping can be improved with double side texture, perpendicular slats, or parquet grooves in order to attain up to 50 passes of the light.

8.5 Shrink Geometries

The present PC solar cells have a significant current crowding loss and large internal series resistance accounting for about $0.002 \Omega \text{ cm}^2$ which represents about 3% power loss at 25 W/cm^2 or $250\times$. The unit cell dimension should be reduced from the current 140 μm to 40 μm , and if possible to 25 μm . The metallisation and inter-metal dielectric technology usually prevents the shrinking of the unit cell. In order to be able to shrink the unit-cell dimension to 40 or even 25 μm , a state-of-the-art plasma etching process for the metal, as well as a plasma-enhanced chemical vapour deposition (PECVD) SiO_2 -based dielectric as inter-metal dielectric layer must be adopted.

8.6 Reduce Series Resistance

Shrinking the geometries of the unit cell in order to reduce the internal series resistance may have a negative effect on the external series resistance. This problem is due to the fact that, if the gap between metal lines is kept constant, the metal coverage fraction decreases with decreasing the dimensions of the unit cell. A new metallisation design, similar to what has been proposed in previous papers [4, 5], must be implemented in order to reduce the series resistance. As in step 8.5, the new metal design requires a plasma etching process for metal and a SiO_2 -based dielectric layer. The target is to reduce the total series resistance to less than $0.001 \Omega \text{ cm}^2$, or about a 2.5% power loss at $500\times$ concentration.

Table 3 Comparison of performance of a commercial PC solar cell (HECO335 from Sun-Power Corporation) cell with the projected new high-performance cell at $100\times$ and $275\times$ (AM1.5D , 10 and 27.5 W/cm^2 , $T_c = 25^\circ\text{C}$). The values at $275\times$ concentration are in brackets.

Parameter	Commercially available PC solar cell	New high-performance cell	Unit
Responsivity	0.403 (0.379)	0.416 (0.416)	A/W
Open-circuit voltage	807 (825)	826 (845)	mV
Fill factor	82.6 (79)	87 (85.9)	%
Efficiency	26.8 (24.7)	29.9 (30.2)	%

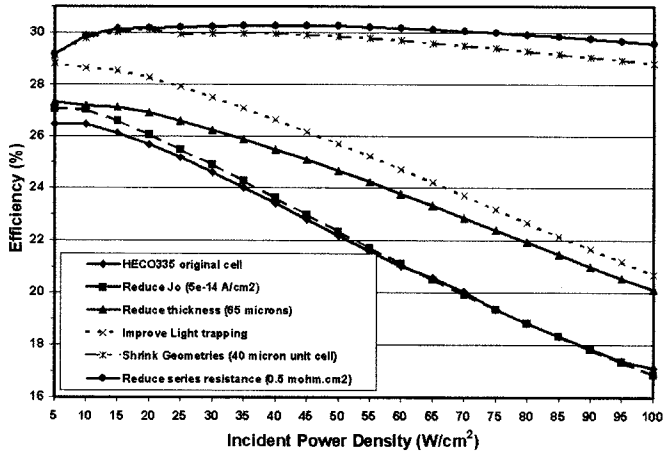


Figure 10 Efficiency (AM1.5D, 25°C) of the point-contact silicon solar cell vs. incident power density after each step of this strategy.

8.7 Target Performance

Table 3 shows the target performance of a 30% efficient silicon solar cell compared to the commercially available point-contact solar cells. Figure 10 shows the improvement in efficiency based on the above strategy. Of course, the full benefit of the polysilicon emitter with low J_o is observed when all the other improvements (thinner cells, improved light trapping and shrunk geometries) are in place.

9 Conclusions

Interdigitated back contact and point-contact silicon solar cells have demonstrated to be the most efficient and the most suitable silicon solar cells for high-concentration applications. Commercially available PC solar cells have demonstrated efficiencies up to 26.8% (at 10 W/cm², AM1.5D, 25°C) in large volume production. This chapter has described the structure of IBC, FSF, TJ and PC cells, as well as the process to fabricate them. A simple model for the simulation, optimisation and analysis of the different recombination mechanisms in concentrator IBC cells has been presented. Finally, we have presented a plan for the development of 30% efficiency concentrator cells.

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References

- [1] Verlinden, P.J., Swanson, R.M., Crane, R.A., Wickham K. and Perkins, J. 1995. A 26.8% Efficient Concentrator, Point-Contact Solar Cell, *Proc. 13th European Photovoltaic Solar Energy Conf.*, Nice, pp. 1582–1585.
- [2] Sinton R.A. and Swanson, R.M. 1992. Development Efforts on Silicon Solar Cells, Final Report, Electric Power Research Institute, Palo Alto, CA, February, pp. 2–44
- [3] Swanson, R.M., Sinton, R.A., Midkiff, N. and Kane, D.E. 1988. Simplified Designs for High-Efficiency Concentrator Solar Cells, *Sandia Report, SAND88-0522*, Sandia National Laboratories, Albuquerque, NM, July.
- [4] Verlinden, P.J., Swanson, R.M., Sinton, R.A. and Kane, D.E. 1988. Multilevel Metallization for Large Area Point-Contact Solar Cells, *Proc. 20th IEEE Photovoltaic Specialists Conf.*, Las Vegas, pp. 532–537.
- [5] Verlinden, P.J., Sinton, R.A. and Swanson, R.M. 1988. High-Efficiency Large-Area Back Contact Concentrator Solar Cells with a Multilevel Interconnection, *Int. Journal of Solar Energy*, Vol. 6, pp. 347–365.
- [6] Verlinden, P.J., Terao, A., Smith, D.D., McIntosh, K., Swanson, R.M., Ganakas, G. and Lasich, J. 2001. Will We Have a 20%-efficient (PTC) Photovoltaic System?, *Proc. 17th European Photovoltaic Solar Energy Conf.*, Munich, pp. 385–390.
- [7] Schwartz, R.J. and Lammert, M.D. 1975. *IEEE International Electron Devices Meeting*, Washington DC, pp.350–351.
- [8] Lammert, M.D. and Schwartz, R.J. 1977. *IEEE Trans. Electron Devices*, Vol. ED-24(4), pp.337–342.
- [9] Swanson, R.M. 1985 Point Contact Silicon Solar Cells, Theory and Modeling, *Proc. 18th IEEE Photovoltaic Specialist Conf.*, Las Vegas, pp. 604–610.
- [10] Swanson, R.M. 1988. Point Contact Solar Cells, Modeling and Experiment, *Solar Cells*, Vol. 7(1), pp.85–118.
- [11] Sinton, R.A. 1987. Device Physics and Characterization of Silicon Point-Contact Solar Cells, Ph.D. Thesis, Stanford University, Stanford, CA.
- [12] Sinton, R.A. and Swanson, R.M. 1987. Recombination in Highly Injected Silicon, *IEEE Trans. Electron Devices*, ED-34(6), p. 1380.
- [13] Sinton, R.A., Verlinden, P.J., Swanson, R.M., Crane, R.A., Wickham K. and Perkins, J. 1995. Improvements in Silicon Backside-Contact Solar Cells for High-Value One-Sun Applications, *Proc. 13th European Photovoltaic Solar Energy Conf.*, Nice, pp.1586–1589.
- [14] Gruenbaum, P.E., Gan, J.Y., King, R.R. and Swanson, R.M. 1990. Stable Passivations for High-Efficiency Silicon Solar Cells, *Proc. 21st IEEE Photovoltaic Specialists Conf.*, Kissimmee, pp. 317–322.
- [15] Verlinden, P.J., Swanson, R.M., Sinton, R.A., Crane, R.A., Tilford, C., Perkins, J. and Garrison, G. 1993. High-Efficiency Point-Contact Silicon Solar Cells for Fresnel Lens Concentrator Modules, *Proc. 23rd IEEE Photovoltaic Specialists Conf.*, Louisville, pp. 58–64.

- [16] Gruenbaum, P.E. 1990. Photoinjected Hot-Electron Damage at the Silicon/Silicon Dioxide Interface in Point-Contact Solar Cells, Stanford University, Stanford.
- [17] Cudzinovic, M., Pass, T., Terao, A., Verlinden, P.J. and Swanson, R.M. 2000. Degradation of Surface Quality due to Anti-Reflection Coating Deposition on Silicon Solar Cells, *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, pp. 295–298.
- [18] Gray, J.L. and Schwartz, R.J. 1985. Why don't we have a 30% efficient Silicon Solar Cell?, *Proc. 18th IEEE Photovoltaic Specialists Conf.*, Las Vegas, pp. 568–572.
- [19] Verlinden, P., Van de Wiele, F., Stehelin, G. and David, J.P. 1986. An Interdigitated Back Contact Solar Cell with High Efficiency under Concentrated Sunlight, *Proc. 7th European Photovoltaic Solar Energy Conf.*, Seville, pp. 885–889.
- [20] Sinton, R.A. et al., 1986. 27.5 Percent Silicon Concentrator Solar Cells, *IEEE Electron Device Letters*, Vol. EDL-7(10), pp. 567–569.
- [21] Sinton, R.A. and Swanson, R.M. 1987. An Optimization study of Si Point-Contact Concentrator Solar Cells, *Proc. 19th IEEE Photovoltaic Specialists Conf.*, New Orleans, pp. 1201–1208.
- [22] Swanson, R.M. 1989. Why we will have a 30% efficient Silicon Solar Cell, *Proc. 4th International Photovoltaic Science and Engineering Conf.*, Sydney, pp. 573–580.
- [23] Gan, J.Y. 1990. Polysilicon Emitters for Silicon Concentrator Solar Cells, Ph.D. Thesis, Stanford University, Stanford.
- [24] Gan, J.Y. and Swanson, R.M. 1990. Polysilicon Emitters for Silicon Concentrator Solar Cells, *Proc. 21st IEEE Photovoltaic Specialists Conf.*, Kissimmee, pp. 245–250.
- [25] Campbell, P. and Green, M. 1986. The Limiting Efficiency of Silicon Solar Cells under Concentrated Sunlight, *IEEE Trans. Electron Devices*, Vol. ED-33(2), pp. 234–239.
- [26] Christel, L.A. 1987. Polysilicon-Contacted P+ Emitter for Silicon Solar Cell Applications, *Sandia National Laboratories Report SAND87-7021*.
- [27] Kwark, Y.H. and Swanson, R.M. 1985. SIPOS Heterojunction Contacts to Silicon, *Sandia National Laboratories Report SAND85-7022*.
- [28] Sakata, H., Kawamoto, K., Taguchi, M., Baba, T., Tsuge, S., Uchihashi, K., Nakamura, N. and Kiyama, S. 2000. 20.1% Highest Efficiency Large Area (101 cm²) HIT Cell, *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, pp. 7–12.