

SIMPLIFIED PROCESSING FOR 23%-EFFICIENT SILICON CONCENTRATOR SOLAR CELLS

D.S. Ruby, P.A. Basore, M.E. Buck,
J.M. Gee, W.K. Schubert and H.L. Tardy

Photovoltaic Technology Research Department
Sandia National Laboratories, Albuquerque, NM 87185-5800

ABSTRACT

We have developed a three-photomask process that requires only a single furnace step above 800°C to fabricate silicon concentrator cells with efficiencies approaching 23% on float-zone (FZ) Si and, for the first time, an efficiency of 20% on solar-grade Czochralski (Cz) Si. Until now, high-efficiency silicon concentrator cells that have demonstrated conversion efficiencies greater than 22% have used FZ silicon and required multiple dopant diffusions and several high-temperature furnace steps. These complexities increase processing costs and preclude the use of lower cost Cz silicon, which is easily degraded by repeated high-temperature cycling.

Our simplified processing schedule retains most of the benefit available from high-performance cell designs while holding down processing costs, and it makes the use of lower cost Cz Si a viable option. The incorporation of a better optimized antireflection coating and a lower recombination back-surface field are projected to increase this performance even further.

INTRODUCTION

Several research groups have fabricated different types of silicon concentrator cells with conversion efficiencies greater than 22%. These cells include the front and back Point Contact cells [1,2], the Interdigitated Back Contact cell [3], and several variations of the Passivated Emitter Solar Cells (PESC) [4-6]. All of these designs require multiple dopant diffusions and up to eight high-temperature furnace steps. The complexity of cell processing, especially the requirement for up to six photomask levels, makes it difficult to reduce processing costs. The large number of high-temperature steps precludes the use of lower cost Cz silicon, which is easily degraded by repeated high-temperature cycling [7]. Therefore, the use of more expensive FZ silicon has always been required to date.

In an attempt to increase cost-effectiveness, we developed a simplified processing schedule that retains most of the benefit

available from high-performance cell designs while holding down processing costs. We began with a Passivated Emitter Cell design and developed a 3-photomask process that requires only a single furnace step above 800°C. In comparison, the Passivated Emitter and Rear Locally diffused (PERL) Cell developed by the University of New South Wales (UNSW) uses eight furnace steps above 800°C and six photomask levels. While the PERL cell has achieved an efficiency of 24.8% using FZ Si at about 20 suns with the use of prism covers [8], the Sandia concentrator cell process has achieved an efficiency of 22.6% on FZ Si at a concentration of 40 suns without prism covers. What is perhaps more significant is that this process resulted in an efficiency of 20.0% at 40 suns on solar-grade Cz silicon that was grown by Siemens Solar Industries.

EXPERIMENTAL PROCEDURE

The cell processing sequence is shown in Table 1.

TABLE 1. CONCENTRATOR CELL PROCESS SEQUENCE

Clean wafers
Deposit APCVD-oxide on wafer fronts (400°C)
Evaporate aluminum on wafer backs (0.5 μm)
Alloy at 800°C in oxygen/ Densify CVD-oxide
1st photomask: Define emitter areas
Etch oxide
Deposit APCVD-oxide on wafer backs (400°C)
Texture etch emitter areas
Pyramid rounding etch
Phosphorus diffusion/passivating oxide growth (110 nm, 900°C)
2nd photomask: Define gridline contact areas (4 μm wide)
Etch oxide
3rd photomask: Define metal pattern using image reversal
Evaporate aluminum on wafer backs (1 μm)
Evaporate Ti/ Pd/ Ag on wafer fronts (100 nm/ 50 nm/ 6 μm)
Liftoff in acetone
Forming gas anneal/ metal sinter (450°C)

A diagram of the cell structure is shown in Fig. 1. Important features of the process sequence include the fact that there is only a single emitter diffusion, not an additional heavy phosphorus diffusion under the gridlines. The emitter surface

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is passivated with a high-quality thermally grown oxide. This emitter diffusion and passivation oxide growth are accomplished simultaneously in a single furnace step. The parameters of this furnace step are set to optimize the tradeoff between emitter sheet resistance losses and cell blue response, and to provide the best surface doping concentration to reduce contact resistance losses without increasing emitter recombination. In addition, the optimum oxide thickness is grown to minimize reflectance when no additional overlying antireflection coating is used. The oxide anneal in forming gas, which minimizes the interface state density, also sinters the metal contacts. The same photomask is used to define the emitter areas and the textured areas. The texturization is done using a Sandia-developed process that produces randomly arranged pyramids with dimensions from 1 to 3 μm , which are large enough to reduce the reflectance of all above-bandgap photons, and yet small enough not to interfere with subsequent photolithography steps [9]. The low-temperature APCVD-oxide diffusion masks are densified early in the process during the back-surface field (BSF) formation to minimize lithographic defects. The Al-alloyed BSF gets an additional drive-in during the emitter diffusion to further reduce back surface recombination. The use of image-reversal photolithography for metal definition allows the easy liftoff of 6 μm thick gridlines that are only about 6.5 μm wide.

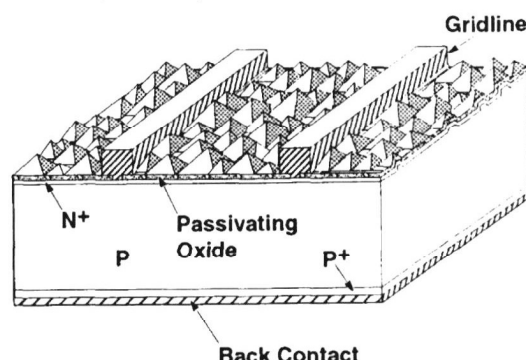


Figure 1. Structure of the Sandia Concentrator Solar Cell.

Unique Features

Our process differs in several ways from the PESC sequence developed at UNSW [4]. We use a CVD oxide deposited at 400°C for a front-side diffusion mask rather than a thermal oxide grown at high temperature. The aluminum back-surface field is alloyed early in the process at a temperature of only 800°C in a step that simultaneously densifies the front CVD oxide. In our experience, we have found that keeping temperatures below 800°C avoids a reduction of minority carrier lifetimes in Cz silicon.

Another feature of our process that differs from UNSW is that emitter areas and textured regions are defined at the same time in the first masking step. After texturing, we perform a unique phosphorus diffusion in the textured areas using a POCl_3

process that produces an emitter region and a passivating oxide layer in a single furnace step. We have calculated that for concentrations in the range from 50-150 suns, an emitter sheet resistance of 85 $\Omega/\square$ is optimum for a single emitter diffusion when using 6- μm -wide and 6- μm -thick silver gridlines. The oxide thickness grown is about 110 nm to minimize cell reflectance when no overlying antireflection coatings are used. The passivating quality of this in situ oxide layer is as good as that of any thermally grown passivating oxides we have produced, yielding values of emitter saturation current density (J_{0e}) as low as 77 fA/cm^2 at 25°C for a textured surface that exposes {111} crystal planes. This value is comparable to the lowest J_{0e} values produced by phosphorus diffusions on textured surfaces that have been found to be stable when exposed to the ultraviolet wavelengths in sunlight [10].

A second masking step is used to open contact windows through the passivating oxide layer. The third and final masking step defines the front Ti/Pd/Ag metallization pattern using image-reversal photolithography and liftoff. The front metals and the rear Al are deposited using vacuum evaporation. This allows us to define tall, high-conductivity, narrow gridlines that carry high currents without excessively shading the cell.

RESULTS

In our first attempts at fabricating concentrator cells, we used 0.4- $\Omega\text{-cm}$ p-type FZ silicon wafers. The best 10 cells from a recent lot had an average peak efficiency of 22.0%. The best cell had a V_{oc} of 648 mV and a J_{sc} of 36.2 mA/cm^2 at one sun, and peaked in efficiency at 22.2% at a concentration of 40 suns with a fill factor of 0.823. It maintained an efficiency of 21.5% at its designed operating point of 100 suns.

Measurements of a typical cell's external quantum efficiency and hemispherical reflectance were made, and the cell's internal quantum efficiency was calculated. These curves are shown in Fig. 2.

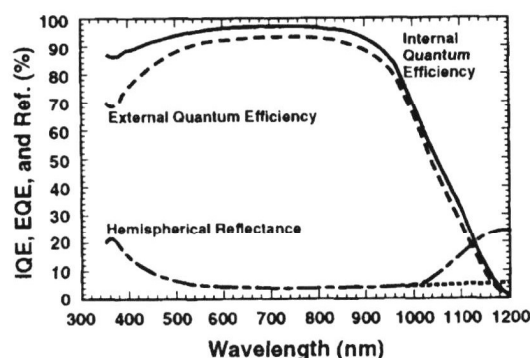


Figure 2. Internal quantum efficiency, external quantum efficiency, and hemispherical reflectance of a FZ Si concentrator cell fabricated using the baseline process outlined in Table 1.

A spectral analysis of internal quantum efficiency developed at Sandia was used to derive base diffusion length and back-surface recombination velocity [11]. These parameters were used in the computer program PC-1D to predict cell performance. Emitter loss mechanisms were adjusted until the predicted performance agreed with the measured cell performance. Then, the various components of power loss at short-circuit and open-circuit conditions were calculated. These are shown in Fig. 3.

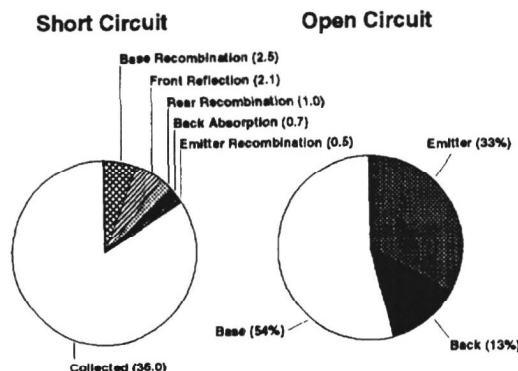


Figure 3. Distribution of carrier recombination. A. Short-circuit condition (expressed in $\text{mA}/\text{cm}^2/\text{sun}$). B. Open-circuit condition (expressed in percent).

Over half of the recombination at open-circuit occurs in the base due to a relatively short diffusion length ($250 \mu\text{m}$) and a $380\text{-}\mu\text{m}$ -thick substrate. This shows that the use of the single emitter diffusion is not a major factor in limiting the device performance. Base recombination can be reduced by wafer thinning, but the back surface recombination velocity (600 cm/s) would also need to be reduced to improve cell performance significantly. Otherwise, recombination would simply be transferred from the base to the back surface. Under short-circuit conditions, base recombination and cell reflectance are the leading causes of current loss.

By modifying the baseline process described in Table 1, we were able to improve cell performance slightly at the cost of some added complexity. By moving the Al-evaporation and alloy steps to occur after the phosphorus diffusion, and by performing the alloy at 900°C to simulate the same Al drive-in conditions that occur in the baseline process, the best cell performance was increased to an efficiency of 22.6% at 40 suns. The cell's efficiency vs. concentration is shown in Fig. 4. This cell maintains an efficiency of 22.3% up to a concentration of 100 suns.

The reason for the performance improvement of cells made using the modified process becomes apparent after examination of the base diffusion lengths shown in Fig. 5. Performing the Al-alloy after the phosphorus diffusion resulted in a statistically significant increase in the electron diffusion length in the base, perhaps because of a reduction in base defect generation during

the long diffusion/ oxidation without the Al-alloyed region present.

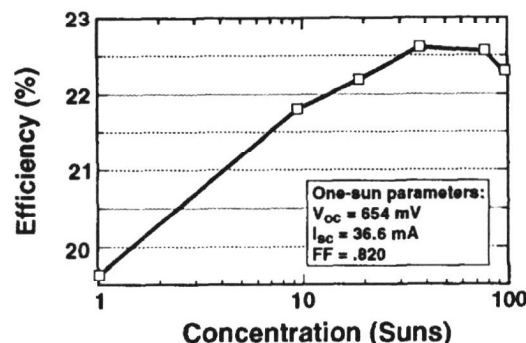


Figure 4. Efficiency vs. concentration of 1.0 cm^2 FZ Si cell made by performing the Al-alloy after the P-diffusion.

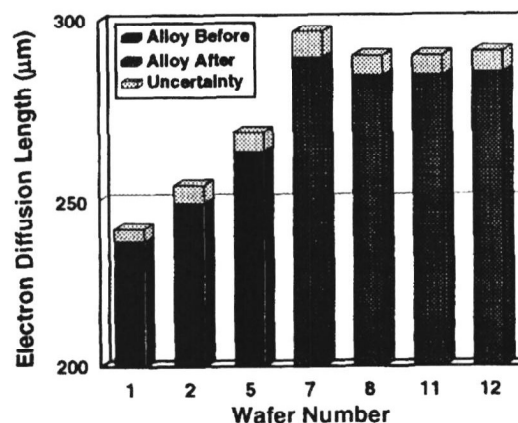


Figure 5. Comparison of base diffusion length of FZ cells with the Al-alloy performed either before or after the P-diffusion.

DISCUSSION

One unique feature of the Sandia concentrator cell process is the in situ oxidation that is performed during the emitter diffusion and drive-in. This 900°C furnace step consists first of a 10-minute deposition of P_2O_5 that results from the reaction of POCl_3 and O_2 at the Si surface. This P_2O_5 layer reacts with the Si to form phosphosilicate glass (P-glass), which provides the source of P for diffusion into the Si. For the next 1.25 minutes, the wafers are allowed to soak in N_2 to allow a fixed amount of P to diffuse into the Si. This soak time can be varied to allow a wide range of emitter sheet resistances to be obtained. Then, the furnace ambient is switched to 100% O_2 for 200 minutes. This grows a passivating oxide under the P-glass and provides a 110 nm total thickness that allows the diffusion oxide also to serve as the antireflection coating. This

passivating oxide layer grows under the P-glass layer faster than phosphorus can diffuse through it, thereby abruptly cutting off the source of phosphorus diffusing into the Si. As a result, the concentration of phosphorus atoms at the Si surface slowly decreases during the oxidation due to finite source diffusion, just as it would if the P-glass layer had been etched away during a normal two-step diffusion and drive-in. This fact, in combination with the high-quality dry oxide growth, allows the surface to be extremely well passivated. Figure 6 shows the characteristic etch rate of the two-layer structure of the diffusion oxide. The initial etch rate of the overlying P-glass layer abruptly changes to that of a dry oxide.

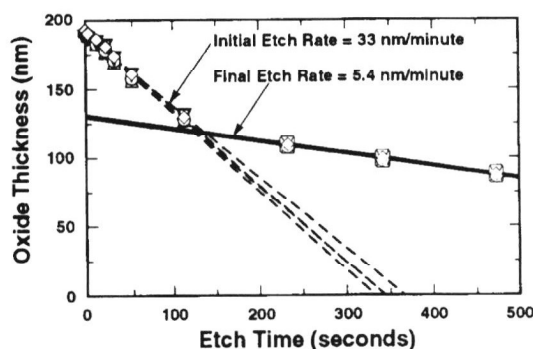


Figure 6. Thickness of POCl_3 1-step diffusion oxide vs. time in a dilute HF etch solution. The initial fast etch rate occurs while the P-glass layer is removed from the outer surface. The slower final etch rate corresponds to removal of the underlying dry SiO_2 .

Figure 7 shows a comparison of the emitter doping profile of the 900°C one-step diffusion with that of 950°C two-step diffusions using either POCl_3 or PH_3 . We selected the 2.5×10^{19} atoms/ cm^3 range of surface phosphorus concentration to minimize the losses associated with the tradeoff of low contact resistance and low emitter recombination. Finally, Fig. 8 shows the measured emitter saturation current density (J_{0e}) for various diffusions. J_{0e} is directly related to the amount of recombination taking place within the diffused emitter region and at the emitter-oxide interface. The J_{0e} values for the one-step diffusions are as low as those of the best two-step diffusions we have been able to produce, and are comparable to those of the best UV-stable passivated emitters [10]. Certainly, the excellent blue response of the cell shown in Fig. 2 indicates good surface passivation, and PC-1D modeling of the IQE data yields a front surface recombination velocity of about 8×10^3 cm/s. This is also comparable to values calculated in Ref. [10].

We employed our baseline cell process on $0.9 \Omega\text{-cm}$ solar-grade Cz Si grown by Siemens Solar Industries. The results of cell

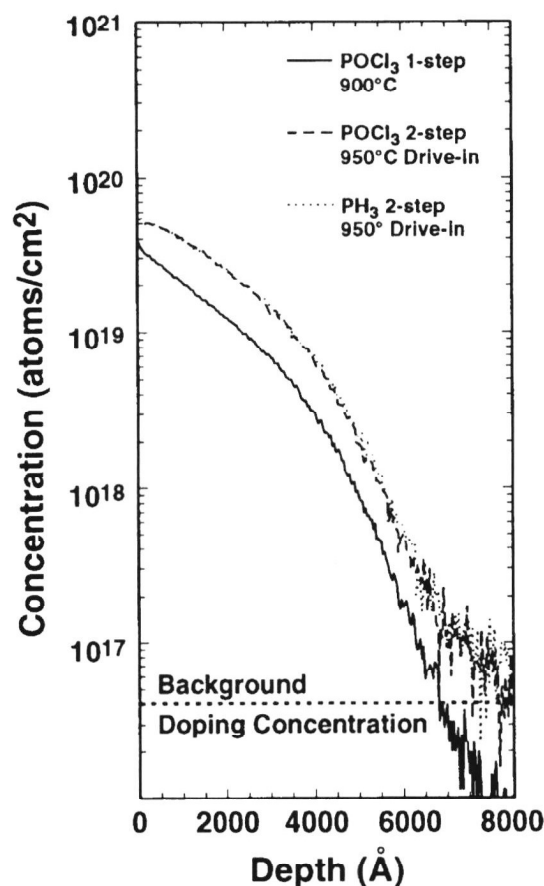


Figure 7. Emitter doping profiles of typical 1-step and 2-step phosphorus diffusions. The low surface doping concentration of the 1-step diffusion is due to isolation of the P-glass layer by the growing dry oxide, so that its resultant profile is very similar to that of 2-step diffusions.

performance measurements are shown in Fig. 9. To our knowledge, this is the first time an efficiency of 20% has been attained on Cz Si under concentrated light without the use of prism covers. The cell achieves an efficiency of 20.0% at a concentration of 40 suns and maintains 19.9% at 80 suns. The rather low efficiency at one sun is due to a photolithography defect that caused severe shunting of the entire batch of cells fabricated at that time. Spectral response measurements of this cell show excellent blue response (IQE at 400 nm of 86%) and also good infrared response, indicating a bulk electron diffusion length of $222 \mu\text{m}$. This is almost as long as that of our $0.4 \Omega\text{-cm}$ FZ material and shows that the process does not degrade the lifetime of Cz Si excessively.

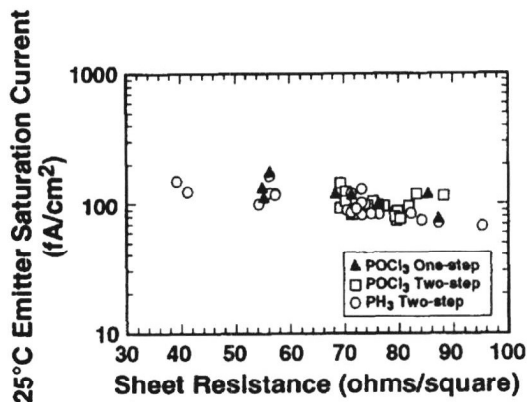


Figure 8. Emitter saturation current density for P-diffusions produced by 1-step and 2-step methods. The methods are equivalent in their ability to produce low-recombination emitter regions and well-passivated Si-SiO₂ interfaces.

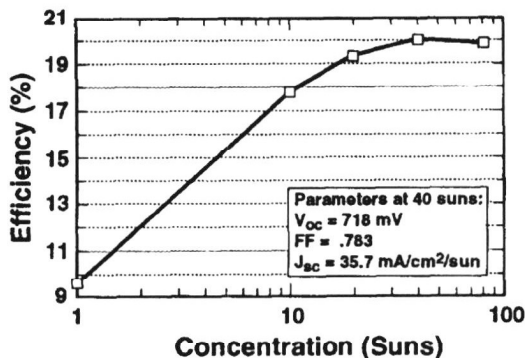


Figure 9. Efficiency vs. concentration of a 1.0 cm² concentrator cell made on solar-grade Cz Si from Siemens Solar Industries. This is the first time an efficiency of 20% has been obtained on this material without the use of prism covers.

Potential Process Improvements

To improve upon the performance of cells produced using the baseline process, we first need to use a higher refractive-index antireflection coating, such as evaporated TiO₂. This will necessitate the use of a thinner (10 nm) passivating SiO₂ layer to minimize reflectance. This thin oxide layer can be produced in two ways: either by using a controlled etch back of the thick 110-nm diffusion oxide produced in the baseline process, or by completely etching off the diffusion oxide and regrowing a thin dry oxide. The disadvantage of the first method is that control of the oxide etch rate and time is critical and may be difficult to maintain in a production environment. In addition, the oxide may not etch uniformly or may develop pinholes that

compromise the quality of the surface passivation. Our preliminary attempt at thinning the oxide was quite good in terms of producing the required 10 nm thickness, but resulted in cells whose blue response and current were not quite as good as those using the baseline process. However, the results are not conclusive because of other processing problems that were encountered in that single attempt.

As UNSW has done in its PESC process, we have also been able to etch off and regrow a thin oxide layer with good surface passivation properties. However, the additional furnace step resulted in a slight decrease in the diffusion length of the Cz material from an average of 217 ± 4 μm to 195 ± 5 μm. While this decrease may be tolerable, the added cost and complexity of an additional furnace step needs to be weighed against any improvement in performance. One option that may help offset the added cost is to grow the thin oxide during an Al-alloy step that follows the P-diffusion. This option would be especially attractive if the post-diffusion alloy is shown to result in longer base diffusion lengths in the Cz material, similar to what has been observed in the FZ Si.

Another feature that could result in improved performance would be the incorporation of a lower recombination back-surface field such as can be obtained from a boron diffusion. Although this may require an additional furnace step, it may also be possible to substitute a boron-doped APCVD-oxide on the wafer backs instead of the undoped oxide deposited in the baseline process. In this way, the boron could be driven in during the phosphorus diffusion.

Because the base diffusion length is shorter than the cell thickness (presently 380 μm), thinning of the wafer would be required to obtain the maximum benefit available from a boron-BSF. Wafer thinning would reduce not only base recombination, but also base series resistance, which is important for cells designed to operate at high concentrations. The base resistance of the present cells represents 90% of the total series resistance of 17 mΩ. If the back-surface recombination can be made low enough, higher resistivity bulk material with longer diffusion lengths could be used because conductivity modulation would be sufficient to keep resistive losses low. This could be especially important for Cz Si, which generally suffers more from short diffusion lengths at low resistivities than does FZ material. These processing changes are projected to increase cell performance to 23%.

CONCLUSIONS

We have shown that near-23% Si concentrator solar cells can be fabricated on FZ Si using a simplified 3-mask process that requires only a single furnace step above 800°C. By limiting the number of high-temperature excursions to one, we have been able to maintain the bulk diffusion length of lower cost solar-grade Cz silicon through the entire fabrication sequence. As a result, we have succeeded, for the first time, in achieving 20% conversion efficiency at 40 suns on Cz material without the use of prism covers.

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