Conf-941203--19
SAND 94-1613C**BACK SURFACE CELL STRUCTURES FOR REDUCING
RECOMBINATION IN CZ SILICON SOLAR CELLS**

Richard R. King, Kim W. Mitchell, and James M. Gee *

Siemens Solar Industries, 4650 Adohr Lane, P.O. Box 6032, Camarillo, CA 93011 U.S.A.

* Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-0752 U.S.A.

ABSTRACT

Mass-produced terrestrial CZ silicon solar cells are currently entering the domain in which bulk diffusion length is comparable to the cell thickness, so that recombination at the back surface can have a significant effect on device performance. Three manufacturable processes that address the problem of back recombination are examined here: boron diffusion from a deposited doped SiO_2 layer[1]; Al-alloyed layers using screen-printed paste[2]; and use of a collecting n^+ layer on the back interdigitated with the positive electrode[3,4]. 104-cm^2 cells fabricated at Siemens Solar Industries using these back surface structures are characterized by current-voltage, spectral response, photoconductivity decay, and SIMS measurements.

characterized by SIMS. The degree of phosphorus compensation in the p^+ Al-doped layer, caused by alloying through a phosphorus diffusion, is also measured by SIMS. Cells with collecting n^+ regions on the back in addition to the front n^+ emitter, fabricated on 104-cm^2 SSI CZ substrates using only screen-printing patterning technology, exhibit current densities up to 35.9 mA/cm^2 . About 5% of this current is contributed by the back n^+ regions which cover ~60% of the back surface in these non-optimized cells. All three of the above methods add a minimal number of steps to the cell fabrication sequence, and use inexpensive, robust processes such as screen-printing. These are key considerations for applying a candidate process in a mass-production environment.

BORON-DOPED LAYERS**INTRODUCTION**

As the substrate thickness of mass-produced silicon solar cells is reduced to minimize costs, recombination at the back becomes increasingly important to the device performance. By virtue of their greater diffusion lengths, single-crystal CZ Si cells are more sensitive to back surface recombination than are multicrystalline Si cells at the same thickness. High-throughput fabrication methods to reduce back recombination are becoming increasingly important for mass-produced CZ cells.

Among the approaches being studied at Siemens Solar to reduce back surface recombination are: diffusion from a borosilicate glass doping source[1]; alloying with screen-printed Al[2]; and formation of n -type regions on the back, interdigitated with p -type areas, that help collect minority electrons in the p -type substrate[3,4]. Cells with 104-cm^2 area have been fabricated with each of these processes on commercial CZ material grown at Siemens Solar Industries (SSI). The boron diffusions are characterized by microwave photoconductivity decay ($\mu\text{W-PCD}$) measurements[5], and by quantum efficiency measurements with light incident on the front and on the back. Al-doped layers formed by alloying with screen-printed Al paste are

For metal-contacted regions on the back, deeper boron diffusions result in a lower emitter saturation current density J_0 of the doped layer. However, processing times and temperatures should ideally be kept low for CZ silicon, to avoid degradation of the bulk lifetime. This results in a trade-off between the bulk lifetime and the J_0 of the metal-contacted portion of the boron-doped layer on the back. If a large fraction of the back is oxide-passivated, the J_0 can be acceptably low even for shallow diffusions, at least for untextured surfaces[1].

Table 1 gives the values of J_0 , measured by $\mu\text{W-PCD}$ at Sandia, for boron diffusions made at SSI under processing conditions suitable for maintaining bulk lifetime in CZ solar cells. These PCD test structures have intrinsic substrates, and had boron-doped SiO_2 deposited on both sides at Sandia. Measured values of the textured n^+ emitter J_0 are also listed in Table 1. The effective surface recombination velocity is calculated from the measured J_0 values, using $n_i(25^\circ\text{C}) = 8.70 \times 10^9\text{ cm}^{-3}$ [6], and $N_A = 1.5 \times 10^{16}\text{ cm}^{-3}$. Values of s_m less than the value of D/L for minority carriers in the substrate, typically about 1500 cm/s for SSI CZ cells, result in reduced cell recombination as the cell thickness is decreased.

Draft

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

Table 1: Measured values of the saturation current density J_0 for samples diffused at SSI.

PCD Sample Structure	Surface Condition	J_0 at 25°C from PCD (10^{-13} A/cm 2)	$s_{eff} = J_0 (N_A/qn_i^2)$ (cm/s)
p $^+$ ip $^+$	bare, textured	9.4	1170
	bare, untextured	8.9	1100
	oxide pass., untextured	1.9	240
n $^+$ in $^+$	bare, textured	10.7	1320
	oxide pass., textured	7.3	900

Fig. 1 shows the measured external quantum efficiency for light incident on the front and on the back of two SSI CZ cells with 228 ± 10 μ m substrates, one with a boron diffusion on the back, and the other with no boron diffusion. The reduced back surface recombination for the boron-diffused cell is evident from the greater back response of that cell, especially at the shorter wavelengths for which charge carriers are being generated near the back surface.

Fig. 1: External quantum efficiency measured with light incident on the back and on the front of SSI CZ cells with two different back conditions. The cell with a boron diffusion on the back has a much greater back response at short wavelengths.

Al-ALLOYED LAYERS

Aluminum alloying provides an alternative to shallow, heavily-doped boron diffusions, by forming a p $^+$ layer which can be many microns deep, but which has a relatively low dopant concentration. Fig. 2 shows the SIMS profile of an Al-doped layer formed by alloying screen-printed Al paste with an SSI CZ Si substrate. The peak Al concentration is $\sim 5 \times 10^{18}$ cm $^{-3}$, and the thickness of the p $^+$ layer is ~ 13 μ m. In practice, Al is often alloyed through a phosphorus-doped layer, which could potentially compensate the Al-doped Si layer regrown from the Al melt. Fig. 2 also plots the SIMS phosphorus profile for the same Al-alloyed sample, showing that the phosphorus, while present in the regrown layer, has a concentration less than one-tenth that of the aluminum.

Fig. 2: Aluminum and phosphorus SIMS profiles for an alloyed layer formed using screen-printed Al.

Table 2: Measured parameters for 104-cm² SSI CZ cells with screen-printed Al alloyed on the back, and for controls with standard processing. The shaded area gives the percent difference between a given experimental group and the 284 μ m group with the standard process.

Cell Process	Number of cells in group	Average measured parameters for each experimental group:					
		Thickness (μ m)	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF	Eff. (%)	Ext. QE at 946 nm (act.area)
Screen-printed Al alloyed on back	8	224	609	33.3	0.752	15.2	0.786
		% diff.	+1.7%	+1.5%	+2.5%	+5.8%	+8.7%
	4	298	603	33.0	0.753	15.0	0.791
		% diff.	+0.8%	+0.8%	+2.6%	+4.4%	+9.3%
Standard process	7	209	589	31.9	0.734	13.8	0.666
		% diff.	-1.5%	-2.7%	+0.1%	-4.1%	-8.0%
	13	284	598	32.8	0.734	14.4	0.724
		% diff.	0.0%	0.0%	0.0%	0.0%	0.0%

SSI cells with this Al doping profile on the back have substantially higher values of V_{oc} and J_{sc} , as expected for this classic back-surface-field formation process. Table 2 shows the average measured cell performance for 104-cm² cells. Cells with an Al-alloyed back and 224 μ m substrate thickness have an average efficiency of 15.2%, or 5.8 relative % higher than for 284 μ m cells with the standard process. The illuminated I-V parameters were measured at SSI at 25°C, 0.100 W/cm² AM1.5G, using a reference cell calibrated at Sandia National Labs. Active-area, external quantum efficiency measurements were made at SSI, using reference detectors that were also calibrated at Sandia.

TRANSISTOR-LIKE STRUCTURE

Cells with three terminals (the normal front n⁺ contact, the back contact to the p-type base, plus an additional contact to an n⁺ region on the back interdigitated with the positive back electrode) have demonstrated enhanced current densities, both for front illumination and for the case in which light is incident on the rear of the cell [3,4]. 104-cm² cells fabricated at SSI with a collecting n⁺ layer on the back have current densities of up to 35.9 mA/cm² when illuminated from the front only. Accounting for a 9% grid shadowing loss, this translates to an active-area J_{sc} of 39.4 mA/cm².

Fig. 3 shows the light I-V characteristics of a cell from a preliminary run of transistor-like cells, made with only screen-printed patterning. The measurements were made with two electrode interconnection

Fig. 3: Light I-V curves for a transistor-like cell with n⁺ collecting regions on the back, for two electrode interconnection configurations. Light is incident on the front of the cell only.

Shouldn't start with number

Table 3: Measured I-V parameters for a cell with back n^+ collecting regions fabricated on SSI CZ silicon using screen-printing methods.

Measurement Configuration	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF	Efficiency (%)
Back n^+ connected to front n^+ emitter	602	35.9	0.719	15.5
Back n^+ shorted to positive back contact	597	34.1	0.727	14.8

configurations: with the back n^+ regions externally connected to the front n^+ emitter; and with the back n^+ regions shorted to the positive back electrode. The light I-V parameters for these two configurations are shown in Table 3. The primary effect of the collecting n^+ layer on the back is to increase J_{sc} by about 5% for these cells with 1.0 Ωcm , 300 μm thick substrates. The light I-V measurements were again made at SSI at 0.100 W/cm^2 AM1.5G, as determined by a reference cell calibrated at Sandia. Because of the nature of the back contact, the cell was not resting on a temperature-controlled chuck, so the cell temperature of 25°C was determined from the V_{oc} for the configuration with the back n^+ region shorted to the positive back contact.

These cells were designed with a fairly coarse pattern on the back, with a center-to-center spacing between fingers of like polarity of 0.254 cm, to make the alignment of the interdigitated back patterns as robust as possible. Large alignment tolerances increase the distance between the fingers of the positive electrode, increasing substrate resistive losses and decreasing fill factor, and also require minority electrons in the substrate to diffuse farther on average to reach a collecting n^+ region on the back. Improved alignment mechanisms can vastly improve the accuracy of the print position, allowing higher cell efficiencies.

SUMMARY

A variety of simple methods exist which hold the potential to increase the efficiency of mass-produced CZ silicon solar cells by 5% or more, impacting the cost per watt of photovoltaic power by a similar fraction. In order to make these processes cost-effective, it is vital that the methods used to implement them are as simple as possible, using robust, high-throughput methods such as screen-printing for cell patterning. Commercial CZ cells, with present substrate thicknesses typically 1 to 2 times their diffusion length, are currently poised to take advantage of both back-surface field structures and collecting n^+ back regions. On thinner substrates, the performance advantages are even greater.

ACKNOWLEDGMENTS

The authors would like to thank the researchers at Sandia National Laboratories, especially P. Basore and B. Silva, for their hard work to deposit SiO_2 layers on the cells in this study, and to measure the J_0 of boron and $\mu\text{W-PCD}$. We would also like to thank R. Balanga; D. Cezar, W. Chesarek, J. Frost, T. Jester, K. Kuehl, A. Münzer, J. Schwartz, D. Tanner, B. Wieting, and the R&D and Engineering staff at Siemens Solar for their encouragement and technical assistance.

REFERENCES

- [1] R. R. King and R. M. Swanson, "Studies of Diffused Boron Emitters: Saturation Current, Bandgap Narrowing, and Surface Recombination Velocity," *IEEE Transactions on Electron Devices*, 38, 1991, pp. 1399-1409.
- [2] P. Löfgen et al., "Aluminum Back-Surface Field Doping Profiles with Surface Recombination Velocities Below 200 cm/s ," *Twenty-Third IEEE PVSC*, 1993, pp. 236-242.
- [3] A. Cuevas, A. Luque, and J. M. Ruiz, "A n^+pn^+ Double-Sided Solar Cell for Optimal Static Concentration," *Fourteenth IEEE PVSC*, 1980, pp. 76-81.
- [4] T. Warabisako et al., "Bifacial Multicrystalline Silicon Solar Cells," *Twenty-Third IEEE PVSC*, 1993, pp. 248-251.
- [5] P. A. Basore and B. R. Hansen, "Microwave-Detected Photoconductivity Decay," *Twenty-First IEEE PVSC*, 1990, pp. 374-379.
- [6] A. B. Sproul and M. A. Green, "Experimental Measurement of the Intrinsic Carrier Concentration of Silicon," *Twenty-First IEEE PVSC*, 1990, pp. 380-385.