Characterization of 23-Percent Efficient Silicon Solar Cells

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***Abstract*—A new silicon solar cell structure, the passivated emitter and rear cell (PERC cell), has very recently demonstrated energy conversion efficiency above 23 percent. The design principles and operating characteristics of this new cell structure are described as is the potential for further efficiency improvements.**

I. Introduction

Despite the 36 years which have elapsed since the demonstration of the first silicon solar cell, the last six years of development have seen improvements in cell performance rivalled only by those during the first six years. During this six-year period, the independently confirmed efficiency of silicon cells has increased from 17.1 percent [1] to 22.8 percent [2]. Most of this improvement has originated from improved cell structures and processing techniques, rather than improved material quality.

The structure responsible for the most recent improvements is the passivated emitter and rear cell (PERC cell) of Fig. 1 as developed by Blakers *et al.* [2]. This paper describes the theory and operating characteristics of the PERC cell including recent developments which have led to efficiencies above 23 percent. It also discusses opportunities for future improvements in silicon cell performance.

II. Cell Structure

The PERC cell structure differs from that of our earlier passivated emitter solar cells [3] (PESC cells) in several important ways. There are also important differences in the processing techniques used to produce these structures.

The main structural differences arise at the rear contact. Rather than an alloyed Al rear contact, the PERC cell uses a thermally grown oxide to electronically passivate most of the rear cell surface. Contact is made at isolated contact holes through this passivating oxide directly to the underlying p-type substrate. This contacting approach is only suitable for relatively low resistivity substrates, with 0.2 Ω-cm substrates giving the best results to date. Diffusing these contact areas or the entire rear surface would remove this constraint, but has given inferior results to date.

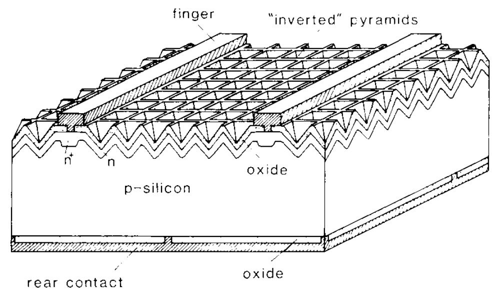

Fig. 1. Schematic diagram of the passivated emitter and rear cell (PERC cell).

The alloyed rear Al contact to earlier PESC cells provided a rough interface which formed the basis of a rudimentary light-trapping scheme [4]. The effectiveness of this scheme was, however, limited by the low effective reflectance of the rear contact [5]. The PERC structure incorporates a highly reflective planar rear surface. This high reflectivity arises from the dielectrically isolated reflector formed by the oxide and nonalloyed rear Al layer. The calculated reflectance of this layer is above 97 percent, giving the potential for very effective light trapping. This potential can be realized with appropriate structure on the top surface of the cell. Best results to date have been obtained with the "inverted pyramid" structure apparent in Fig. 1. This structure is calculated to give better light trapping than an upright pyramid structure, although tilting the pyramids should give better results in both cases [6].

The other structural difference relates to the use of a heavy diffusion in areas immediately underlying the top metal contact. In this way the properties of the top diffused layer can be separately optimized in contacted and noncontacted areas which increases the open-circuit voltage of these devices by about 10 mV. This feature was not required in earlier generation PESC cells due to their lower operating voltages.

These structural changes would not have resulted in improved cell performance without corresponding processing changes. The rear Al alloying step used in earlier PESC sequences was an effective gettering step [7] which allowed high cell bulk lifetimes and correspondingly high

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TABLE I
OUTPUT CHARACTERISTICS OF ASSORTED 0.2 Ω-cm PERC CELLS WITH DIFFERENT SURFACE STRUCTURES (MEASUREMENTS BY SANDIA NATIONAL LABORATORIES OR RELATIVE TO SANDIA CALIBRATED CELLS, GLOBAL AM1.5 SPECTRUM, 25°C, 4 cm^2 CELL AREA)

Cell	Surface Geometry	Rear Contact Spacing (mm)	V_{OC} (mV)	J_{SC} (mA/cm2)	FF (%)	Effic. (%)
T23a	Planar	4 x 4	681	34.0	79.0	18.3*
T25q	µ Grooved	4 x 2	694	39.3	81.3	22.2*
WA53	Figure 1	2 x 2	696	40.3	81.4	22.8*
Z042	Figure 1 (DLAR)	2 x 1	688	40.8	82.1	23.1

* Sandia confirmed

performance to be obtained. However, the alloyed Al had limitations in relation to its ability to passivate the rear surface and as a rear reflector. To progress beyond the performance levels established by the PESC cell, the dependence upon alloyed Al had to be removed.

The path to achieving this independence had already been demonstrated by the high-efficiency cell work of Sinton *et al.* [8] and Verlinden *et al.* [9]. This lay in the use of chlorine based processing which allows high bulk lifetimes to be maintained during processing, eliminates the need for a separate gettering step. This processing also produces better oxide passivation than that obtained in our earlier sequences.

For the highest efficiency devices, the top surface oxide is etched back to about 250 Å thickness and a MgF_2/ZnS double layer antireflection coating (DLAR coating) applied.

Table I shows the output parameters of some of the PERC cells to be discussed in subsequent sections.

III. Rear Contact Design

An unusual feature of the cell design of Fig. 1 is the way rear contact is made at isolated contact points directly to the cell bulk. A low density of small contact points will minimize rear contact recombination, maximizing the V_{OC} and J_{SC}. However, this will have less desirable effects upon the contact resistance and the resistance due to lateral flow of light generated carriers in the bulk, reducing cell fill factor.

The rear Al is known to form a Schottky barrier to p-type silicon with a relatively low barrier height of 0.4–0.6 eV [10]. However, measured contact resistances to p-type silicon are lower than would be predicted from such barrier heights [11]. A model of the rear contact as a Schottky diode shunted by a resistance equal to the experimental contact resistance would appear to resolve these conflicting features. Physically, the shunting resistance could be associated with locally poor regions of the

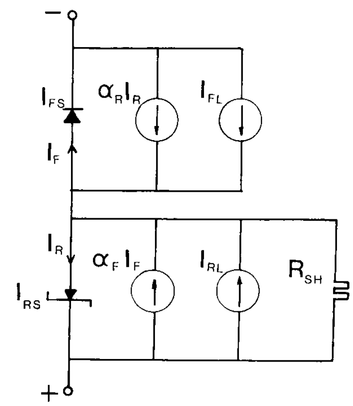

Fig. 2. Modified Ebers-Moll equivalent circuit of the PERC cell.

diode whose formation was encouraged by the subeutectic sintering conditions (e.g., see [12]).

The contribution to the specific resistance of the cell from rear contact resistance will be the specific contact resistance of the contact multiplied by the fraction of the rear surface contacted. For a one sun cell, any specific resistance contribution less than about 0.1 Ω cm^2 will have little effect upon cell performance. Since the specific contact resistance of Al to 0.2 Ω-cm p-type Si (circa 10^{17} cm^{-3} doping level) is about 10^{-4} Ω-cm^2, it follows that rear contact resistance should not be much of a problem provided more than about 0.1 percent of the rear surface is contacted.

If the contact holes are squares of side a, spaced a distance S on a square matrix, the fractional power loss associated with lateral flow in the bulk to the contact can be calculated from Laplace's equation as:

$$f_{lb} = \frac{\rho}{8W} \frac{J_{mp}}{V_{mp}} S^2 [\ln (S/a) - 0.75] \quad (1)$$

where W is the cell thickness and J_{mp} and V_{mp} refer to the current density and voltage at the maximum power point. For typical S/a ratios in the 5–100 range, this gives large values of contact spacing in the 2–5 mm range for fractional power loss less than 1 percent. These very large values are due to the low sheet resistivity of a 280-µm-thick, 0.2 Ω-cm substrate of 7 Ω/square. Note that this cell design bears little relationship to that of a point contact solar cell where the contact hole spacing is only about 50 µm [8].

Note that much of the variation in fill factor apparent for the cells of Table I arises from differences in the spacing between rear contact points.

The effect of the rear contact scheme upon V_{OC} and J_{SC} can be discussed in terms of the modified Ebers-Moll equivalent circuit [10, p. 152] of Fig. 2. This takes into account the partially rectifying action of the rear contact points, having the normal form for bipolar transistors with additional elements added.

The diode symbols represent ideal diodes associated with the top and rear junctions. Their respective saturation current densities (I_{FS} and I_{RS}) are calculated with the other junction shorted, i.e., the junction area replaced by an infinite recombination velocity surface. Also shown are the normal current controlled current sources with values determined by the current flowing in the opposite junction multiplied by the injection efficiency α of this opposite junction. α_F tends to be quite high in these cells since the bulk diffusion length is several times the bulk (base) thickness, as subsequently discussed, α_R is small due to the low injection efficiency of Schottky diodes. An important reciprocity relationship is that $\alpha_F I_{FS} = \alpha_R I_{RS}$.

To the normal Ebers–Moll circuit is added an additional current source across each junction to model photogenerated current. The values assigned to these (I_{LF} and I_{LR}) correspond to the current flowing to the respective junctions at short circuit, with the opposite junction also short circuited, i.e., with the two junctions fighting for their respective share of the photogenerated current. Also added to the equivalent circuit is a shunt resistance (R_{SH}) across the rear junction to model the lower than theoretical contact resistance of the Schottky contact, as previously discussed.

When this shunting resistance is low, as required for highest performance, the voltage across the rear junction is held low as is the current I_R through the rear junction. This essentially eliminates many of the interactions which would otherwise occur between the two junctions.

The equivalent circuit shows that the rear contact points can affect V_{OC} in two ways. One is by the voltage generated across the rear Schottky diode, although this value is constrained by the shunting resistance as previously noted. This open-circuit voltage is given by:

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{I_{LF}}{I_{FS}} + 1 \right) - (\alpha_F I_{LF} + I_{LR}) R_{SH} \quad (2)$$

provided the second term (the voltage generated across the Schottky contact) is small. At the maximum power point, the latter voltage will approach the value $(I_{mp}(1 - \alpha_F) + \alpha_F I_{LF} + I_{LR}) R_{SH}$. If α_F approaches unity, the Schottky voltage drop will be similar on open circuit and at the maximum power point. Hence, if the rear contact resistance is sufficient to affect the cell fill factor, it would also affect the open-circuit voltage, according to this model.

The second way the rear contact affects the V_{OC} is by its influence on the saturation current density of the main cell (I_{FS}). The rear surface consists of two regions, one with a very high recombination velocity and the other with a very low velocity. Experiments have been conducted with planar surface PERC cells with contact over the entire rear surface at one extreme and with contacts spaced over 2 cm apart at the other in an attempt to identify the saturation current density associated with each region. Open-circuit voltage of 663 mV was obtained on the former corresponding to a saturation current density of 0.3 pA/cm^2 (27°C).

The highest open-circuit voltage observed in the other case was 705 mV, corresponding to a saturation current density of 0.06 pA/cm^2. The latter value implies a minimum value of the base lifetime of 160 μs and a diffusion length much larger than the cell thickness (280 μm). This implies that, in the case of contact over the entire rear surface, the saturation current density can be almost entirely attributed to recombination at the rear contact, limited only by the rate of diffusion of minority carriers to this contact.

As the rear contact area decreases, this recombination component will not decrease proportionately due to "fringing field" effects. Because of the large diffusion lengths, the equation to be solved to calculate these fringing effects reduces to Laplace's equation which has been solved in this context in the past [13]. For circular contact points of radius r, the saturation current density can be calculated as:

$$J_0 = J_{100} f \left[1 + \frac{W}{r} \frac{4 \ln 2}{\pi} + \frac{W^2}{8r^2} \right] \quad (3)$$

where J_{100} is the saturation current density with 100-percent rear contact coverage, f is the fractional coverage, and the term in brackets accommodates fringing field effects. This suggests that rear contact recombination contributes 0.02 pA/cm^2 in the worst case of Table I (2 mm × 1 mm matrix of 100-μm-radius contact holes).

The rear contact also competes with the main junction for light generated carriers as previously noted. For the case of complete rear surface coverage by the contact and large bulk lifetimes, computer simulations indicate that approximately 10 percent of the photogenerated carriers recombine at the rear surface. Reducing the rear contact area will reduce this loss, but again not proportionately to the contact area reduction. The "fringing" effects in this case will be related to those discussed regarding saturation current densities. The corresponding multiplier (the term in brackets in (2)) could be used as a first approximation in the present case. This suggests that about 1 percent of generated carriers are being lost to the rear contact in the worst case of Table I.

IV. Noncontacted Rear Surface

The regions of the rear surface of the PERC cells which are not contacted also raise interesting device physics.

The rear oxide is overlain with Al held at much the same potential as the underlying substrate. For the present oxide thickness (circa 1100 Å), this will drive the surface into weak depletion, a condition likely to enhance surface recombination. The experimental work of Girisch *et al.* [14], whereby the potential along the undoped surface of a p-type solar cell was varied by an overlying polysilicon gate, clearly shows this condition to be unfavorable from the point of view of maximizing cell V_{OC}. However, as the injection level increases, the disadvantage of this condition significantly reduces.

This can be understood from the combined theoretical/experimental work of Eades and Swanson [15] dealing with flat-band conditions in silicon. This work predicted superior surface recombination properties for n-type silicon compared to p-type silicon, at least until high injection at the surface was attained. Fundamentally, this is due to the much lower surface state capture cross section measured by these authors for holes compared to electrons.

In the present case, the large diffusion lengths ensure that quasi-Fermi level separations at the rear of the cell are comparable to the cell applied voltage. As the illumination level and hence the cell operating voltage increases, so does the electron concentration at the surface. Due to the initial depletion of holes at the surface, the electron concentration dominates at the surface well before high injection is reached in the bulk. The electron and hole surface concentrations therefore have similar values as within n-type material and similarly low recombination rates would be expected.

Other experimental work in this context is that of Yablonovitch *et al.* [16] which studies surface recombination as a function of surface potential for a fixed injection level in p-type substrates. This confirms the advantages of having a "quasi-n-type" surface, although the advantages were not as pronounced as predicted by calculations based on the work of Eades and Swanson [15].

V. Light Trapping

The highest efficiency PERC cells of Table I include much higher levels of light trapping in the cell bulk than demonstrated by earlier PESC devices. This results most fundamentally from the highly reflective properties of the planar, dielectrically isolated rear reflector.

Fig. 3 compares the measured hemispherical reflectance from the planar, microgrooved, and inverted pyramid solar cells of Table I. Each uses an oxide AR coating which provides nonoptimized reflectance performance. The measured reflectance also includes reflection from cell fingers.

The device with the planar top surface shows high reflection right across the spectrum due to the relatively poor oxide AR coating. It is high at short wavelengths due to the high real and imaginary components of the Si refractive index at these wavelengths combined with the inappropriate AR coating thickness for these wavelengths. Beyond 1-μm wavelength, the reflectance also increases rapidly as the silicon becomes increasingly transparent and light is reflected from the rear contact out the top of the cell. Beyond 1.15 μm, the reflectance is constant at higher than 90 percent due to the high reflectance of the rear contact. The microgrooved cell shows similar characteristics apart from the reflectance being lower across the spectrum due to the "double bounce" experienced by incident light. Beyond 1.15 μm, the reflectance is again constant at about 82 percent. Since ideally, the microgrooved top surface/planar rear surface combination should not give rise to light trapping [17], a similarly high reflection to that observed in the planar cell might be expected at these wavelengths. However, nonidealities in implementing the mi-

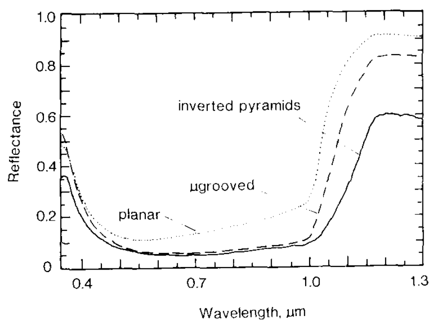

Fig. 3. Hemispherical reflection versus wavelength for three treatments of the top surface of the PERC cell (reflection from metallization fingers also included).

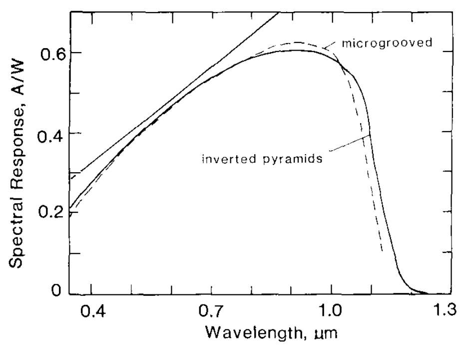

Fig. 4. Spectral responsivity of microgrooved and "inverted pyramid" PERC cells (oxide antireflection coating in both cases).

crogrooves, (namely the "flats" along the top surface between grooves and the quite high reflection from a single surface of the groove for both externally and internally incident light) produce a small light-trapping component. Since the rear reflector provides virtually the only absorption mechanism in the cell for wavelengths beyond 1.15 μm, the reflectance at these wavelengths gives a measure of the effectiveness of the light trapping scheme. For the "inverted pyramid" structure, the reflection across most of the spectrum is similar to the microgrooved case. However, beyond 1.15 μm, the reflection plateau has a value of about 62 percent, indicating more effective light trapping.

Even in this case, theory would predict that over half of the incident light would have only one double pass across the cell and then escape [17]. This indicates that the remainder which is trapped in the cell must be very effectively trapped. This would be consistent with the increased prospects for rays (which would otherwise escape from the top surface of this structure) to reenter the silicon compared to the case of "upright" pyramids.

The results of this improved light trapping are apparent in Fig. 4 which compares the spectral response of the inverted pyramid and microgrooved cells. The improved response of the inverted pyramid cell at wavelengths beyond 1 μm is apparent. At wavelengths beyond 1.18 μm where the cells have a small but finite response, the energy of at least two phonons must augment the photon energy [16]. It is not clear at this stage whether this transition occurs by the virtually simultaneous coincidence of the three quasi-particles (a transition which may be theoretically impossible [18]) or by the earlier scattering of the photon by the Raman process [19], whereby the energy of the Raman phonon (64 meV) is imparted to the photon. Subsequently, this photon is absorbed with the assistance of a single additional phonon. The distinction is important in the design of light trapping schemes seeking to take advantage of multiphonon absorption processes, due to the randomizing effect of the Raman scattering process [19].

An obvious approach to improving the present light trapping scheme is to prevent the escape of such a large fraction of the light after a single double-pass. This can be achieved by using structure on both cell structures [17] or by using tilted geometries on the top cell surface [6]. The latter may be preferable since the multiple rear reflections associated with the former reduces the effective rear surface reflectance.

VI. Potential for Improvements

As apparent from Fig. 3, there is still about 5-percent reflection from the top surface of the oxide AR coated "inverted" pyramid cells. About 2 percent of this arises from reflection from the cell fingers. The remainder arises from reflection from the flat regions between the pyramids in Fig. 1 and from reflection from the pyramid walls after two bounces. Replacing the oxide by a better AR coating would significantly reduce reflection from the flat regions.

Etching back the passifying oxide below about 250 Å can cause significant loss in both V_{OC} and J_{SC}. By etching back to just above this critical thickness and applying a DLAR, a boost of nearly 2 percent in J_{SC} has been demonstrated, taking silicon cell efficiency above 23 percent for the first time (Table I).

Incorporation of an improved light trapping scheme such as by using tilted geometrical features [19] should improve J_{SC} further by a similar amount. There is also scope for further optimization of the rear contact design which should improve both V_{OC} and J_{SC}. Along with further optimization of emitter surface recombination, this should allow PERC cell efficiency to approach 24 percent.

Once a processing regime is found which will allow boron diffusion at the rear contact points or over the entire rear surface without degrading the exceptionally high bulk lifetimes observed in the present cells, efficiency above 24 percent becomes feasible. Multiplying the best individual values of V_{OC}, J_{SC}, and FF observed to date in our 4-cm^2 cells gives an "efficiency" of 24.7 percent. This suggests that 25-percent silicon cell efficiency is not impossible with the present understanding of high efficiency cell design. The parameters of a cell with this efficiency might be a V_{OC} of 710 mV, a J_{SC} of 42 mA/cm^2 or higher, and a fill factor approaching 84 percent.

VII. Conclusions

Chlorine based techniques originally developed to meet the stringent requirements upon bulk lifetime and surface passivation for rear contacted solar cells [8], [9] have been adapted to a more conventional bifacially contacted cell, the passivated emitter and rear cell (PERC cell). This cell has demonstrated energy conversion efficiency above 23 percent for silicon for the first time.

A number of interesting features of the PERC cell design have been discussed. Rear contact design is based on a balance between the beneficial effects of small sparsely spaced contact points upon the open-circuit voltage and short-circuit current of the cell and the corresponding negative effects upon cell fill factor. The noncontacted regions of the rear surface are held in weak depletion by an optically isolated but electrically connected rear Al reflector. Once bulk injection levels become appreciable, the disadvantage of this surface condition disappears.

The structure incorporates a reasonably effective light-trapping scheme although there remains scope for improvements in this area. Along with other improvements, efficiency approaching 24 percent seems feasible with the present cell structure. If a processing regime can be found which allows boron passivation of the contact holes or the entire rear surface without loss of the present exceptionally high bulk lifetimes, efficiencies above 24 percent are likely.

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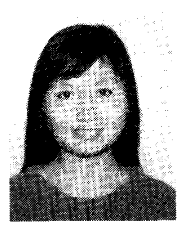

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