HIGH EFFICIENCY N-SILICON SOLAR CELLS USING REAR JUNCTION STRUCTURES

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ABSTRACT

This paper reports two rear junction structures for n-silicon solar cell. They are respectively rear totally- (PERT) and rear locally-diffused (PERL) junction cells. The electrical contacts are deployed on both sides of the cells with n- on the front and p- on the rear, most surface area being passivated by silicon dioxide. A shunt problem in the rear PERL structure, resulting in a low fill factor, FF, has been identified and solved by using the different contact characteristics of PtSi/p-silicon and PtSi/n-silicon. Open-circuit voltages up to 694 mV are obtained for the rear PERT structure, and 696 mV for the PERL. Both of the rear junction n-silicon solar cells have achieved high energy conversion efficiencies of 21.9% and 21.2% respectively. The results were measured at one sun (0.100 W/cm^2), Global AM 1.5 spectrum, 25°C by Sandia National Laboratories. Some front junction n-silicon cells have also been fabricated to compare with the rear junction cells. The measured results have shown that the open-circuit voltage for the front junction cells is about 34 mV lower than the rear junction cells. The reason for this is discussed.

1. INTRODUCTION

The PERL cell (the passivated emitter, rear locally-diffused cell) has demonstrated a high energy conversion efficiency of up to 23.1% on a p-type silicon substrate [1]. To create this PERL structure on a n-silicon substrate, an opposite polarity junction diffusion element (most commonly Boron) is required. A considerable effort has been made to produce a high quality boron diffusion process for n-silicon cells. After some development, open-circuit voltages up to 671 mV were obtained with planar top surface solar cells. Inverted pyramid structure cells were then fabricated and they resulted in an improved short-circuit current density and efficiency compared to their planar counterparts, but with the sacrifice of 20-30 mV in open-circuit voltage (see Table 1). A simple explanation for this is that, with the boron diffusion conditions used, the cell open-circuit voltage was being limited by the large saturation current density contribution from the boron diffused top surface. One way of overcoming this deficiency for n-silicon substrate is to make a boron diffusion on the rear surface and a planar phosphorus diffusion along the top surface of the n-type substrate, thus forming a rear junction and front surface field structure. King et. al. from the Stanford University have reported a rear junction structure n-silicon solar cell [2], in which the metal contact grids were made all on the backside of the cells, the front side being free from any metal shading.

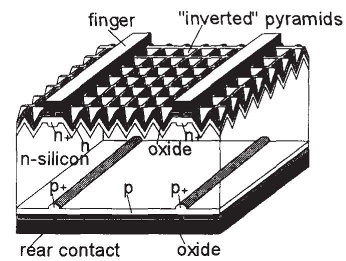

Figure 1: Rear junction PERT cell.

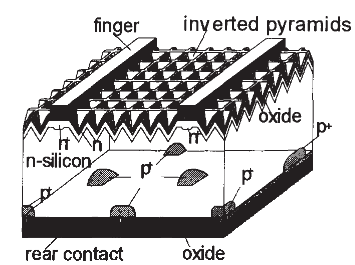

Figure 2: Rear junction PERL cell.

In this paper, we report two newly developed rear junction structures (see Fig. 1 and 2) for n-silicon solar cells. They are respectively called rear PERT and rear PERL n-silicon cells. Both have metal contacts on both top and back surfaces. The cells have demonstrated surprisingly good results with energy conversion efficiency of 21.9% measured for rear PERL cells and 21.2% for rear PERT (see Table 1). The efficiency of 21.9 % is the highest ever for a n-type silicon cell measured at Sandia National Laboratories. The cell were measured with a 4.03 cm^2 perimeter mask and with the remainder of the wafer shielded from light.

2. CELL STRUCTURES AND FABRICATION

As shown in Fig. 1 and 2, both rear junction PERT and PERL cells have a shallow planar phosphorus diffused layer along the top surface to form a front surface field [3]. The top metal finger contacts are made at heavily doped phosphorus regions. The difference between the two cells is in the backside junction structure. For the rear junction PERT cell, a lightly diffused boron layer over the whole backside active area forms a large p-n junction and heavily boron doped stripes provide rear contact regions. The pattern for backside boron diffusion is exactly the same as used for the front-side phosphorus diffusion, and they are almost perfectly aligned to each other. The heavily doped area of either phosphorus or boron is about 1.3% of the total cell area; the metal contact area for both of them is about 0.5% and the metal shading area on the front for both cell structures is about 4%. For the rear junction PERL cell, heavy boron is locally diffused, with the lightly diffused boron layer absent. The p-n junction takes the form of many discretized small squares dispersed over the rear side surface (see Fig. 2). The total area of these squares are about 3% of the whole cell area, while the metal contact area is about 0.74%. Other features of these two rear junction n-silicon cells are similar to the p-silicon PERL solar cell [1]. For instance, SiO_2 film is used as a passivator covering the most of the front and rear surfaces to reduce the surface recombination; additionally SiO_2 (~1100Å thick) acts as a rudimentary antireflection (AR) coating on the top surface and forms part of a highly reflective rear surface reflector. An inverted pyramid structure for light trapping is produced on the top surfaces in both rear junction PERT and PERL cells.

All cells were made on 1Ω-cm, FZ, n-type silicon substrate, with 4 cm^2 cell area. The wafers were thinned first from 28µm to 150-160µm by etching in 50% KOH solution at 85°C. A chemical polish etch (HNO_3:HF:CH_3COOH) was subsequently carried out to ensure clean wafer surfaces. We found that, without this polish etch, the open-circuit voltage of a thinned cell was about 20 mV lower. This suggests that the KOH solution could contaminate the wafer surfaces and some cleaning is required after KOH etching. The inverted pyramid structure was formed on the top surface after wafer thinning. The heavy and light boron were then diffused into the rear surface. This was followed by the heavy and light phosphorus diffusion into the front surface. All the diffusion patterns were made by standard lithographic technology. The next step is oxidation of the wafer surfaces, the resulting SiO_2 layer being a passivator as well as an AR coat. The cells are completed with Ti-Pd-Ag metallisation and sintering in forming gas at 400°C.

A serious shunt failure at the rear of the PERL cells has been identified. The problem arises from pin-holes or other damage in the backside oxide. Two methods have been demonstrated to solve this shunt problem. One uses an extra boron diffusion to convert any exposed n-type silicon surface into p-type, so avoiding the rear metal electrode directly contacting the n-type substrate, short circuiting at the rear junction. The other method is to use a PtSi or Pd_2Si silicide film as an intermediate layer (see Fig. 3) between the wafer and the electrode metal. These two films produce different contact characteristics with n- and p-silicon, they tending to form a (Schottky) diode with n-type silicon but a good ohmic contact with p-type silicon. Therefore, the two silicide films can prevent the short circuit problem without affecting the ohmic contacts in the boron doped area. The fill factors are respectively 81% for PtSi film and 79% for Pd_2Si film. The PtSi film is better because it has a higher Schottky barrier on n-type silicon and a lower Schottky barrier on p-type silicon than Pd_2Si. A low fill factor of 73% is obtained by the additional boron diffusion method. The I-V characteristics of the rear junction PERL cells using PtSi, Pd_2Si and additional boron diffusion are plotted in Fig. 4.

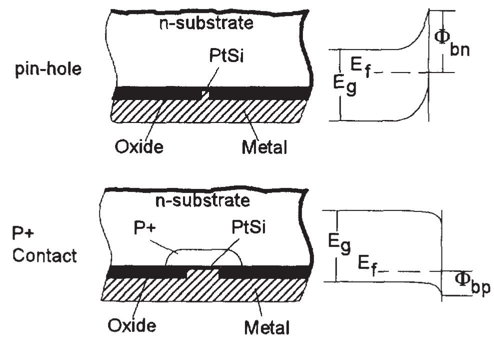

Figure 3. Back contact of rear PERL cell using PtSi film. Simplified energy band diagram illustrating the different contact barrier height at pin-hole and p$^+$ contact. At room temperature, PtSi/p-silicon contact (low barrier) presents a good ohmic characteristic.

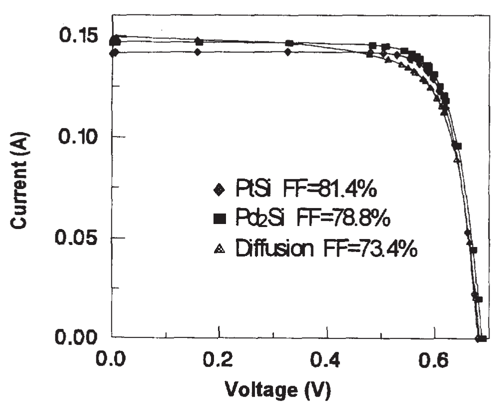

Figure 4. Illuminated I-V curves of the rear junction PERL cells showing the FF improvements by using three different methods

3. CELL RESULTS AND DISCUSSIONS

Open circuit-voltage V_{oc} As shown in Table 1, the rear junction PERL cell has achieved an open-circuit voltage, V_{oc}, of 696 mV, while V_{oc} for the rear junction PERT cell is 694 mV, only 2 mV lower. It has been found that although rear junction PERL cell has less rear surface recombination velocity S_h than that (S_e) of the rear junction PERT cell, a relatively serious current crowding phenomenon due to the locally-diffused boron region has caused a rather complicated carrier collection process which results in a higher top surface carrier concentration and higher bulk recombination than usually expected [2]. Additionally, in present designs, the total backside heavy boron and metal contact areas of the rear PERL cell are larger than that of the rear PERT cell. As a result, the advantages of the locally-diffused boron structure are almost eliminated. It should be noticed that both the open-circuit voltages mentioned above are measured from the cells made on thinned wafers. Un-thinned cells with the same structures give a few millivolts lower V_{oc} (see Table 1) due to bulk recombination increasing. The rear junction PERT and PERL cells without front surface field structure (ie. no top phosphorus diffusion) show open-circuit voltages about 20-25 mV lower than that with surface field structure. This is obviously due to higher surface recombination in such cells.

Also shown in Table 1 are the results for front junction n-silicon solar cells. Those cells have the same structure as that of the p-silicon PERL cell [1], but with all doping polarities reversed, the boron doped emitter being sited at the top surface. It has been already identified experimentally that, at the same heavy doping level, boron diffusion induces much more interface states and oxide charge than phosphorus diffusion at the Si/SiO_2 interface [4], and boron-diffused surfaces have much higher surface recombination velocities than that of phosphorus-diffused (at the same surface doping level below 10^{19} cm^{-3} [5]). Therefore, a large surface recombination can be expected at the sunward top surface in the front junction n-silicon PERL cell. This surface recombination effect can be further enhanced when inverted pyramids are introduced. The difference in V_{oc} between the planar and the inverted pyramid front junction PERL cell is 13 mV (see Table 1). Comparing with the rear junction cells, the open-circuit voltage losses due to the large sunward surface recombination in the front junction n-silicon solar cells are over 30 mV.

Short circuit current density J_{sc} As shown in Table 1, both the rear PERT and PERL cells have lower short-circuit current, J_{sc} than that of the front junction cell. This can be simply explained as follows. The rear junction cells have a quite low top surface recombination, yet, the minority carriers, most being generated near the top surface by the short wavelength photons, have to diffuse a relatively long distance to reach the rear p-n junction and be collected as majority carrier current. For a finite carrier diffusion length in the bulk region, this long diffusion increases the probability of minority carrier recombination, then leading to the loss of short-circuit current J_{sc}. Bulk recombination limits the short-circuit current of the rear junction cells. The present results show that the front junction cell has a higher J_{sc} in spite of the lower open-circuit voltage.

One dimensional simulation by PC-1D has indicated that the internal quantum efficiency of the rear junction cells at short wavelengths can be improved by using high resistivity substrate or thinned wafers. It can be seen from Fig. 5 the internal quantum efficiency (measured by Sandia National Laboratories) of the thinner rear PERT cell is better at short wavelengths, but lower at long wavelengths. The net result is that the both thinned and un-thinned cells have very similar short-circuit current (see Table 1). Additionally, the internal reflectance of the cells are also quite similar, with the thinner cell being slightly better [6]. The carrier-collection efficiency has been found essentially perfect in the thin cell, and only slightly worse in the thick cell [6]. The performance of the both cells are shown in Table 1.

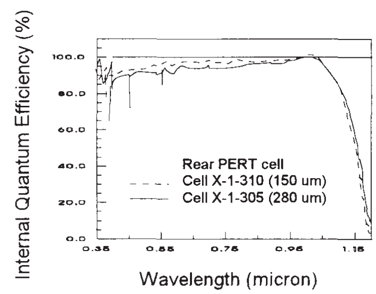

Figure 5. Measured internal quantum efficiencies of the thinned and un-thinned rear junction PERT cells.

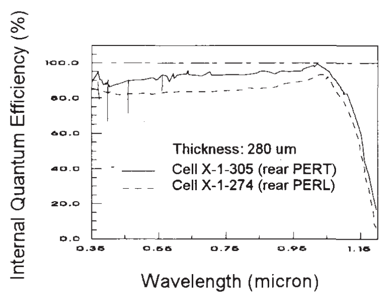

Figure 6. Measured internal quantum efficiencies of the un-thinned rear junction PERT and PERL cells.

From Table 1 one can find that the rear PERL cells produce a lower short-circuit current than the rear PERT cells. There are two main reasons for such a difference. First, although the back surface recombination velocity is relatively large in the rear PERT cells, this is of little importance in determining current output compared to the bulk and top surface recombination. Second, the current crowding effect around the locally-diffused boron emitter in the rear PERL cells enhances bulk and top surface recombination [2]. This also explains why wafer thinning has more influence on rear PERL cells than that on rear PERT cells. The measured internal quantum efficiencies of the un-thinned rear junction PERL and PERT cells are shown in Fig. 6.

Fill Factor FF A high FF (see Table 1) of the front junction PERL cells arises primarily from a low ideality factor which lies in rang of 1.03 to 1.06. The ideality factors of the rear PERL and PERT cells are respectively 1.2 and 1.3. Both values are relatively high and responsible for the less-than-ideal fill factors.

It has been experimentally found that the fill factor, FF, of the rear junction cells varies sensitively with the phosphorus doping level at the front surface. This suggests that the top phosphorus-diffused layer has a large effect on the majority electron current distribution, especially on the current flowing laterally near the surface, and so on the resistive power loss. A clear picture of how majority electron flows in the bulk and near the top requires a 2-D or even 3-D simulation.

4. CONCLUSION

The high surface recombination at the boron-diffused top surface limits the open-circuit voltage in the front junction n-silicon cells. By using rear junction structure, the top surface becomes phosphorus-diffused and has relatively low surface recombination. The open-circuit voltage, V_{oc} is hence significantly improved. The rear PERL cells have low surface recombination on both sides. Because of the current crowding effect, bulk recombination is enhanced and dominates the cell performance. In the rear PERT cells, high rear surface recombination velocity can be expected, but it has less effect on excess electrons which are mostly generated in the bulk (n-type) region. The present results show that the rear PERT cell has almost every feature better than the rear PERL cell. Wafer thinning results in more improvement to the rear PERL cell than the rear PERT cell. The highest energy conversion efficiency of 21.9% is obtained from the thinned rear PERT cell. Further improvements for both rear PERT and PERL cells will be possible when the design optimisation is completed.

5. ACKNOWLEDGMENTS

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Table 1: A summary of results for n-type substrates for a variety of inverted pyramid front and rear junction PERL and PERT cells with different thickness. The results were measured at 0.1W/cm^2, AM1.5G, 25°C by Sandia National Laboratories. The cell area is 4 cm^2.

Cell	Junction	Cell Structure	Thickness (μm)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
X-1-305	Rear	PERT	150	694	39.3	80.3	21.9
X-1-310	Rear	PERT	280	692	39.2	80.4	21.8
X-1-280R	Rear	PERL	160	696	37.8	80.5	21.2
X-1-274R	Rear	PERL	275	693	37.2	79.0	20.3
X-1-158R	Front	PERL (planar top surface)	280	671	34.0	81.3	18.6
X-1-201R	Front	PERL	280	658	39.8	81.6	21.3