INVESTIGATION OF HIGH-EFFICIENCY SCREEN-PRINTED TEXTURED SI SOLAR CELLS WITH HIGH SHEET-RESISTANCE EMITTERS

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ABSTRACT

In this study it is found that the efficiency enhancement ($\Delta \eta$) resulting from the use of a 100 $\Omega$/sq emitter instead of a conventional 45 $\Omega$/sq emitter is substantially enhanced further by surface texturing. This enhancement is greater for textured cells by at least ~0.4% absolute over the enhancement for planar cells, and is mainly due to the greater difference in the front-surface recombination velocity (FSRV) between the high- and low-sheet-resistance emitter textured cells. A FSRV of 60,000 cm/s resulted in a reasonably good $V_{oc}$ of ~642 mV for the 100 $\Omega$/sq emitter textured cell. Our investigation of the Ag-Si contact interface shows a more regular distribution of Ag crystallite precipitation for the textured emitter (mainly at the peaks of the texture pyramids). The high contact-quality resulted in a series resistance of 0.79 $\Omega$-cm, a junction leakage current of 18.5 nA/cm$^2$ yielding a FF of 0.784. This resulted in a record high-efficiency 4 cm$^2$ screen-printed cell of 18.8% (confirmed by NREL) on textured 0.6 $\Omega$-cm FZ, with single-layer antireflection coating.

INTRODUCTION

The cost performance targets of Si photovoltaics can be reached by enhancing cell efficiency while utilizing high throughput processing [1]. Front-surface texturing and high sheet-resistance emitters have consistently enhanced the solar cell performance resulting in high efficiencies [2-4]. However, they have not yet been implemented together using the simple conventional screen-printed cell processing (i.e. single-step diffusion and co-firing of the screen-printed contacts). Therefore, in this study, we have investigated the combination of high sheet-resistance emitters with surface texturing using screen-printed contacts. We have previously demonstrated high fill factors (>$0.78) on high sheet-resistance planar emitters through understanding and optimization of an appropriate Ag paste and firing recipe [5]. This led to the fabrication of 17.4%-efficient solar cells on float-zone Si with screen-printed contacts on a planar 100 $\Omega$/sq phosphorus-doped emitter. In this paper we report on the investigation of textured high-sheet-resistance emitters. Both the short-wavelength response and the screen-printed contact behavior for high sheet-resistance emitter textured cells have been investigated. A study of these factors has been also performed for planar cells.

RESULTS AND DISCUSSION

As shown in Fig. 1 the short-wavelength response for a textured emitter is lower than that for the planar emitter. This is attributed to the higher front-surface recombination velocity because of the increase in surface area due to the textured surface. Nevertheless, the lower reflectance due to texturing results in a 3.94 mA/cm$^2$ enhancement in transmitted current over the planar surface, calculated from the reflectance curves in Fig. 2. Therefore, the loss in short-wavelength response shown in Fig. 1 is relatively negligible.

As shown in Fig. 3, the enhancement in efficiency due to the 100 $\Omega$/sq emitter compared with a 45 $\Omega$/sq emitter is significantly more pronounced for textured cells.
emitter compared with the low sheet-resistance emitter. The first factor investigated is the enhancement in IQE ($\Delta$IQE, the enhancement in IQE due to the high sheet-resistance emitter) due to the longer light path for a textured emitter versus a planar emitter. The increased light path increases absorption for a textured surface since the absorption for a textured surface is $\alpha_{\text{tex}} = \alpha_{\text{pl}} \cos(\theta)$ where $\alpha_{\text{pl}}$ is the absorption for a planar surface and $\theta$ is the refracted angle [6]. The effect of the increased optical path-length in textured cells was simulated in PC1D for 45 $\Omega$/sq and 100 $\Omega$/sq cells. Figure 4 shows that the short-wavelength IQE was almost identical for the 100 $\Omega$/sq textured and planar cells when other device parameters (i.e. FSRV) were unchanged. Similarly, the short-wavelength IQE results were almost identical for the simulated cells with 45 $\Omega$/sq planar and textured emitter with the same FSRV. Therefore, the difference in the light path-length in a textured emitter versus a planar emitter has a negligible effect on the improvement due to the high sheet-resistance emitter.

The second effect resulting in the higher $\Delta$Jsc and higher $\Delta\eta$ is due to the lower reflectance of the textured surface, which would result in a greater enhancement due to the high-sheet resistance emitter as compared to the enhancement for a planar emitter with the same passivation. This can be described by the following simple equation: $\Delta SR(\lambda) = \Delta IQE(\lambda) (1-R(\lambda)) (\lambda/1.24)$, where $\Delta SR$ is the enhancement in spectral response due to $\Delta IQE$. Therefore, for a lower reflectance the enhancement in spectral response due to the high sheet-resistance emitter would be more pronounced. For the reflectance values obtained from Fig. 2, $\Delta$Jsc for the textured emitter would be more pronounced by a factor of 1.096 compared to the planar emitter. However, this factor does not account for more than ~0.1 mA/cm$^2$ of the improvement in $\Delta$Jsc in favor of the textured cells. This is also in agreement with PC1D modeling results assuming that the FSRV is the same for textured and planar cells for the same emitter (i.e. $\Delta IQE_{\text{tex}} = \Delta IQE_{\text{pl}}$).

The third aspect investigated is the FSRV difference between textured and planar cells for 100 and 45 $\Omega$/sq emitters. This was found to be the main effect that results...
in the greater performance enhancement observed due to the high sheet-resistance emitter for textured cells. This is because the change in FSRV between the 100 and 45 Ω/sq emitter is greater for textured than for planar cells. In order to prove this behavior the FSRV was extracted by matching the measured short-wavelength IQE with the PC1D-modeled IQE for planar and textured cells. As an example of the FSRV extraction, the measured and simulated short-wavelength IQE for a FZ cell with a 100 Ω/sq textured emitter is shown in Fig. 5. The extracted FSRV values for each case are shown in Table 2. The textured surface results in an area 1.73 times greater than that of the planar surface. The extracted FSRV values are in agreement with this area factor as shown in Table 2, where the FSRV for the textured emitter is ~1.7 times greater than that of the planar emitter, for the same emitter sheet-resistance. This is observed for both 45 and 100 Ω/sq emitters. As shown in Table 2, the effect of the FSRV change is more pronounced for the textured versus planar emitters resulting in a greater change in FSRV when going from the 45 Ω/sq emitter to the 100 Ω/sq emitter. This is because the effect of FSRV increase due to the textured area factor has less of an impact for the 100 Ω/sq emitter with lower FSRV (35,000 cm/s for the planar emitter increases to 60,000 cm/s for the textured emitter) compared with the 45 Ω/sq emitter with a significantly higher FSRV (90,000 cm/s for the planar emitter increases to 150,000 cm/s for the textured emitter). Consequently, this more pronounced effect is reflected in the greater efficiency enhancement (Δη) for textured cells as shown in Fig. 3. The effect of the FSRV change for textured versus planar emitters is the main factor that results in the greater enhancement in ΔJsc of ~0.3 mA/cm² and Δη of ~0.3% absolute in favor of textured cells. Using the FSRV values in Table 2, PC1D simulation results show an enhancement of ~0.4 mA/cm² in ΔJsc and 0.4% absolute in Δη in favor of textured cells for a 0.6 Ω-cm base resistivity, which supports the experimental results in Fig. 3.

B. Contact Interface Study

We have also investigated the contact interface for both textured and planar high sheet-resistance emitter cells. Figure 6 shows top-view SEM images of the area underneath the Ag gridline (25×25 µm) after etching away the bulk metal of the gridline and the glass layer. As shown in Fig. 6(a) the planar surface has a more irregular distribution of Ag segregation (or Ag crystallite precipitation) compared with the textured emitter surface in Fig. 6(b). Figure 6(b) shows that there is Ag precipitation at the peaks of the texture pyramids even in regions where the Ag crystallite precipitation is sparse. However, this is not the case for the planar surface where many regions are void of Ag crystallite precipitation. This results in a less regular distribution of Ag crystallites for the planar emitter surface as opposed to the textured emitter surface. This may explain the smaller standard deviation of 0.48 Ω-cm² in the series resistance for textured emitter cells compared with a standard deviation of 1.19 Ω-cm² for planar emitter cells. This may be attributed to the ease with which the glass frit can etch through the SiNx layer for a textured surface, particularly at the peaks of the pyramids, compared with a planar emitter surface. However, more work is needed to support this result and to prove that it is not a surface orientation effect (i.e. (111) for a textured surface versus (100) for a planar surface). The fill factors achieved on the high-performance textured and planar 100 Ω/sq cells are very close comparing the high efficiency cells.

C. Record High-Efficiency Cell and Device Modeling

Through the understanding and implementation of
the above effects, we have fabricated record high-efficiency screen-printed cells of 18.8% with a textured 100 Ω/sq emitter (independently confirmed by NREL using a mask aperture area of 3.802 cm²). This cell has 0.6 Ω-cm base resistivity and a single-layer antireflection coating (PECVD SiNₓ), the original cell area is 4 cm². This high-efficiency is primarily due to the high current of 37.3 mA/cm² and high FF of 0.784 (Fig. 7) while maintaining a good Vₜₐₜ. This high FF is made possible by the low series resistance of 0.79 Ω-cm² as well as the low J₀ value of ~18 nA/cm², which shows that the p-n-junction was not badly affected by the paste firing even at the peaks of the pyramid texture. The Vₜ is also maintained to a reasonably good value of 641.5 mV for the textured SP 100 Ω/sq emitter cell. This Vₜ is close to the Vₜ of the planar 100 Ω/sq cell of ~646 mV, which indicates the small loss in Vₜ due to the change in FSRV from 35,000 cm/s to 60,000 cm/s due to texturing (Table 2). Ten cells were confirmed by NREL with efficiencies in the range of 18.4% to 18.9% on 0.6 Ω-cm as well as 1.3 Ω-cm with both sides textured.

Table 3 shows the PC1D device modeling parameters for an 18.6% 100 Ω/sq textured cell (also confirmed by NREL). The modeled parameters are obtained by matching the short- and long-wavelength IQE response while using the measured reflectance of the cell. The variation in the second-diode ideality factor (n₂) is probably responsible for the observed cell efficiency variation of 0.4% absolute for several high-efficiency cells fabricated in the same way. In agreement with the findings of Weeber et al. [7], our device modeling indicates that a better front-surface passivation (<20,000 cm/s) is necessary for further improvement of the 100 Ω/sq textured FZ cell to reach >20% cell efficiency.

Table 3: PC1D parameters that model the high efficiency 100 Ω/sq textured FZ cells.

<table>
<thead>
<tr>
<th>Cell Parameters</th>
<th>Tex. 100 Ω/sq FZ</th>
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<tr>
<td>Vₜ (mV)</td>
<td>541.5</td>
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<tr>
<td>J₀ (mA/cm²)</td>
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<tr>
<td>FF</td>
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<tr>
<td>Eff. (%)</td>
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</table>

CONCLUSION

Our results show synergism between high sheet-resistance emitter and a textured front-surface, which results in a greater efficiency enhancement due to the lightly doped textured emitter versus the enhancement due to the lightly doped emitter for planar cells. This is mainly attributed to the greater increase in FSRV due to texturing of the highly doped emitters. The textured surface also shows more robustness in achieving consistently low series resistance compared with the planar emitter surface due to the ease of the Ag crystallite precipitation and contact formation at the tips of the texture pyramids. This work resulted in a high FF of 0.784 on 100 Ω/sq textured emitter and a record efficiency of 18.8% using a high-throughput SP contact co-firing process.

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REFERENCES


