Investigation of Evaporated Rear Contacts for Al-LBSF Silicon Wafer Solar Cells

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Abstract

Silicon wafer solar cells with a local back surface field ("LBSF") formed by aluminium are currently intensively investigated for industrial application. The non-metallised rear surface regions of this structure are passivated by a dielectric film, whereby this film receives line or point openings for contact formation. In this work we report on Al-LBSF solar cells with thermally evaporated and screen-printed Al as the rear metal and screen-printed silver as the front contact. The interaction of Al and the locally opened dielectric film is investigated in detail, using techniques such as photoluminescence imaging and scanning electron microscopy. The impacts of the laser patterns used for opening of the dielectric film and void formation at the rear contact are investigated.

1. Introduction

The silicon wafer based sector of the photovoltaic industry is continuously trying to reduce costs by increasing the efficiency for increasingly thinner Si wafer solar cells. The standard screen-printed silicon wafer solar cells
 wafer solar cell currently features a full-area Al back surface field (Al-BSF). This Al-BSF provides only a moderate level of passivation of the rear surface, with a surface recombination velocity ($S_{\text{rear}}$) in the range of 200 to 600 cm/s [1, 2]. To improve the rear passivation, silicon wafer solar cells with dielectric passivation and an Al local back surface field (LBSF) [3] are of great interest due to their potential for low cost and high efficiency. For Al-LBSF cells, the non-metallised rear surface regions of this structure are passivated by a dielectric film, whereby this dielectric film has line or point openings for contacting the base of the solar cell. The rear surface passivation quality is significantly improved compared to an Al-BSF solar cell and, in addition, the reflection of near-bandgap photons is greatly enhanced leading to a further increase in the solar cell efficiency. Efficiencies of above 20% have been achieved for large-area (156 mm) screen-printed Al-LBSF Cz p-type Si cells with a selective emitter [4, 5].

A major issue that is typically observed in Al-LBSF solar cells is the formation of voids at the rear contact between the Si substrate and the Al rear contact [6, 7]. These voids are formed during the Al-Si alloy interaction due to the lateral transport of Si from the edge of the contact area into the aluminium paste [6]. These voids significantly increase the series resistance of the cells, as they reduce the amount of the rear contact area. Consequently, the fill factor of the cells is reduced. In addition the Al diffusion profile is affected by these voids, thereby reducing the surface passivation quality of the local contacts.

Screen printing of the rear Al and front Ag followed by co-firing is a popular metallisation method in industrial application, due to its high throughput and robustness. It, however, has some significant drawbacks as the thick Al film does not only increase overall cell production costs by about 6% [8], but also promotes the outwards transport of Si and the void formation. Other rear metallisation alternatives such as thermal evaporation [9-12] and sputtering [13-15] that require much less Al have also been investigated in recent years. Thermally evaporated Al has a better electrical conductivity and lower contact resistance on highly-doped substrates compared to screen-printed Al contacts, due to its high level of uniformity in the thickness [9]. The amount of Al required for evaporation (minimum 2 μm thick) is much less than screen printing, which potentially reduces the vertical and lateral diffusion of silicon participated in the Si-Al alloy formation during firing process.

In this work, thermally evaporated rear contacts for Al-LBSF cells were investigated to reduce the formation of voids by replacing the traditional screen-printed rear Al. About 1-2 μm of Al was evaporated onto the rear of the solar cell. The impact of the laser patterns used for the laser-based opening of the dielectric film was studied by photoluminescence (PL) imaging. The local rear contacts formed were studied using scanning electron microscopy (SEM). Finally, solar cells with evaporated and screen-printed Al rear contacts were fabricated and compared.

**2. Experimental details**

Test samples and complete solar cells with evaporated Al rear and screen-printed Al rear were fabricated on 156×156 mm² p-type Cz mono-Si wafers with bulk resistivity of 1-3 Ωcm. The experimental flow and cell structure are shown in Fig. 1. After a cleaning procedure including a KOH-based saw damage etch, a masking layer of silicon nitride (SiNₓ) was deposited at the rear, followed by single-side texturing and phosphorus diffusion at the front. The phosphosilicate glass (PSG) and SiNₓ mask were subsequently removed by HF etching. A SiNₓ antireflection coating was deposited at the front of the wafers and a stack of aluminium oxide (AlOₓ) and SiNₓ was deposited at the rear of the wafers. All the dielectric layers were deposited by plasma-enhanced chemical vapour deposition (PECVD) in an industrial inline deposition system (SiNA-XS, Roth & Rau). The wafers were then split into two groups.
One group was fabricated into test samples and a second group was completed into full solar cells with laser-opened line contacts (60 μm and 100 μm lines with a pitch of 1 mm or 2 mm). At the rear of the test samples 16 different patterns were laser-processed prior to thermal evaporation of 1-2 μm Al or screen printing of ~20 μm Al. For the laser processing, a picosecond laser was used (Lumera, 532 nm). Both groups were then fired in a belt fast firing furnace (Ultraflex, Despatch Industries) with peak temperature of 750°C. Afterwards, characterisation techniques like photoluminescence imaging and scanning electron microscopy were applied to investigate the impact of the laser patterns on the formed contacts.

Photoluminescence imaging is an extremely fast, efficient and spatially resolved characterisation technique for silicon wafer solar cells [16-19]. The PL intensity \( I_{PL} \) measures the amount of photons emitted due to radiative recombination. It was shown that the PL intensity can be described by

\[
I_{PL}(\Delta n) = C N_A \Delta n + C \Delta n^2,
\]

where \( C \) is the calibration constant, \( N_A \) the bulk doping concentration, and \( \Delta n \) the excess carrier concentration [18]. As \( \Delta n \) scales linearly with the effective lifetime \( \tau_{eff} \) under steady-state illumination, \( I_{PL} \) scales linearly with \( \tau_{eff} \) under low-level injection conditions. It is well known that \( \tau_{eff} \) is related to the bulk lifetime \( \tau_{bulk} \) and the surface recombination velocities \( S_{front} \) and \( S_{rear} \) by [20]:

\[
1/\tau_{eff} = 1/\tau_{bulk} + (S_{front} + S_{rear})/W,
\]

where \( W \) is the sample thickness. With a high \( \tau_{bulk} \) and comparatively good front surface passivation, \( \tau_{eff} \) is largely affected only by the \( S_{rear} \), hence \( I_{PL} \) can be used to study the rear electronic quality.

\[\text{Fig.1. (a) Experimental flow of Al-LBSF test samples and solar cells. The peak temperature during the co-firing step was 750°C. (b) A schematic of the final Al-LBSF solar cell structure obtained in this experiment.}\]
3. Results

3.1. Impact of laser patterns

PL images of screen-printed Al rear and evaporated Al rear test samples were taken without front metallisation, to ensure that the observed differences in the PL intensity were only attributed to changes at the rear of the test sample. The PL images are shown in Fig. 2. Each test sample consists of 16 boxes with different laser patterns. The absolute PL intensity of every box was normalised by the PL intensity of the unablated box 1 of the same sample, to avoid the discrepancy due to wafer quality, bulk doping level, or dielectric passivation. This way, a fair comparison between evaporated Al rear and screen-printed Al rear could be obtained. The normalised PL intensity as a function of the metal fraction is shown in Fig. 3.

![PL images of test samples](image)

Fig. 2. Photoluminescence intensity images of the test samples with (a) evaporated Al rear and (b) screen-printed Al rear. For both images, the following laser patterns were used: Box 1: unablated; Box 2: fully ablated; Boxes 3-8: point contacts; Boxes 9-16: line contacts.

In Fig. 3 it can be seen that boxes with a point contact geometry generally give a higher normalised PL intensity than boxes with line contact geometry for the evaporated Al samples. The point contact laser patterns give a better effective rear surface passivation compared to line contact laser patterns. Thus, a higher $V_{oc}$ will be expected for solar cells ablated with point contacts. For the screen printed test samples, however, the result is reverse. Line contacts yield a higher $I_{PL}$ in this case.

For the samples with an evaporated Al rear the normalised $I_{PL}$ correlates strongly with the metal fraction; an increase in the metal fraction results in a decrease of the $I_{PL}$. But for the screen printed rear test samples, the normalised $I_{PL}$ increases very little when the metal fraction is reduced to less than 5%. When the metal fraction is too low, like in the cases of point contacts, the normalised $I_{PL}$ is even lower compared to line contacts with metal fraction about 3%.

In addition, $I_{PL}$ of the fully ablated box on the evaporated rear test sample is much lower than that of the fully ablated box on the screen-printed rear test sample. As the entire passivating dielectric at the rear has been ablated, the effective rear surface passivation is only provided by the BSF formed by Al. This could suggest that the Al-BSF formed by our evaporated Al is not as good as the Al-BSF formed by screen printing.
It is also interesting to note that, although the screen-printed rear boxes with line contacts look much brighter than those made by evaporation, there are some dark lines observed, especially in box 13. These dark lines might be due to a clustering of voids along those lines, which significantly affects the $I_{PL}$ near the lines.

![Graph showing PL intensity of different laser opening geometries normalised by the PL counts of box 1](image)

**Fig. 3.** PL intensity of different laser opening geometries normalised by the PL counts of box 1

### 3.2. Contact formation

To better understand the contact formation, the samples were studied by means of cross-sectional SEM. As mentioned in the introduction, voids are frequently observed at the laser opening area when using a screen printed Al rear. Similar observation has been reported by other research groups. Voids are more frequently found when the line width of the laser opening decreases. An Al p⁺ layer is normally found between the eutectic layer and bulk silicon after the firing process. It provides a back surface field which provides rear surface passivation. The p⁺ layer appears brighter in the SEM images than the bulk of the silicon wafer due to different local ionisation energies [21]. A stain etching was applied to the sample to make the p⁺ layer more visible.

![Cross-sectional SEM image of laser openings (line) at the rear contact of a screen-printed Al-LBSF solar cell with (a) a void with no Al p⁺ layer, (b) a void with Al p⁺ layer, (c) no void](image)

**Fig. 4.** Cross-sectional SEM image of laser openings (line) at the rear contact of a screen-printed Al-LBSF solar cell with (a) a void with no Al p⁺ layer, (b) a void with Al p⁺ layer, (c) no void

Both the voids and Al p⁺ layer are formed during the alloying process caused by the firing process. This can easily be explained using the Al-Si binary phase diagram shown in Fig. 5 [22]. During the firing process, the organic solvents of the paste are first burnt out before the temperature reaches the eutectic temperature of Al and Si (577°C). When the temperature increases above the eutectic temperature, Al and
Si start to form a “lake” of liquid Al-Si [23] at their interface. The concentration of Si in Al increases with increasing firing temperature according to the phase diagram. At the peak temperature, the maximum amount of Si dissolved into Al is reached. During the cooling process, Si starts to be rejected out of the Al-Si mixture to satisfy the equilibrium concentration indicated by the phase diagram. When the temperature drops below the eutectic temperature, the mixture solidifies to an eutectic layer containing 12.6% Si. The Si rejected out of the mixture in the cooling process contains about 1% Al and epitaxially forms the Al p+ layer. During the ramp up process a higher amount of silicon will travel into aluminium since the solubility of silicon in aluminium is much higher than that of aluminium in silicon [6, 24, 25]. In the case of an Al-LBSF rear structure, only the Si below the laser opening is available to participate in the process. As illustrated in Fig. 6(c), both the vertical transportation of dissolved Si from bulk into the Al paste above the laser opening and the lateral transportation of Si further into the Al paste besides the laser openings occur. This lateral transportation of Si promotes the void formation.

The Al p+ layer is normally not observed beneath the voids, as shown in Fig. 4(a). However, in a few cases a thin p+ layer is found as shown in Fig. 4(b), in agreement with reports by other groups [23]. When the line width of the laser opening is large, fewer voids are observed. A thick Al p+ layer (3-5 μm) is found as shown in Fig. 4(c).

However, for the evaporated Al rear samples with the identical firing condition, no voids were found as shown in Fig. 7. The eutectic layer is only 3-5 μm thick, compared with 8-12 μm for screen-printed Al. As the evaporated Al film is much thinner than the screen-printed Al film, less silicon is participating in the alloy formation. The Al p+ layer thickness for evaporated Al rear sample is only 200 nm or less. Since much less amount of Si is available for the alloy formation, less Si is rejected and thus a very thin Al p+ layer is formed.

Fig. 5. Si-Al binary phase diagram [22]
Fig. 6. Cross-sectional schematics of laser openings (line) at the rear contact of a screen printed Al-LBSF solar cell (a) after laser ablation, (b) after printing, (c) after firing.

Fig. 7. Cross-sectional SEM image of laser openings (lines) at the rear surface of an Al-LBSF solar cell made with evaporated Al. No voids can be seen.

4. Solar cell results

To investigate the influence of the laser pattern and contact formation on the solar cell performance, Al-LBSF solar cells with evaporated and screen-printed Al were fabricated on 156×156 mm² p-type Cz silicon wafers according to the process flow in Fig. 1. Table 1 summarises the performance of the best cell for both evaporated and screen printed Al rear and their corresponding laser pattern used.

The solar cell with evaporated Al rear shows a much higher $FF$ but lower $V_{oc}$ compared to the screen-printed solar cell. The higher $FF$ is due to a lower series resistance value, which is calculated from a combination of light and dark I-V measurements according to the method published by Aberle et al. [26]. As shown in Section 3.2, samples with evaporated Al rear demonstrate a much better contact formation than samples with screen-printed Al rear in terms of number of voids. Thus, it improves the conductivity of the rear contact and lowers the overall series resistance. The difference of more than 20 mV in $V_{oc}$ was expected from the PL images and cross-sectional SEM images. Only a very thin Al-p⁺ layer was formed for the samples with an evaporated Al rear, resulting in a relatively poor back surface field. The different rear surface passivation is also reflected in their PL intensity images, and subsequently reflected in the cell performance in terms of $V_{oc}$. 
Table 1. Parameters of Al-LBSF cells fabricated in the same batch using evaporated or screen-printed Al on the rear

<table>
<thead>
<tr>
<th>Rear metallisation</th>
<th>Laser parameters</th>
<th>Cell parameters</th>
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<tbody>
<tr>
<td></td>
<td>Laser pattern</td>
<td>Metallisation fraction</td>
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</tr>
<tr>
<td>Screen printing</td>
<td>Line</td>
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<tr>
<td>Screen printing</td>
<td>Line</td>
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5. Conclusions

Evaporated and screen-printed aluminium rear test samples and solar cells with Al-LBSF structures were fabricated. The impact of the laser pattern on the contact formation was investigated using photoluminescence and scanning electron microscopy. Our preliminary results show that evaporation of Al for Al-LBSF cells effectively reduces the number of voids and improves the FF of the cells. However, since only 1-2 $\mu$m of Al was evaporated in our experiments, the back surface field (BSF) formed is not sufficiently thick, which limits the $V_{oc}$ of the solar cells. Further optimisation of evaporated Al thickness, firing temperature and post laser processing is expected to give significantly improved cell efficiency.

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References


