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Rear-Side Contact Opening by Laser Ablation for Industrial Screen-Printed Aluminium Local Back Surface Field Silicon Wafer Solar Cells

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Abstract

Aluminium local back surface field (Al-LBSF) cells are currently being investigated for the next generation of high-efficiency industrial silicon wafer solar cells. These Al-LBSF solar cells feature passivating dielectric layers with local contact openings at the rear side of the cell. These local contact openings can be made by inkjet printing, laser ablation or mechanical scribing. Cell efficiencies of up to 19.0% have been achieved for screen-printed p-type Al-LBSF solar cells at SERIS, whereby the dielectric layer was locally opened by laser ablation. This paper reports on the optimisation of the laser process for this kind of solar cell by various characterisation techniques. Optical microscopy and scanning electron microscopy (SEM) are used to determine the degree of ablation of the dielectric layers and to examine the heat affected zone. Photoluminescence measurements are used to study if the electronic quality of the underlying silicon is affected by laser dielectric ablation. We demonstrate that similar solar cell efficiencies can be obtained using either a nanosecond (ns) or a picosecond (ps) laser for the laser ablation process, with the ns laser being an industrially more mature technology. Post-laser etching for laser-induced damage removal is found to be a crucial step to improve the efficiency of those cells which have their contact openings formed with the ns laser.

Keywords: Laser ablation; contact opening; post laser etching; Al-LBSF cells

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1. Introduction

The main target of the photovoltaic (PV) industry is to continuously reduce the cost per kWh of PV electricity. One very effective way to decrease this cost is to increase the solar cell efficiency in a cost effective way, preferably using a structure that is only slightly different from the conventional silicon wafer solar cell architecture. Aluminium local back surface field (Al-LBSF) cells, which were invented in the 1980s at Fraunhofer ISE, represent one of these slightly modified structures with the desired potential for cost reduction [1]. The Al-LBSF solar cell structure has gained the interest of the industry in recent years because it allows a significant increase in the solar cell efficiency by the addition of only a few steps to the standard solar cell processing sequence. The rear side of an Al-LBSF solar cell features a dielectric film covered with an Al rear electrode with local contact openings. This rear surface has a strongly reduced surface recombination and increased reflection for near-band-gap photons compared to the standard Al back surface field (Al-BSF) solar cell. The local contact openings in the Al-LBSF solar cell can be made by inkjet printing [2], laser ablation, photolithography or mechanical scribing [3].

Laser ablation is considered to be one of the best candidates for industrial Al-LBSF cell fabrication because of the unique properties of laser processing. It eliminates physical contact during processing, thus minimises the risk of contamination. The speed of the scanning laser beam can be controlled by mirrors; hence, the laser processing speed can be extremely fast enabling high-throughput processing. This is unattainable by mechanical means such as mechanical scribing. In addition the operation of a laser only requires electricity in contrast to photolithography and inkjet printing whereby additional chemicals are needed during processing. This is beneficial from a total cost of ownership point of view. However, laser ablation can cause unintended laser-induced damage such as surface melting, heat affected zone, micro cracks, point defects etc, which can negatively affect the solar cell device performance. The interaction between laser light and matter depends strongly on the parameters of the laser light and the physical and chemical properties of the material. Thus it is very important to choose a proper laser source and to optimise laser parameters so that negligible laser induced damage introducted to the sample. Many research groups have demonstrated superior ablation characteristics using short or ultra-short pulsed UV lasers [4, 5]. During the laser material interaction, the electrons in the material absorb the photon energy and then collide and transfer energy to the lattice. The time scale for electron cooling and energy transfer to the lattice is in the order of picoseconds. For short-pulsed lasers, the pulse width is typically in the nano-second (ns) range, which is much longer than this energy transfer time, thus resulting in the thermalisation of the material. Ultra-short pulsed lasers with pico-second (ps) or femto-second (fs) pulse width ablate material without thermalisation due to negligible electron-lattice coupling [6]. Therefore, ultra-short pulsed laser ablation potentially further reduces laser induced damage which is demonstrated in the literature [4, 7, 8].

Solar cell efficiencies of up to 19.0% have been achieved for screen-printed p-type Al-LBSF solar cells at SERIS, whereby the dielectric was locally opened by laser ablation. This paper reports on the optimisation of the laser process by various characterisation techniques. In this paper, nanosecond (ns) and picosecond (ps) solid-state lasers (Nd:YAG) were used. Both lasers were operated at a wavelength of 532 nm, with a pulse duration of 40 ns and about 10 ps for the ns and ps laser, respectively.

2. Experiment

Test samples were fabricated on 156×156 mm² pseudosquare p-type Cz mono-Si wafers with bulk resistivity of 1-3 Ωcm in a process sequence shown in Fig. 1. KOH-based chemicals were used to remove the saw damage from the raw wafers. After a standard RCA clean (Radio Corporation of America) with a
final HF dip, the wafers were dried and a stack of aluminium oxide (AlOₓ) and silicon nitride (SiNₓ) was deposited by plasma-enhanced chemical vapour deposition (PECVD, SiNA-XS, Roth & Rau) on both sides of the sample. The thickness of AlOₓ film was about 40 nm and the thickness of SiNₓ film was about 100 nm. These symmetrical test samples were used for the subsequent laser ablation experiments.

A series of laser ablation experiments was conducted using the ns and ps lasers, with various fluences and pulse overlap ratios. The pulse overlap ratio is defined as the ratio between the laser pulse overlap length and the laser pulse diameter, as shown in Fig. 2. Optical microscopy (Eclipse L200N, Nikon) and scanning electron microscopy (SEM, Auriga, Carl Zeiss) were used to determine the degree of ablation of the dielectric layers and to examine the heat affected zone. Photoluminescence (PL, LIS-R1, BT Imaging) imaging was used to study if the electronic quality of the underlying silicon was affected by the laser dielectric ablation process. It is well known that un-optimised laser conditions can result in defects such as micro cracks, point defects, defects due to thermal induced stress etc. These defects reduce the minority carrier lifetime in the silicon wafer and thus result in a localised lower PL intensity. Optimised laser parameters were used to fabricate Al-LBSF cells on 156×156 mm² pseudosquare p-type Cz mono-Si wafers with bulk resistivity of 1-3 Ωcm. KOH-based chemicals were used to remove the saw damage from the raw wafers. After the standard RCA cleaning with final HF dip, a silicon nitride masking layer was deposited at the rear, followed by single-sided texturing and POCl₃ diffusion (TS 81004, Tempress) at the front. Subsequently, 10% HF was used to remove the phosphosilicate glass (PSG) and SiNₓ masking layer. A 75 nm thick SiNₓ antireflection coating (ARC) was deposited onto the front of the wafers and 40 nm aluminium oxide (AlOₓ) deposited onto the rear capped by 100 nm SiNₓ layer by PECVD (SiNA-XS, Roth & Rau). Subsequently the dielectrics were opened by optimised ns and ps laser ablation processes. After laser processing, half of the samples received a post-laser chemical etch in KOH for 1 minute. Finally all samples were screen printed with Ag as front metal contact and screen printed with Al as rear metal contact and co-fired (Ultraflex, Despatch).

Fig. 1. Schematic of the process flow used in this study.  
Fig. 2. Definition of laser pulse overlap ratio used in this study.
3. Results and discussion

3.1. Optical microscope and SEM analysis

Figure 3 shows the ablation characteristics observed by an optical microscope for ns and ps laser ablation. Each point in the graph represents a combination of different laser fluence and laser pulse overlap ratio. For ns laser ablation, the ablation process starts when the laser fluence exceeds 5 J/cm². This is also known as the ablation threshold. For ps laser ablation, the ablation threshold is about 1.2 J/cm². Figure 4 shows the ablation characteristics of ns laser ablation from low fluence to high fluence. Ps laser ablation characteristics show a similar dependence on the laser fluence. As expected, when the laser fluence increases, the laser ablated area increases for both ns and ps lasers. When the laser fluence further increases, to 8.4 J/cm² for the ns laser and 2.7 J/cm² for the ps laser, molten silicon was observed at the ablated area. This indicates that the laser has already affected the silicon below the dielectric at these laser fluences. Therefore, laser parameters which result in surface melting should be avoided if low-damage laser dielectric ablation is desired.

In contrast to ns laser ablation, the ablation characteristics of ps laser ablation are also strongly dependent on the laser pulse overlap ratio. This can be seen from Fig. 3(b) and SEM images in Fig. 5(d-f). At a fluence of 2.3 J/cm², for an overlap ratio of 20%, partially ablated dielectric film was observed as shown in the circled area in Fig. 5(d). The rippled structures in Fig. 5(d) were observed for ps laser ablation. Similar observations were presented by other groups [4, 5, 9, 10]. Knorz et al. attributed the formation of these ripple structures due to interference of laser beam with its reflection from the opposing slopes of the adjacent pyramids [5]. At an overlap ratio of 60%, local surface melting at the peak of the pyramids was observed as shown in the circled area in Fig. 5(f). Furthermore, the ripple structures were also destroyed. This implies that a certain degree of damage has been introduced to the bulk silicon. These changes in the ablation characteristics with respect to different laser pulse overlap were only observed from SEM images and were unable to be distinguished from optical microscope images as shown in Fig. 5 (a), (b) and (c).

![Figure 3](image-url)  
**Fig. 3.** Overview of the obtained laser ablation results as a function of laser fluence and pulse overlap ratio, for (a) ns laser pulses and (b) ps laser pulses. The four types of result (no ablation, partial ablation, full ablation, ablation with melting) were obtained from optical microscope images.
Fig. 4. Optical microscope images (a-c) and SEM images (d-f) of ns laser ablated spots; (a, d) with low laser fluence, (b, e) with medium fluence, and (c, f) with high fluence.

Fig. 5. Optical microscope images (a-c) and SEM images (d-f) of ablated lines formed with the ps laser. The pulse overlap ratio was 20% in (a) and (d), 40% in (b) and (e), and 60% in (c) and (f).

3.2. Photoluminescence analysis

In addition to defects that can be detected by optical or electron microscopy, there can be more laser induced damage to the underlying silicon which can potentially affect the solar cell performance. In this
study, photoluminescence (PL) imaging was used to study the laser induced impact to the underlying silicon. PL allows us to get spatially resolved information of the electronic quality of a sample. On silicon wafers coated with a dielectric film, patterns consisting of 25 boxes were produced by laser dielectric ablation. Each box was ablated using a different combination of laser fluence and pulse overlap ratio, as shown in Fig. 6. From the study by optical and SEM microscopy we know that the laser parameters used to ablate the 5 boxes at the first column (boxes in the black circle) will only partially ablate the dielectric film. The laser parameters used to ablate the 5 boxes at the last column (boxes in the red circle) will cause surface melting. These two columns of boxes will be used as comparison and the mid three columns of boxes will be of interest because they had best ablation characteristics observed from optical microscopy and SEM. Subsequently, half of the laser processed test samples underwent a post-laser etching step to remove the laser induced damage. All of these silicon wafers were then cleaned and coated on each side with a silicon nitride film providing a high level of surface passivation.

The PL image taken after re-passivation is shown in Fig. 7 and Fig. 8 for the ns laser and ps laser processed test samples, respectively. The images show district low and high intensity areas. Low-intensity areas in the PL image indicate a poor electronic quality, while high intensity indicates a high electronic quality. The poor electronic quality in this case can be attributed to laser induced bulk defects, as the whole wafer has a uniform surface passivation on both the front and rear surface. It can be seen that some laser conditions lead to a very high degree of laser-induced damage, which would negatively affect the solar cell efficiency. It should be noted that this laser induced damage cannot completely be removed by post-laser chemical etching. By carefully choosing the laser conditions, laser damage can be minimised.

A post-laser etching is very effective in removing laser induced damage as shown in Fig. 7(b) and Fig. 8(b). Most of the damage induced by ns laser ablation was removed by the post-laser etching, as it can be seen in Fig. 7(b) that the PL intensity at the laser ablated area is almost the same as at the un-ablated areas. In Fig. 8(b) the last two columns of boxes have a very low intensity in spite of having a post-laser etching. This shows the location of laser induced damage can be deep in the bulk silicon although the laser fluence used was only slightly higher compared to the laser conditions that resulted in minor damage to the silicon. Hence, the range of laser parameter for ps laser needs to be more carefully optimised with the help of PL imaging, although ps laser can have superior ablation characteristics without a post-laser chemical cleaning.

Fig. 6. Test structure pattern of 25 laser ablated boxes.
Fig. 7. PL intensity images taken after SiN re-passivation. (a) without post-laser etching; (b) with post-laser etching for 25 boxes opened with different ns laser parameters. Rows 1-5 correspond to 0, 10, 20, 40 and 60 % pulse overlap, respectively, while columns 1-5 correspond to laser fluences of 5.43, 7.21, 7.55, 8.42 and 8.83 J/cm², respectively.

Fig. 8. PL intensity images taken after SiN re-passivation. (a) without post-laser etching; (b) with post-laser etching for 25 boxes opened with different ps laser parameters. Rows 1-5 correspond to 0, 10, 20, 40 and 60 % pulse overlap, respectively, while columns 1-5 correspond to laser fluences of 2.10, 2.28, 2.37, 3.11 and 3.49 J/cm², respectively.
3.3. Solar cell performance

Table 1 shows our best results achieved as yet for ps and ns laser processed cells. A maximum efficiency of 19.0% has been achieved for both ps and ns laser processed cells. Table 2 summarises the average electrical performance results of ps and ns laser processed cells with standard deviation. The average values were taken from at least 5 cells of the same batch. A higher average efficiency and higher average open-circuit voltage for ps laser processed cells demonstrates superior ablation characteristics of ps laser dielectric ablation. There is a significant improvement of the open-circuit voltage and thus efficiency for ns laser processed cells with post-laser chemical etching. The low average open-circuit voltage of 607 mV shows considerable amount of laser induced damage to the cell if no post-laser etching is applied. After a post-laser etching step, the average open-circuit voltage raises to 632 mV, which is close to that of ps laser processed cells. This demonstrates the high effectiveness of post-laser etching for laser induced damage removal. The increase by about 0.5 efficiency points shows that the post-laser etching is a crucial step after ns laser ablation. For ps laser processed cells, the post-laser etching has negligible effect on the open-circuit voltage and efficiency, and thus can be omitted.

Table 1. One-sun I-V measurement result for the champion ps and ns laser processed cells

<table>
<thead>
<tr>
<th>Laser source</th>
<th>Voc [mV]</th>
<th>Jsc [mA/cm²]</th>
<th>FF [%]</th>
<th>Eff [%]</th>
</tr>
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<tbody>
<tr>
<td>ns laser</td>
<td>628</td>
<td>38.4</td>
<td>78.6</td>
<td>19.0</td>
</tr>
<tr>
<td>ps laser</td>
<td>633</td>
<td>38.9</td>
<td>77.5</td>
<td>19.0</td>
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</table>

Table 2. Average results of at least 5 cells with standard deviation for ps and ns laser processed cells

<table>
<thead>
<tr>
<th>Laser source</th>
<th>Post-laser etching</th>
<th>Voc [mV]</th>
<th>Jsc [mA/cm²]</th>
<th>FF [%]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns laser</td>
<td>No</td>
<td>607 ± 1</td>
<td>37.7 ± 0.2</td>
<td>77.6 ± 0.2</td>
<td>17.8 ± 0.1</td>
</tr>
<tr>
<td>ns laser</td>
<td>Yes</td>
<td>632 ± 5</td>
<td>38.1 ± 0.1</td>
<td>76.0 ± 0.5</td>
<td>18.3 ± 0.3</td>
</tr>
<tr>
<td>ps laser</td>
<td>No</td>
<td>634 ± 3</td>
<td>38.0 ± 0.1</td>
<td>77.4 ± 0.2</td>
<td>18.6 ± 0.1</td>
</tr>
<tr>
<td>ps laser</td>
<td>Yes</td>
<td>635 ± 2</td>
<td>38.3 ± 0.1</td>
<td>76.3 ± 0.4</td>
<td>18.6 ± 0.1</td>
</tr>
</tbody>
</table>

4. Conclusion

In this paper, the ablation characteristics for different laser parameters including ns or ps laser, laser fluence and laser pulse overlap ratio were experimentally investigated by using optical microscope, SEM and PL imaging. High efficiency of up to 19.0% for Al-LBSF cells with dielectric opening by laser ablation was demonstrated. It was found that ns laser processing, being an industrially more mature technology, achieves similar solar cell efficiencies as ps laser processing. It was also found that when using the ns laser, a post-laser etching step is required to obtain high solar cell efficiency and when using the ps laser, the post-laser etching step can be omitted.
Acknowledgements

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References