Investigation of rear localized back surface field formed from boron laser doping and screen-printed aluminum paste in high-efficiency solar cells

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Abstract

A localized back surface field (LBSF) cell was developed using boron laser doping (LD) and screen-printed aluminum paste firing to produce p-type passivated emitter, rear locally diffused cells with the objective of further enhancing the efficiency of the cell. After LD, the B dopant depth was over 6.0 \textmu m and the B surface concentration was $1 \times 10^{19}$ atoms/cm$^3$. The Al paste was screen-printed and fired to form electrodes, and the LBSF composed of Al and B was observed using scanning capacitance microscopy. Secondary ion mass spectrometry was used to detect the B dopant in the LBSF area after firing the Al paste to clarify the reason for the improvement in the performance of the cell, and the ratio of B/Al was determined to be more than 0.9 wt\%. The LBSF cell had an efficiency of 19.5\%, which exceeded that of the reference cell by ~1.1\%, and the open circuit voltage of the cell improved remarkably. This indicated that the B content resulting from LD influenced Al diffusion and enhanced the LBSF effect.

Keywords: Boron laser doping; Si paste; Localized back surface field; LBSF

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1. Introduction

P-type Si solar cells with an aluminum-alloy back surface field (BSF) fabricated using screen-printed Al paste are commonly used as passivated emitter and rear contact (PERC) cells [1-5]. Recently, Al paste with boron additives was studied as a way of improving the BSF effect caused by a high dopant concentration for high-efficiency solar cells [6-8]. These studies indicated that B additives can enhance the dopant concentration compared with the use of Al alone, because although the solubility of Al in Si is still limited [9,10], the co-diffusion of B and Al can occur. However, as a large amount of B compound (over 0.9 wt%) is needed to attain useful BSF properties [8], this might result in degradation of the electrode properties.

Boron laser doping (LD) is a well-known technique for achieving the local diffusion of boron needed for high-efficiency passivated emitter, rear locally diffused (PERL) and PERC solar cells [11-13]. It was reported that the regions in which boron is heavily diffused avoid the Kirkendall void and improve the fill factor, $J_{sc}$, and $V_{oc}$ characteristics of the solar cell through good electrode contact and the BSF effect. We have previously reported on the use of boron LD for a p-type rear localized back surface field (LBSF) cell using screen-printed Al paste [13], and found that this clearly improved the cell efficiency. In addition, it was suggested that boron LD might enhance the LBSF effect produced by the Al paste.

In the present study, we fabricated and evaluated p-type LBSF cells with and without boron LD to clarify the reason for the improvement in cell performance achieved as a result of using boron LD. The LBSF area of the cells was evaluated by scanning capacitance microscopy (SCM) and elemental mapping profiles measured by imaging scanning secondary ion mass spectrometry (SIMS) to analyze boron dopant diffusion in the boron LD area after firing with Al paste.

2. Experiments

A schematic showing boron LD on a passivated Si wafer is shown in Fig. 1(a). Boron-doped Si paste (NanoGram® boron-doped Si paste: nSol-32113, B dopant concentration of $~1 \times 10^{21}$ atoms/cm$^3$) was used as a dopant source for boron LD. A 532-nm Q-switched pulsed laser (frequency: 150 kHz, pulse width: 20 ns, laser fluence: 3.5 J/cm$^2$) was applied to achieve boron LD through the passivation layer. The layer of dried Si nanoparticles was ~800 nm thick. The sheet resistance in the LD area was 35 $\Omega$/sq, as measured using the four-point probe method. The SIMS profile after boron LD on a passivated Si wafer is shown in Fig. 1(b). The depth of the B dopant exceeded 6.0 $\mu$m and the concentration of B at the surface was $~1 \times 10^{19}$ atoms/cm$^3$.

Fig. 1. Schematic illustration of (a) boron LD and (b) SIMS profile.
The fabrication process flow for the boron LD-LBSF cell and a schematic diagram of a boron LD–LBSF cell (with local B doping area (p++ layer)) are shown in Fig. 2 and Fig. 3, respectively. Figure 4 shows a schematic illustration of the boron LD procedure. A conventional passivated emitter and rear contact (PERC) cell was used as a reference cell (Fig. 4(b)). The illustration shows three steps, including: (1) printing and boron LD or laser opening, (2) printing and firing of Ag and Al paste, and (3) schematics of the LBSF cell and PERC cell after firing.

Cells with a size of 50 × 50 mm² were processed on p-type Czochralski-grown Si wafers with a thickness of 200 ± 30 μm. The sheet resistance after POCl₃ diffusion was 80 ± 5 Ω/sq. Local boron diffusion into the rear side was performed using LD with B-doped Si paste. The Si paste was printed on Al₂O₃/SiNx layers and dried at 200 °C for 10 min. The line width and pitch of the LD were 40 μm and 1 mm, respectively. After screen printing the Al paste and Ag paste on both sides of the cell, they were co-fired in a furnace to ensure contact between the paste and the cell. Cross-sectional scanning electron microscopy (SEM) of the cells was performed in the boron LD area on the rear side, as shown in Fig. 4, and the void percentage was determined from observation of more than 30 local contact points at the rear side of the solar cells.

![Fig. 2. Fabrication process flow of boron LD-LBSF cell.](image)

![Fig. 3. Schematic diagram of boron LD–LBSF cell.](image)
3. Results and discussion

3.1. Characterization of LBSF formed by boron laser doping using screen-printed aluminum paste

As shown by the SEM and SCM images of Al diffusion in the boron LD area in Fig. 5, Al paste readily diffuses into the Si wafer after firing. This results in an Al-Si-B alloy being formed, as shown in Fig. 5(a), with an LBSF (light green) clearly observed between the p-type Si wafer (green) and Al-Si-B alloy (black) in Fig. 5(b). The elemental mapping profiles of B and Al measured by imaging SIMS that are shown in Fig. 6 were used to detect B in the LBSF area (yellow line) of the cross-sectional view in Fig. 5(b). Note that B was detected in the LBSF area even though Al diffusion reached a depth of ~20 μm, which indicates that co-diffusion of B and Al occurred in the boron LD area (Fig. 4(a)-(2)) and formed Al–B BSF in the local contact area (Fig. 4(a)-(3)). The ratio of B to Al in the LBSF was calculated as more than 0.9 wt%. As Al paste generally contains some boron additives, a conventional PERC cell without boron LD was also observed as a reference to clarify the contribution of boron LD. The boron concentration in the Al diffusion area of this PERC cell was less than $10^{18}$ atoms/cm$^3$, and the LBSF area had a B/Al ratio of less than 0.1 wt%. It has been reported that although the solubility of Al in Si is limited, B additives can improve the dopant concentration by more than $10^{19}$ atoms/cm$^3$, thereby enhancing the BSF properties [6-8]. As BSF reduces surface recombination [8], the 0.9 wt% B/Al ratio observed at a depth of over 4 μm in Fig. 6 is likely to influence the saturation current density $J_0$ over the wide range of effective peak temperature of the firing process [6,7]. The value of $J_0$ of the boron LD–LBSF cell was therefore expected to be less than half that of the conventional...
PERC cell, which in addition to the BSF effect, explains why the LBSF of the boron LD–LBSF cell exhibited a higher open-circuit voltage.

As the use of additives may cause the electrode properties to degrade, another approach to forming an Al-Si-B alloy has been proposed in which a large amount of B compound (over 0.9 wt%) is used to obtain useful BSF properties [8]. However, our results indicate that boron LD is a very useful method for forming Al-Si-B alloys with an LBSF obtained by co-diffusion in the contact area that is suitable for use in high-efficiency solar cells.

Figure 7 shows a comparison of the average Kirkendall void percentage in the boron LD–LBSF cell (49 %) and conventional PERC cell (70 %). Note that as the Al paste used in this study was not a specialized variety for PERC, the void percentage of the PERC cell is higher. Nevertheless, these results suggest that boron LD may in fact reduce the number of Kirkendall voids [11], as it is thought that reactivity between the Al paste and Si surface with boron might be different than that in a conventional PERC cell. Furthermore, boron LD contributes to the formation of a thicker LBSF [11], with a 2 μm thicker LBSF clearly observed in Fig.5 (b). Boron LD combined with a specialized Al paste could therefore be expected to leave no voids and provide a suitably thick LBSF for high-efficiency solar cells.

(a)

![Cross-sectional view of LBSF cell obtained using SEM](image1)

(b)

![Cross-sectional view of LBSF cell obtained using SCM](image2)

Fig. 5. Cross-sectional views of LBSF cell obtained using (a) SEM and (b) SCM. Green area shows the p-type area of the Si wafer.
Fig. 6. Element mapping profiles of Al and B at the yellow line in Fig. 5(b), as measured by imaging SIMS, and B/Al weight ratio calculated from these doping concentrations.

Fig. 7. Kirkendall void percentage of (a) boron LD–LBSF cell and (b) conventional PERC cell.
3.2. PV cell evaluation

Table I presents the properties of the boron LD–LBSF cell and a conventional reference PERC cell. The LBSF cell has an efficiency of 19.5%, which exceeds that of the reference cell by ~1.1%. The open-circuit voltage of the LBSF cell was obviously higher than that of the conventional PERC cell, which indicates that the B dopants in the LD area influenced Al diffusion and enhanced the LBSF. Furthermore, the corresponding values for the fill factor and Jsc also improved, which suggests that creating a region in which boron is heavily diffused prevents the formation of Kirkendall voids [9]. The improvement in the properties of the boron LD–LBSF cell is clearly caused by the rear-side of the cell, because the internal quantum efficiency (IQE) increased in the long-wavelength region from 800 to 1100 nm (see Fig. 10 of [13]). These results demonstrate that the B content of LD influences Al diffusion, thereby enhancing the LBSF effect and improving the properties of the cell.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Voc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
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<td>(a) boron LD–LBSF cell</td>
<td>0.654</td>
<td>37.9</td>
<td>78.9</td>
<td>19.5</td>
</tr>
<tr>
<td>(b) conventional PERC cell</td>
<td>0.642</td>
<td>36.8</td>
<td>77.9</td>
<td>18.4</td>
</tr>
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</table>

4. Conclusion

We investigated the efficiency of a localized back surface field (LBSF) cell created using boron laser doping (LD) and screen-printed aluminum paste firing to fabricate a p-type passivated emitter, rear locally diffused cell. The Al and B composition of the LBSF was observed using SCM and SIMS imaging, from which B/Al ratio was found to exceed 0.9 wt%. The B dopants in the LD area are considered to have influenced Al diffusion and enhanced the LBSF, which subsequently reduced surface recombination and improved the properties of the boron LD–LBSF cell by increasing its open circuit voltage by a remarkable extent. As a result, the efficiency of the cell exceeded that of the reference cell by more than ~1.1%. We remain hopeful that boron LD will provide a new process for forming Al-Si-B alloys that can be used to create an effective LBSF for high-efficiency solar cells.

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References


