

# Efficient Boron Doping in the Back Surface Field of Crystalline Silicon Solar Cells via Alloyed-Aluminum–Boron Paste

Guoping Du, Bin Chen, Nan Chen, and Ruiyi Hu

**Abstract**—Back surface field (BSF) can effectively reflect minority carriers from the back surface area of a crystalline silicon (c-Si) solar cell and therefore improves its photovoltaic performance. Aluminum BSF (Al-BSF) is presently the most widely used BSF for p-type c-Si solar cells. Due to the relatively lower solubility of Al in c-Si, it is hard to achieve a high doping concentration in the Al-BSF, which, in turn, limits the conversion efficiency of c-Si solar cells. This letter presents a technique to achieve a much higher doping concentration in the BSF by boron doping through the screen-printed alloyed-aluminum–boron paste. It was found that a lower sheet resistance was resulted in the BSF. This technique is expected to be beneficial to the improvement of conversion efficiency of c-Si solar cells.

**Index Terms**—Back surface field (BSF), boron doping, crystalline silicon (c-Si) solar cell, paste, screen print.

## I. INTRODUCTION

IN THE present global photovoltaic market, more than 80% of solar cells are based on p-type crystalline silicon (c-Si) wafers. A typical c-Si solar cell comprises front electrode contact, antireflection coating, emitter, base, back surface field (BSF), and back electrode. The emitter ( $n^+$  type) is phosphorous doped, while the BSF ( $p^+$  type) is formed by sintering the screen-printed aluminum paste on the cell back. Hence, a c-Si solar cell has an  $n^+pp^+$  junction structure. The  $pp^+$  structure at the cell back introduces a built-in field, which passivates the cell back by reflecting the minority carriers (free electrons) from the cell back toward the  $n^+p$  junction region [1], [2].

During the sintering process, Al and Si from the wafer back start to form an Al–Si liquid above the Al–Si eutectic temperature (577 °C) following the Al–Si phase diagram [3], and the liquid has a temperature-dependent composition. The typical peak sintering temperature is about 750 °C–850 °C. At the cooling stage, Si is rejected from the Al–Si liquid and epitaxially recrystallizes on the wafer surface [4]. In the

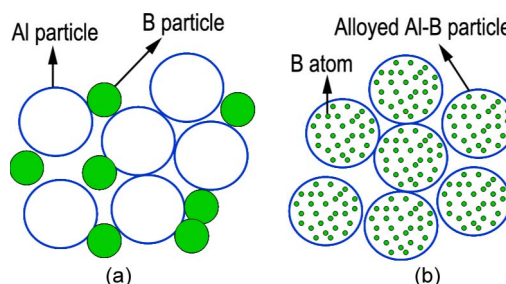


Fig. 1. Sketches for (a) the standard Al paste added with B powder as in [7] and (b) the paste composed of alloyed-Al–B powder of this work.

meantime, some Al atoms are incorporated into the regrown Si, and a  $p^+$ -type BSF [also often called aluminum BSF (Al-BSF)] is formed [5].

There is a strong need to increase the conversion efficiency of c-Si solar cells. Employment of higher  $p^+$  doping concentration in the BSF is one of the effective techniques to fabricate high-efficiency c-Si solar cells [6]. However, due to the limited solid solubility of Al in c-Si, the  $p^+$  doping concentration in Al-BSF of c-Si solar cells is usually about  $3 \times 10^{18}$  atoms/cm<sup>3</sup> or less [3]. Boron, on the other hand, has a much higher solid solubility in c-Si. Therefore, B doping is an effective choice to achieve heavier  $p^+$  doping in BSF for c-Si. However, B diffusion in c-Si requires a high temperature, which will usually degrade the electrical properties of c-Si wafers. Low-temperature process is always preferred in solar cell production.

Lölgén *et al.* [7] demonstrated that B can be doped into c-Si at 850 °C through the Al–Si liquid during the sintering process. This temperature is similar to the typical sintering temperature of Al paste for c-Si solar cells. They used a standard Al paste as the starting material and added 1% of B powder (relative to the Al amount) to the standard Al paste. After it was screen printed on a c-Si wafer and sintered at 850 °C for less than 1 min, the B-added Al paste reached a B doping concentration of about  $3 \times 10^{19}$  atoms/cm<sup>3</sup>, while the standard Al paste reached an Al doping concentration of about  $3 \times 10^{18}$  atoms/cm<sup>3</sup>, which is one order lower than the former.

When used for the BSF of c-Si solar cells, there are two potential disadvantages associated with the method described in [7]: 1) B particles may not be distributed uniformly in the paste [Fig. 1(a)], and therefore, a nonuniform BSF may result, and 2) when B and Si are forming Al–Si liquid, it takes some time for the B atoms in B particles to diffuse and be incorporated into the Al–Si liquid (it is noted that the sintering process for

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G. Du, B. Chen, and N. Chen are with the School of Materials Science and Engineering, Nanchang University, Nanchang 330031, China (e-mail: guopingdu@ncu.edu.cn; nanchen@ncu.edu.cn).

R. Hu is with the Jiangxi Institute of Solar Energy Technology, Xinyu 338012, China.

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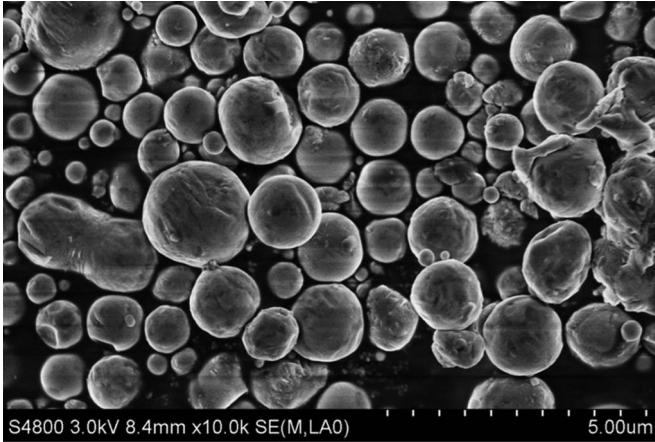


Fig. 2. SEM micrograph of the alloyed-Al-B powder.

c-Si solar cells is usually a few seconds, which may be too fast for B atoms to diffuse sufficiently), and thus, this may result in an inefficient and nonuniform B doping in the BSF.

In this work, we used a different approach and intended to avoid these potential drawbacks as stated previously. We first prepared alloyed-Al-B powder with a desirable particle size [8] and then employed the alloyed-Al-B powder to fabricate paste for screen printing on c-Si wafers. As shown in Fig. 1(b), Al and B coexist in the Al-B particles, and they are distributed uniformly on the atomic scale. Whenever Al forms Al-Si liquid with Si, B atoms are simultaneously incorporated into the Al-Si liquid in a direct manner. Thus, a more efficient B doping is expected, and this technique will be beneficial to fabricating high-quality BSF for c-Si solar cells with high efficiency.

## II. EXPERIMENTAL DETAILS

Alloyed-Al-B powder was prepared using the gas atomization method [9]. High-purity Al powder and B powder were used, and the B contents were 0%, 0.5%, 1.0%, and 2.0% in weight. Depending on the B content, the atomization temperature was selected based on the Al-B phase diagram [10]. Molten Al-B mixture was sprayed into a chamber using cold high-pressure argon gas, and fine Al-B mist was quickly cooled down to form alloyed-Al-B fine powders (Fig. 2). The alloyed-Al-B paste was prepared using the alloyed-Al-B powder (75 wt%), glass binder (7 wt%), organic binder (15 wt%), and other additives (3 wt%). The paste was screen printed on standard p-type CZ c-Si ( $\rho = 3 \Omega \cdot \text{cm}$ ) wafers after removal of saw damage and a chemical polishing process and then sintered in an industrial belt furnace at 800 °C, 850 °C, and 900 °C under the same procedures as for c-Si solar cells. The firing time over 650 °C was about 10 s. After etching off the sintered aluminum metal and aluminum-silicon alloy, the BSF was exposed, and its sheet resistance and B doping profile were measured using the four-probe method and the secondary ion mass spectroscopy (SIMS), respectively.

## III. RESULTS AND DISCUSSION

Fig. 3 shows the sheet resistance of the BSF prepared at different sintering temperatures from these four sets of paste

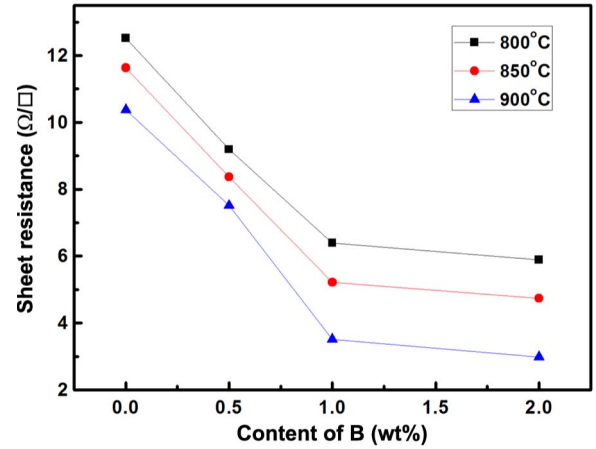


Fig. 3. Dependence of the sheet resistance of BSF on the B content for different sintering temperatures at 800 °C, 850 °C, and 900 °C.

with different contents of alloyed B, i.e., 0, 0.5, 1.0, and 2.0 wt%. For each paste (Fig. 3), the sheet resistance of the BSF reduced with the increase of sintering temperature. For instance, the BSF prepared from the Al paste without alloyed B has sheet resistances of 12.5  $\Omega/\square$  at 800 °C, 11.6  $\Omega/\square$  at 850 °C, and 10.4  $\Omega/\square$  at 900 °C, while the one prepared from the alloyed-Al-B paste with B content of 1.0 wt% has sheet resistances of 6.4  $\Omega/\square$  at 800 °C, 5.2  $\Omega/\square$  at 850 °C, and 3.5  $\Omega/\square$  at 900 °C. This dependence behavior of BSF sheet resistance with sintering temperature is consistent with the earlier results of BSF prepared from the standard Al paste [4], [11]. The reason is that higher sintering temperature results in a higher  $p^+$  doping concentration and larger thickness in the BSF, and therefore, a lower sheet resistance is expected.

For each sintering temperature (Fig. 3), the sheet resistance of BSF dropped quickly from the paste without containing alloyed-B content to that with alloyed-B content of 1.0 wt% and then dropped slowly with the B content over 1.0 wt%. For instance, at 850 °C, the BSF sheet resistance was 11.6  $\Omega/\square$  for the paste without containing alloyed B, and it quickly dropped to 8.4  $\Omega/\square$  for the alloyed B at 0.5 wt% and 5.2  $\Omega/\square$  for B at 1.0 wt%; then, it slowly dropped to 4.7  $\Omega/\square$  for B at 2.0 wt%. The reducing behavior of the BSF sheet resistance with the increase of alloyed-B content in the Al-B paste suggests that the alloyed-B atoms were effectively doped into the BSF and increased the  $p^+$  doping concentration in the BSF.

To further estimate B doping concentration in the BSF, we employed SIMS to measure the doping profile of B in the BSF region. Fig. 4 shows the Al and B doping profiles within the BSF sintered at 850 °C using the alloyed-Al-B paste with the alloyed-B content of 1.0 wt%. The B concentration reached about  $4.2 \times 10^{19}$  atoms/cm<sup>3</sup> at the depth from 5.7 to 7.1  $\mu\text{m}$  within the BSF, while the highest Al concentration was about  $3.1 \times 10^{18}$  atoms/cm<sup>3</sup> at the depth from 5.5 to 7.2  $\mu\text{m}$ . Hence, within the BSF, B concentration was about 14 times higher than that of Al. The results were generally in agreement with the results in [7], in which the highest B concentration was about  $3 \times 10^{19}$  atoms/cm<sup>3</sup> while the Al concentration was about  $3 \times 10^{18}$  atoms/cm<sup>3</sup>. Based on the sheet resistance and the doping profile in Fig. 4 for the BSF sintered from the paste with 1 wt%

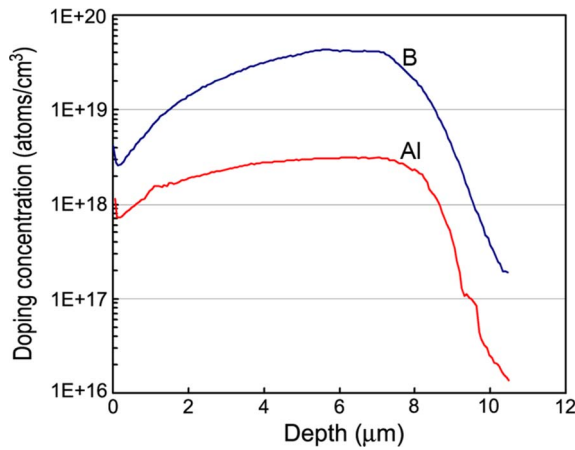


Fig. 4. B and Al doping profiles in the BSF (sintered from the alloyed-Al-B paste with 1-wt% B at 850 °C) measured with SIMS.

of B at 850 °C, the peak active B doping concentration was estimated to be about  $3.8 \times 10^{19}$  atoms/cm<sup>3</sup>. This indicates that about 91% of the B atoms in the BSF were electrically active. A higher percentage of active B atoms will lead to a lower sheet resistance of the BSF. Factors affecting the percentage of active B atoms are being investigated. Compared with the standard Al paste, the higher doping concentration in the BSF of c-Si solar cells achieved by the alloyed-Al-B paste is expected to improve the photovoltaic performance of c-Si solar cells.

#### IV. CONCLUSION

Alloyed-aluminum-boron paste was successfully prepared, and BSF was fabricated by screen printing the paste on p-type c-Si wafers. The sheet resistance of the BSF dropped quickly with boron concentration in the paste from 0 to 1.0 wt%, and then, the dropping rate slowed down when the boron concen-

tration further increased from 1.0 to 2.0 wt%. Much higher p<sup>+</sup> doping concentration was realized through the alloyed-aluminum-boron paste. When sintered at 850 °C, the alloyed-aluminum-boron paste resulted in a B doping concentration of  $4.2 \times 10^{19}$  atoms/cm<sup>3</sup> at a depth from 5.7 to 7.1 μm within the BSF. This is 14 times higher than the Al doping concentration.

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