Development of aluminum paste with/without boron content for crystalline silicon solar cells

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Abstract

Improvement of aluminum alloyed p + back surface fields (p + BSF) which is an essential requirement for achieving high efficiency silicon solar cells has been an important task. One of the ways to have better quality BSFs can be to introduce screen printable aluminum pastes with boron content. Two type of pastes were developed in this work and recipes were provided in detail: screen-printable aluminum paste without boron content (B-free-Al-paste), screen-printable aluminum paste with boron content (Al-B-paste). The ingredients of the pastes were optimized and basically evaluated in terms of alloying and impurity characteristics by measurement of sheet resistances, carrier lifetimes and SIMS analysis. Carrier lifetimes of the wafers processed by Al-B-paste maintained at around 300 μs relatively higher than the wafers processed by B-free-Al-paste. P-type silicon solar cells were fabricated using developed pastes and were compared with those of the cells fabricated by commercial aluminum pastes. Best efficiency of 17.8% was achieved with totally vacuum-less cell production process and Suns-Voc analysis were also carried out for fabricated solar cells.

1. Introduction

Crystalline silicon solar cells still dominate the photovoltaic market with a share of more than 90%. In a conventional p-type solar cell structure, high-quality p + back surface field (p + BSF) is a crucial requirement for achieving high efficiencies. BSF can significantly minimize the carrier recombination on rear side of solar cells by introducing a built-in field and reducing the recombination velocity [1, 2]. Screen-printing aluminum alloying process is used for full or local p + BSF formation on p-type crystalline silicon solar cells [3, 4]. Because obtaining high concentration when forming a p + BSF is important for high efficiency solar cells [5, 6], low solubility of aluminum (at level of 10^{18} atoms/cm^3) in crystalline silicon is the main limitation for achieving high penetrating ratio [7, 8]. Boron doping, on the other hand, found to be an effective solution to achieve densely doped p + BSFs (at level of 10^{19} atoms/cm^3) [9]. However, the need of high temperature processing (>950 °C) and high cost make it difficult to use boron diffused p + back surface fields for industrial silicon solar cells [5, 10]. As a feasible solution to achieve high penetrating ratio while processing the wafers at around common firing temperatures (~850 °C) with low cost, aluminum pastes with a small percentage of boron concentration were introduced [6, 9, 11, 12]. These pastes are mainly based on introduction of boron content into the commercial aluminum pastes. G Du et al prepared aluminum-boron powder with gas atomization method which includes 0–2 wt% boron and showed the decrease of sheet resistance with the effect of boron content and increase of doping concentration [9]. X Gu et al presented low temperature aluminum-boron (paste with boron concentration of 0.5 wt%) co-doped back surface field with increased doping concentration [6] which also offers thinner BSF than that of conventional aluminum pastes. Similarly, M Rauer et al introduced the increase of acceptor concentration in p + BSF by introducing aluminum diboride or boron trioxide into the aluminum pastes [12]. Moreover, printable boron doped pastes was reported for laser doping processing in solar cell
manufacturing process. Y Tomizawa et al introduced printable silicon paste with boron content for laser doping process in order to establish local boron back surface field by laser doping. In that study, the beneficial effect of local boron back surface field on the quantum efficiency and on the conversion efficiency was shown which also presents the importance of application of boron doped pastes to improve solar cell performance [13].

On the other hand, lifetime killing impurities such as heavy metals (Fe, Ni, Ti, etc) inside silicon act as recombination centers which increases the recombination of carriers. Fortunately, minimizing these impurities through gettering is possible during the solar cell fabrication process especially by phosphorus diffusion and aluminum alloying. Aluminum alloying in silicon, produces gettering effect by the movement of metallic impurities towards the aluminum layer due to the higher solubility of metals in aluminum [14]. Therefore, BSF structure plays an important role on carrier lifetime of solar cells which is another crucial parameter for achieving high conversion efficiencies. In case of boron included aluminum pastes, besides increasing the alloying concentration, addition of boron content into the aluminum can alter the gettering effect at the same time. However, production of such a paste and adaptation of it to the silicon solar cells is necessary.

In this work, we provide detailed recipes and analysis to produce highly efficient aluminum pastes with or without boron content. A comprehensive experimental flow including the preparation of the pastes and step-by-step processing details were explained for repeatability and better understanding of the contents. Two type of pastes were introduced in this work: screen-printable aluminum paste without boron content (B-free-Al-paste), screen-printable aluminum paste with boron content (Al-B-paste). A commercial aluminum metallization paste (C-Al-Paste) was also used for comparison purposes. Gettering efficiencies of introduced pastes were analyzed further and totally vacuum-free processed high efficiency silicon solar cells were fabricated by utilizing developed metallization pastes.

2. Experimental

2.1. Preparation of B-free-Al-paste and Al-B paste

When the aim is to develop a screen-printing paste for solar cell applications, ingredients need to be determined and optimized that influence the basic parameters of the pastes including printing characteristics (easy printability, viscosity of the paste) and processing conditions (temperature, time). As the main solid component of developed pastes, aluminum powders with various sizes of aluminum particles were utilized in this work. Aluminum powder with particle size of 45 μm (Kanto Chemical), 3.0–3.6 μm (# 800, Minalco), aluminum oxide powder 35–50 μm (Kanto Chemical) were used with fixed amounts of 2 g, 16 g and 2 g, respectively. Other additives were ethanol, α-terpineol, ethyl cellulose, and boric acid (H3BO3). Figure 1 shows the detailed flow chart of the production sequence of B-free-Al-paste and Al-B-paste. First, 16 g of aluminum powder with particle size of 3.0 to 3.6 μm, 2 g of aluminum powder with particle size of 45 μm and 2 g of aluminum oxide were placed in a mortar. Then, 2 mL of ethanol was added in the mortar each time and mixed with powders (this step was repeated for 10 cycles). After this preparations 100 mL ethanol was added into the mixed mortar and then transferred into a beaker and sonication with an ultrasonic homogenizer was applied in cycles of (2 s work/2 s rest) for 2 min α-terpineol and ethyl cellulose (10 wt% in ethanol) were added and stirred further using an
ultrasonic homogenizer (The amount of $\alpha$-terpineol and ethyl cellulose in figure 1, are the optimized values). Finally, B-free-Al-paste was obtained by evaporating ethanol from the mixed mortar using an evaporator. In case of production of Al-B-paste, boric acid was added into the mixture and sonicated by homogenizer prior to the introduction of $\alpha$-terpineol.

2.2. Evaluation of Gettering Effect by B-free-Al-paste and Al-B-paste

Optimization of $\alpha$-terpineol (75% or 120% with respect to ethyl cellulose), ethyl cellulose (from 6% to 16%) and boric acid ratios (from 0% to 5%) for each developed pastes were processed separately by the assessment of carrier lifetimes and sheet resistance measurements on the wafers after printing and thermal processing. The flow chart of lifetime study in order to understand the gettering effect of the Al-B-paste is given in figure 2. At first, 500 $\mu$m thick silicon wafers were cut into 25 mm x 25 mm square sizes. All wafers immersed in a mixed acidic solution of HF:HNO$_3$ (1:5 in volume) for polishing the wafer surface. Further cleaning process of RCA-1 by NH$_4$OH:H$_2$O$_2$:H$_2$O (1:1:5 in volume) and subsequence RCA-2 by HCl:H$_2$O$_2$:H$_2$O (1:1:5 in volume) were performed to remove organic/inorganic contaminations [15, 16]. At this point, lifetime of reference wafer (etched and cleaned bare silicon wafer) were measured as a reference of initial lifetime. Then, B-free-Al-paste or Al-B-paste was screen-printed on both sides of wafers and fired in a quartz tube at 870 °C for 10 s. Optimization of firing was carried out previously between temperatures of 810 °C–890 °C in terms of carrier lifetime and sheet resistances due to the investigation of gettering effect. Sheet resistance and bulk lifetimes of aluminum alloyed wafers were estimated. In order to measure the sheet resistances, aluminum electrodes were removed by diluted HCl acid (10 wt% in water). For bulk lifetime estimations, formed p+ layers were removed by a mixed solution of HF:HNO$_3$. Prior to the bulk lifetime measurements, iodine+ethanol passivation was applied to reduce dangling bonds and minimizing the recombination on surface of the wafers. Lifetime measurements were performed by $\mu$-PCD (Advantech, Industrial Computer 610 H) and QSSPC (Sinton Instruments, QFlash X5d-R) (In this work, measured lifetimes by QSSPC will be provided each time in parenthesis). Sheet resistance measurements were carried out by Loresta-EP (MCP-T 360: Mitsubishi Chemical).

2.3. Fabrication of silicon solar cells

For silicon solar cell fabrication, CZ-Si p-type wafers with size of 25 mm x 25 mm (thickness: 500 $\mu$m) were used. All wafers were etched in acidic solution containing HF:HNO$_3$ (1:5 in volume) in order to remove saw damages. Prior to alkaline texturing and phosphorus diffusion, a SiO$_2$ layer was coated on wafer surface at each time using polysilazane on rear side of the wafers. After alkaline texturing by KOH solution and subsequent cleaning of wafers in diluted HF, further cleaning process of RCA-1 by NH$_4$OH:H$_2$O$_2$:H$_2$O (1:1:5 in volume) and cleaning process of RCA-2 by HCl:H$_2$O$_2$:H$_2$O (1:1:5 in volume) were carried out to remove organic/inorganic contaminations [15, 16]. The POCl$_3$ diffusion was performed to form n+ front emitter. After removal of front phosphate-silica glass (PSG) and back side SiO$_2$ layer by soaking the wafers in diluted 10% HF aqueous solution, antireflection coating (ARC) of TiO$_2$ was coated by spray pyrolysis deposition on n+ emitter stacked with Al$_2$O$_3$ film [17]. Finally, B-free-Al-paste, Al-B-paste or C-Al-paste were coated by screen printing on the back side of the wafers. B-free-Al-paste, Al-B-paste were dried at 310 °C for 30 min while the C-Al-paste was dried at 125 °C for 5 min prior to firing process. For front side metallization, a commercially available silver
paste was printed on the front size of the wafers and dried at 125 °C for 5 min Co-firing was performed at peak of 870 °C for 10 s by rapid thermal annealing (RTA). Al2O3 (d = 60 nm)/TiO2 (d = 30 nm) stack films was formed by spray pyrolysis method as an antireflection coating layer. At last, each edge of wafer was cut with 2.5 mm width for the isolation. The resulting size of the samples used for photocurrent voltage (I-V) measurements was 20 mm × 20 mm. An AM1.5 solar simulator (with a 500 W Xe lamp, YSS-80A, Yamashita Denso, Japan) calibrated to 100 mWcm-2 using a reference silicon photodiode (Bunkou Keiki, Japan) was employed for photovoltaic measurements. I-V curves were obtained by applying an external bias to the cell and measurement of the generated photocurrent with a DC voltage current source (B2901A, Agilent).

3. Results and discussion

3.1. Optimization of ethyl cellulose ratio

Optimization of B-free-Al-paste, consisting of aluminum powder, aluminum oxide powder, ethyl cellulose (10 wt% in EtOH) and α-terpineol was carried out. In order to determine the optimum value of ethyl cellulose (10 wt% in EtOH) ratio in the paste, amount of ethyl cellulose was varied while the weight ratio of ethyl cellulose with respect to α-terpineol was kept in ratio of 4:3. Primarily, six type of pastes with the amount of 32 g, 28 g, 24 g, 20 g, 16 g and 12 g of ethyl cellulose (10 wt% in EtOH) were prepared which correspond to 16%, 14%, 12%, 10%, 8% and 6% ratio of ethyl cellulose simple substance to the solid particles (aluminum powders and aluminum oxide powders) in the paste. Three samples were prepared for each group and all were fired at 870 °C after screen-printing of the paste on both sides of the wafers. Figure 3 shows the measured bulk lifetime (figure 3(a)) and the sheet resistances (figure 3(b)) of the processed wafers as a function of ethyl cellulose ratio in the paste.

Bulk lifetime of reference wafer of this batch was measured (after polish etching + RCA cleaning) as 76.23 μs (73.36 μs by QSSPC). Lowest bulk lifetime was observed when the ethyl cellulose ratio was 16% and increased by decreasing the ratio. The peak value of around 270 μs was obtained when the ethyl cellulose ratio was 10%. Average lifetime of 3 samples was 243.52 μs (242.81 μs by QSSPC) which is around 3 times greater than the initial lifetimes. In figure 3(b) there is a clear trend of decreasing of sheet resistance when ethyl cellulose ratio decreases below 16% and stabilize at the ratio of 10%. This indicates amount of aluminum increases during the alloying process by reducing the ethyl cellulose concentration down to 10%. The average value of the sheet resistance was 37.0 Ω/sq when the ratio of ethyl cellulose was 10%. Decrease of the lifetime with high sheet resistance by varying the amount of ethyl cellulose, may be attributed to the decrease of penetrating volume and influence of printed thickness [18]. According to these results, ethyl cellulose ratio was set to 10% for rest of this work.

3.2. Optimization of boric acid ratio

After the optimization of ethyl cellulose ratio in the paste, Al-B-paste was produced by adding boric acid into the optimized paste. Five types of pastes were prepared with a content of 0.2 g, 0.4 g, 0.6 g, 0.8 g and 1.0 g of boric acid that corresponds to the ratio of 1%, 2%, 3%, 4%, 5% of solid particles (aluminum powders and aluminum oxide powders) in the paste. Amount of ethyl cellulose was fixed to previously optimized ratio of 10% and α-terpineol was fixed to 75% with respect to ethyl cellulose. Additionally, B-free-Al-paste with no boric acid content was also produced. Three samples were prepared for each group and all screen-printed Al-B-paste wafers were fired at 870 °C. Figure 4 shows the measured bulk lifetimes (figure 4(a)) and the sheet resistances (figure 4(b)) as a function boric acid ratio in the paste.

In this batch of wafers, bulk lifetime of the reference bare silicon wafer (after polish etching + RCA cleaning) was 56.73 μs (52.89 μs by QSSPC). Average carrier lifetime of the processed wafers with Al-B-paste containing boric acid (1%-3% boric acid) were higher than that of the wafers went through alloying process using the B-free-Al-paste. The highest average lifetime (average of 3 samples) was 229.36 μs (222.11 μs by QSSPC) for the alloying process with the paste containing 1% boric acid. The highest achieved lifetime was 257.41 μs (255.84 μs by QSSPC). Lifetime improvement by adding boron content into the paste can be attributed to the improved gettering effect by the additional boron content. The average value of the sheet resistance of the wafers processed by Al-B-paste with 1% boric acid content was 29.7 Ω/sq. Further decrease of sheet resistances when comparing with those of wafers processed by B-free-Al-paste is because of the boron content in the Al-B-paste. Sheet resistances of the wafers were decreased by increasing amount of boric acid in the paste which can be due to the increase of penetrating ratio. However, this phenomenon may not be significant as the reduction is not strong.

Because the peak lifetime was observed for the wafers processed by the Al-B-paste with 1% ratio of boric acid, ratio of boric acid was changed further between 0.25%~2% (0.05 g (0.25%), 0.1 g (0.5%), 0.3 g (1.5%), 0.4 g (2%)) to determine the optimum amount. Measured bulk lifetimes and sheet resistances of the wafers with...
pastes contains 0.25%–2% boric acid was shown in Figure 5. The bulk lifetime of the reference wafers (after saw damage etching + RCA cleaning) was 102.97 μs (129.86 μs by the QSSPC). The average bulk lifetime reached a maximum value of 297.80 μs (277.64 μs by the QSSPC) when the boric acid ratio was 0.25%. The maximum lifetime was 310.71 μs (298.83 μs by the QSSPC). Sheet resistance of the wafers processed with aluminum paste including boric acid ratio of 0.25% were around 35.70 Ω/sq.

3.3. SIMS analysis of impurities
To further confirm the impurity profiles, SIMS (Secondary Ion Mass Spectrometry) measurement was carried out in the doped p+ region. Similar preparation steps were followed as that of the preparations processed prior to lifetime measurements; after mirror etching and RCA cleaning of silicon wafer, Al-B paste was screen-printed on silicon surface and fired at 870 °C. After firing process Al-B paste residue was removed by diluted HCl acid.
and wafer was further cleaned by deionized water. SIMS measurement was performed with the depth of 11 μm. Four separate measurements were carried out for three different pastes with varied contents. Table 1 summarizes the contents of the paste for each group. The ‘solid’ content stands for the mix of aluminum particles total of 20 g: <small Al particle (d = 3.0–3.6 μm, 16 g), large Al particle (d = 45 μm, 2 g) and Al₂O₃ particle (2 g)>.

SIMS measurements were given in figure 6: figure 6(a) for Paste 1 (solids: 20 g, ethylcellulose: 3.2 g, α-telpineol: 28 g), figure 6(b) for Paste 2 (solids: 20 g, ethylcellulose: 2 g, α-telpineol: 15 g), figures 6(c) and (d) for Paste 3 (solids: 20 g, H₃BO₃: 0.2 g, ethyl cellulose: 2 g, α-telpineol: 15 g). Figures 6(a)–(c) shows the detection of

![Figure 4](image-url)
Figure 5. Measured bulk lifetimes (a) and sheet resistances (b) as a function of boric acid ratio (from 0% to 2%).

Table 1. Contents of Al pastes alloyed to form BSF for SIMS measurements.

| Figure | Solids (g) | \( \text{H}_3\text{BO}_3 \) (% by solids) | Ethylcellulose (% by solids) | \( \alpha \)-terpineol (% by ethylcellulose) |
|--------|------------|--------------------------------------|----------------------------|----------------------------------|
| 6a     | 20         | 0                                    | 16                         | 120                              |
| 6b     | 20         | 0                                    | 10                         | 75                               |
| 6c     | 20         | 1.0                                  | 10                         | 75                               |
| 6d     | 20         | 1.0                                  | 10                         | 75                               |
oxygen, carbon, aluminum and copper using a Cs ion gun and figure 6(d) shows the detection of aluminum, copper and boron using an O2 ion gun.

It was clear that the alloying amount of aluminum with silicon surface was larger for the paste with 10% ethyl cellulose content (figure 6(b)) than that of the paste with ethyl cellulose content of 16% (figure 6(a)). A possible explanation for this might be the packing ratio of aluminum and thus concentration of aluminum in silicon increase when the amount of ethylcellulose and α-terpineol is small. Lower sheet resistances of the wafers processed by the paste with less amount of ethylcellulose (figure 3) also support these results.

Carbon diffuses into the silicon simultaneously with aluminum and provides a similar profile. Oxygen concentration was greater for the pastes without boric acid content. When boric acid was added into the paste (figures 6(c), (d)), degradation of aluminum concentration was observed which can be due to the limiting of
aluminum alloying because of the boron content. Concentration of boron was greatly dominant through deep level of the $p^+$ region. However, concentration of aluminum was higher at near the surface till to the depth of 2 $\mu$m. No significant reduction of ratio of residual copper was detected.

3.4. Evaluation of fabricated silicon solar cells

Fabricated silicon solar cells with full area BSF formed by B-free-Al-paste, Al-B-paste and C-Al-paste were evaluated by I-V curve measurements and Suns-Voc (Sinton Instruments, WCT-120) measurements. It is important to mention that the solar cell fabrication process in this work was not an industrial state of art processing. Fabricated solar cells has the structure of $\langle$Ag/Al$_2$O$_3$-TiO$_2$ ARC/ n + emitter/p-Si base/p + BSF/Al$\rangle$. Table 2 summarizes the measured electrical characteristics of fabricated solar cells and I-V curves of best cell of each group were given in figure 7.

Solar cells fabricated with developed B-free-Al-paste and Al-B-paste showed better performances than that of the reference cells with C-Al-paste. Achieved average conversion efficiencies of solar cells with B-free-Al-paste, Al-B-paste and with C-Al-paste were 17.45%, 16.13%, 14.72%, respectively. The short circuit current density ($J_{SC}$) of the cells with C-Al-paste was 38.83 mA cm$^{-2}$ and has a fill factor (FF) of 64%. FF of solar cells with developed B-free-Al-paste reached to 75% with slight increase of $J_{SC}$ to 38.96 mA cm$^{-2}$ than that of C-Al-paste. However, average $J_{SC}$ of the cells with Al-B-paste BSF were 37.32 mA cm$^{-2}$. The main reason for the low FF of the cells processed by C-Al-paste and Al-B pastes than that of the B-free paste is the higher series resistances. Average series resistances were 1.98, 1.09 and 0.87 $\Omega$ cm$^2$, respectively for the cells processed by C-Al, Al-B and B-free aluminum pastes. Shunt resistances of those cells were high enough to provide good isolation.

The record efficiency of 17.81% was achieved with developed B-free-Al-paste. $J_{SC}$ and open circuit voltage ($V_{OC}$) of record cell were 39.50 mA cm$^{-2}$ and 598 mV, respectively with a FF of 75.3%. In order to investigate the decrease of $J_{SC}$ in those of the cells with Al-B-paste BSF, IPCE measurements were carried out. IPCE measurements of the cells from three sets of solar cells are given in figure 8.

$J_{SC}$ of 37.43 mA cm$^{-2}$, 37.27 mA cm$^{-2}$, 36.97 mA cm$^{-2}$ were achieved for the cells produced by using B-free-Al-paste, Al-B-paste and C-Al-paste, respectively. Because there is no degradation of IPCE observed on
Figure 8. IPCE measurement of best solar cells of each group.

Table 3. Simulated photovoltaic characteristics of fabricated silicon Solar cells with different aluminum pastes, measured by Suns-Voc tool.

| Paste            | $J_{sc}$ (mA cm$^{-2}$) | $V_{oc}$ (mV) | FF (%) | Pseudo $\eta$ (%) |
|------------------|--------------------------|---------------|--------|------------------|
| B-free-Al-paste  | 37.71                    | 603           | 80.4   | 18.3             |
| Al-B-paste       | 37.27                    | 601           | 80.3   | 18.0             |
| C-Al-paste       | 36.97                    | 594           | 73.4   | 16.1             |

Figure 9. I-V curve of solar cells measured by Suns-Voc tool.
blue range of the spectrum, deterioration of the ARC film is not considered a likely possibility. The reason of poor $J_{SC}$ might be the reduction of light receiving active area of the solar cells which can be due to the poor physical properties of screen-printed front metallization. Other explanation for poor $J_{SC}$ and limited $V_{OC}$ can be the lack of passivation effect of applied Al$_2$O$_3$/TiO$_2$ stack on n-type emitter.

Additionally, Suns-Voc measurements were carried out using $J_{SC}$ values calculated from IPCE in order to estimate the potential performance of the fabricated solar cells. Table 3 shows the photoelectric characteristics by Suns-Voc and figure 9 shows the I-V characteristics by Suns-Voc measurement. Solar cells with developed aluminum pastes show better performance than that of the cells with C-Al-paste. Pseudo efficiency of the cells with B-free-Al-paste and Al-B-paste BSFs were 18.3% and 18.0%, respectively.

Although, the effect of the boric acid included aluminum paste on the improvement of bulk quality of silicon through gettering observed in this work, its effect on the solar cell performance was not so apparent. This can be due to the dispersion of boron element into the gas phase during the firing process. The dispersed boron can be diffuse towards the front side of silicon solar cells which can deteriorate the photovoltaic properties. It is important to consider this phenomenon in further studies in order to improve the performance of silicon solar cells using boron-doped aluminum pastes. On the other hand, it is expected that solar cell performances can be improved with the use of quality passivation such as SiN$_x$ or by a stacked SiO$_2$ layer as in state of art solar cells.

4. Conclusion

Screen printable aluminum pastes with and without boron content were introduced in this work for crystalline silicon solar cells. Both pastes provided high carrier lifetimes after alloying by thermal processing. Carrier lifetimes of $>300$ $\mu$s could be achieved by the aluminum paste with boron content where the lifetimes of the wafers processed with boron-free aluminum paste was around 250 $\mu$s. Although the boron included aluminum paste lead higher carrier lifetimes after alloying with silicon and that can be attributed to the improved gettering, fabricated solar cells with boron-free aluminum paste provided better cell performances. Best conversion efficiency of 17.8% was reached after totally vacuum-less processed solar cell fabrication procedures. These finding can suggest that boron content in aluminum pastes is supportive to improve the bulk quality of silicon solar cells. However, poor performance of such pastes on solar cell fabrication is needed to be investigated further for higher efficiencies.

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References

[1] Mandelkorn J and Lamneck J H Jr 1973 J. Appl. Phys. 44, 4785
[2] Fossum J G 1977 IEEE Trans. Electron Device 24 202
[3] Riegel S, Mutter F, Lauermann T, Terheiden B and Hahn G 2012 Energy Procedia 21 14
[4] Kim K H, Park C S, Lee J D, Lim J Y, Yeon J M, Kim I H, Lee E J and Cho Y H 2017 Jpn. J. Appl. Phys. 56 08MB25
[5] Das A, Meemongkolkit V, Ramanathan D S and Rovatgi A 2010 IEEE Trans. Electron Devices 57 2462
[6] Gu X, Xu X, Xu J, Fan R and Yang D 2013 Prog. Photovolt: Res. Appl. 21 456
[7] Murray J and McAlister A 1984 Bull. Alloy Phase Diagrams 5 74
[8] Krause O, Rysel R and Pichler P 2002 J. Appl. Phys. 91 5645
[9] Du G, Chen B, Chen N and Hu R 2012 IEEE Electron Device Lett. 33 573
[10] Okamura M 1969 Jpn. J. Appl. Phys. 8 1440
[11] Løglen P, Sinke W C, Legujic C, Weeber A W, Alkemade P F A, Alkemade L A and Verhoeof I A 1994 Appl. Phys. Lett. 65 2792
[12] Rauer M, Schmiga C, Glatthaar M and Glunz W S 2013 IEEE J. Photovolt. 3 206
[13] Tomizawa Y, Imanura T, Soeda M, Ikeda Y and Shiro T 2015 Jpn. J. Appl. Phys. 54 08KD06
[14] Porre O, Martinuzzi S, Pasquinelli M, Perichaud I and Gay N 1996 Proc. of 25th IEEE Photovoltaic Specialists Conf. 629
[15] Kern W and Puotinen D A 1970 RCA Review 31 187
[16] Reinhardt K and Kern W (ed) 2008 Handbook of Silicon Wafer Cleaning Technology (William Andrew) 2nd edn
[17] Kanda H, Uzum A, Harano N, Yoshinaga S, Ishikawa Y, Uraoka Y, Fukui H, Harada T and Ito S 2016 Energy Science & Engineering 4 269
[18] Zanesco I, Gonçalves V A and Mochlecke A 2014 Energy Procedia 57 47