DEVELOPMENT OF SCREENPRINTABLE CONTACTS FOR P^+ EMITTERS IN BIFACIAL SOLAR CELLS

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ABSTRACT: We present a study on the development of screenprinted front-contacts for p^+ emitters in p^+nn^+ bifacial solar cells with screenprinted boron and phosphorus emitters. By systematically varying the concentration of various components in the p^+ electrode it is demonstrated how the screenprintable contact paste affects the macroscopic electrical output characteristics such as contact resistance towards the B emitter and cell output parameters. Whereas the contact resistance between the B emitter and the fired p^+ electrode strongly decreases for higher Al content in the p^+ contact paste, good performance of n^+np^+ monofacial and bifacial cells can already be achieved by using a relatively low Al content. After selecting the p^+ contact paste that yields the most stable electrical performance optimization of the firing conditions was carried out. High efficiencies of 15.4% for monofacial cells and 14.4% for bifacial cells (area 2.25 cm^2)were obtained at a low peak temperature of around 725 ºC, fine-tuning is yet to be done.

Key Words: Bifacial solar cells, screenprintable contacts, boron emitters, contact resistance

1 INTRODUCTION

During recent years, bifacial solar cells have received increased interest because they couple enhanced conversion efficiencies to a potential solution of the feedstock problem. Bifacial cells can be manufactured using either p- or n-type silicon substrates. Part of the silicon shortage can be overcome if a fraction of the large amounts of highly doped n-type material from semiconductor industry is made suitable for PV while at the same time industrial processing sequences for multi-crystalline n-type wafers are introduced. A large advantage of n-type silicon is its low sensitivity to the presence of metallic impurities, leading to significantly higher minority carrier lifetime compared with p-type material [1]. Although high conversion efficiencies above 20% have been obtained for n-type silicon based high efficiency solar cells [2] the research on cost-effective, industrial processes is ongoing [3,4,5]. In earlier work [3] we have shown that homogeneous n^+ and p^+ emitters can be made using a simple screenprinting process followed by inline diffusion. It was also observed that n^+pp^+ cells showed significant higher Voc than p^+nn^+ cells which was attributed to the shunting of the frontside B emitter by the non-optimized Ag/Al electrode.

One of the key factors for achieving high efficient p^+nn^+ cells is the optimization of screenprinted contact electrodes for the p^+ emitter. This paper describes the steps towards optimization of a screenprinted front electrode for p^+ boron emitters in bifacial solar cells. The process of n^+ contact formation, which has been studied intensively during the last years (e.g. [6,7]), is mainly governed by Ag island formation and the properties of the interfacial glass layer. It is useful to determine if similar mechanisms also play a role in p^+ contact formation. Therefore the interface between the p^+ emitter and the contact electrode has to be studied with similar microscopic techniques as used for n^+ emitters. Moreover, the relation between the composition of the contact paste and the macroscopic electrical device performance should be analyzed in detail.

2 EXPERIMENTAL

The work was carried out in close cooperation between Ferro EMS and TIM. In order to achieve Ohmic electrical contact between B emitter and Ag electrode, less noble metals like e.g. Al have to be added. However, it is known that pure Al leads to shunting of the p^+ emitter [8]. In this work two Ferro silver pastes with different glass frit composition were selected as base pastes. A set of identical modifications was made to both pastes in order to obtain improved p^+ contact paste. Samples containing the lower melting glass frit are referred to as type 1, higher melting glass frit samples as type 2. The test pastes were screenprinted on 0.8 Ω·cm n-type CZ wafers for contact resistance and IV analysis. Small area (2.25 cm^2) monofacial and bifacial solar cells were obtained by co-diffusion of the Ferro diffusion paste DP99-038 for the phosphorous emitter and FX99-033 for the boron emitter. Diffusion was carried out in a belt furnace. The P backside emitter was screenprinted with the Ferro Ag paste CN33-462 to contact the n^+ surface. The B emitters were contacted with p^+ contact pastes with variable composition. Co-firing of the frontside and backside electrodes was done in a 3-zone IR belt furnace at peak temperatures ranging from 725 to 850 °C.

The samples for cell analysis were edge-isolated by means of dicing and measured in a cell tester at continuous AM1.5 illumination. Contact resistance analysis was performed using the Transfer Length Method (TLM). A part of the cells was selected for SEM microscopy analysis and underwent a basic interface and surface study, as described in [6,7].

3 RESULTS

3.1 Contact resistance

Emitter profiling

Since the contact resistance between the Ag electrode and the B emitter is very sensitive to both B surface concentration and junction depth the conditions for co-diffusion of B and P emitters must be carefully chosen. In previous work [3] we have shown that high minority carrier lifetimes of >70μs are achieved in bifacial cells on n-type substrates when co-diffusion is performed at 950 ºC for 4 minutes. However, as mentioned before the resulting B emitter was heavily shunted by the Al-doped Ag electrode. This resulted in low Voc values of ~510 mV. Since the junction depth of the B emitter was only 0.15 μm, the first step to decrease the shunting risk is deepening of the B emitter. This can be done by increasing the thermal budget for co-diffusion by means of a higher peak temperature and/or longer diffusion time. One should take into account that this may lead to higher recombination rates and lower minority carrier lifetime.

Spreading resistance analysis was done to gain insight into the properties of the B emitter. Figure 1 shows the depth profile of two emitters after diffusion for 8 minutes at 950 ºC and 1000 ºC. The latter profile with a surface concentration of 1.5e20 cm^{-3} and a depth of 0.33 μm, yielding a sheet resistivity of 30-40 Ω/□, was carefully chosen as a starting point for this study.

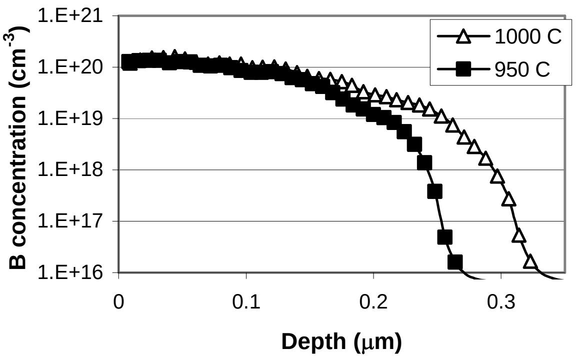


Figure 1: Emitter profiles after diffusion for 8 minutes at 950 ºC and 1000 ºC

Contact paste composition

The contact resistance Rc of pure Ag contacts toward the p^+ emitter can be lowered by adding aluminum to the electrode material. However, as mentioned before pure Al has the risk of shunting the emitter leading to deteriorated cell performance. For this reason Al was added in the form of an alloy. Figure 2 shows the contact resistance between the B emitter and the p^+ electrode as a function of Al content in the contact paste for two peak firing temperatures.

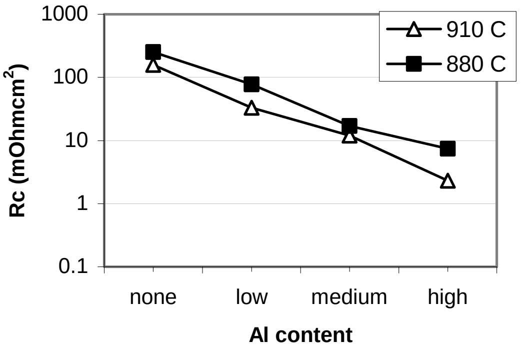
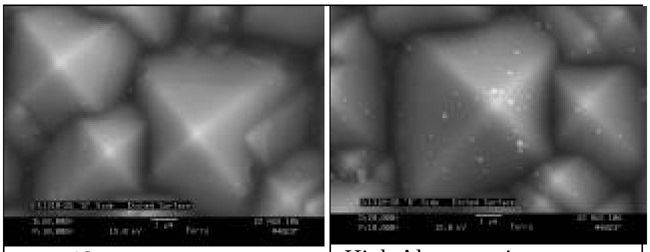


Figure 2: Rc between B emitter and Ag/Al electrode (only type 1 samples) as a function of Al content

The best performance in terms of a low contact resistance was found for the samples with medium and high Al content (< 10 $m\Omega cm^2$). This was confirmed by SEM micrographs of the p^+ surface that were taken after etching away the Ag fingers (see Fig. 3). Comparing the samples with high and low Al content in the source paste, an increased density and size of Ag islands on the emitter surface is observed for a high Al content. Since Ag(-Si) islands are assumed to play a critical role in the contact formation mechanism [6,7] the higher Ag island density may be associated with a lower contact resistance. However, when applied in solar cells these configurations may lead to shunting pathways resulting in high emitter saturation currents. Also other factors such as the choice of glass frit may affect the overall cell performance. Therefore the next step is to prepare a number of solar cells using different p^+ electrode composition and measure the cell characteristics.



Low Al content in paste | High Al content in paste

Figure 3: SEM micrographs of p^+ surface after etching off the Ag fingers when using two different p^+ contact pastes

3.2 IV analysis

Selection of glass frit

Both monofacial cells and bifacial cells with B and P emitters were prepared using p^+ contact pastes of type 1 and type 2 with variable Al content. The cells were fired at peak temperatures between 725 and 850 ºC at variable beltspeed. IV-analysis revealed that the samples based on low-melting glass frit (type 1) significantly outperformed the high-melting samples (type 2) in the whole temperature and composition range in terms of all electrical parameters. Based on this it was decided to further focus on p^+ contact pastes with glass frit of type 1.

Selection of Al content

In order to focus on the relationship between the performance and the stability of the p^+ contact and the Al content, monofacial cells were investigated. The most stable data and best performance in terms of a low shunt conductance and high efficiency were found for the cells containing a low content of Al in the front electrode (see Table I).

Table I: IV-data for monofacial cells for different Al content at typical firing settings (peak temperature of 765 ºC)

Al content	Voc (mV)	Gsh (Ω^{-1}/cm^2)	FF	Efficiency (%)
None	591	4.57e-3	61.1	10.6
Low	597	1.01e-3	70.0	12.8
Medium	584	1.83e-3	73.7	11.4
High	599	5.24e-3	69.8	12.3

Cross-sectional SEM study of samples containing a low Al concentration (see Figure 4) revealed a dense microstructure with a thin interfacial glass layer between the Ag layer and the and silicon surface, which has also been observed for good performing n^+ contacts [6].

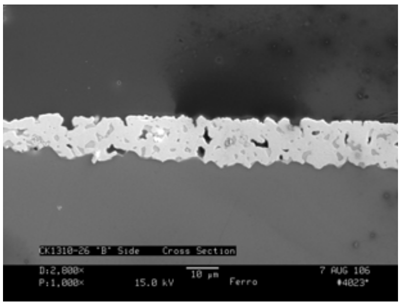


Figure 4: SEM micrograph of cross-section of p^+ emitter and Ag finger for low Al content in contact paste

Based on these findings the rest of the experiments were carried out using p^+ contact pastes with a low Al content.

Firing optimization

The electrical performance of monofacial and bifacial p^+nn^+ cells was used as a guideline for optimization of the firing conditions. The results are summarized in Table II and III.

Table II: Cell output for monofacial cells (2.25 cm^2); firing process 1 refers to lowest T, lowest beltspeed and process 3 to highest T and highest beltspeed

Firing process	Voc (mV)	Isc ($mAcm^{-2}$)	FF	R_{ser} (Ωcm^2)	Eff. (%)
1	607	32.4	78.0	0.32	15.4
2	592	31.7	73.6	0.52	13.4
3	595	29.2	75.8	0.60	13.2

Although a trade-off is observed between diffusion time and peak firing temperature the highest output for monofacial cells was found for firing at relative low temperature (actual wafer temperature around 725 ºC) at low beltspeed (>25s in high temperature zone). In particular this yields a high Voc of 607 mV and a high FF of 78.0, resulting from a low shunt conductance of 4.12e-4 Ω^{-1}/cm^2 and a minimal series resistance of 0.32 Ωcm^2. Since both shunt and series resistance show a tendency to improve at lower firing temperatures more experiments should be conducted to complete fine-tuning of the firing conditions.

Table III: Cell output for bifacial cells

Firing process	Voc (mV)	Isc ($mAcm^{-2}$)	FF	R_{ser} (Ωcm^2)	Eff. (%)
1	604	31.8	75.2	0.85	14.4
2	602	30.7	76.5	0.74	14.2
3	592	28.6	71.4	1.05	12.1

Comparing the results for the bifacial cells with the monofacial cells one concludes that on the average the monofacial cells outperform the bifacial cells. The high series resistance of bifacial cells probably originates from a non-optimal rear contact which may be due to a too high thermal budget for the diffusion of phosphorus. In addition, poor bifaciality values below 20% were measured which also point towards a non-optimized P emitter. Bifaciality can also be improved by using thinner wafers and/or wafers with a higher base resistivity (3-5 Ωcm) in order to generate higher carrier lifetimes. For the samples described in this section the minority carrier lifetime was measured to be 40 – 60 µs. Finally, the incorporation of an anti-reflective coating will be another important step towards further efficiency enhancement.

4 SUMMARY

- A contact resistance between 30-40 Ω/□ B emitters and Ag contacts of less than 10 $m\Omega cm^2$ has been achieved when using a relatively high Al content in the Ag contact paste. This can be attributed to a high number and size of Ag islands on the Ag-Si interface.
- Solar cells with a relatively low Al content in the p^+ electrode have shown optimal IV-characteristics, in particular due to minimal shunting losses.
- When using the optimized p^+ contact paste, featuring a low Al content, the best performing small area p^+nn^+ bifacial solar cells have yielded efficiencies of 14.4% at optimal firing settings.
- A higher efficiency of 15.4% was obtained for monofacial cells, mainly resulting from a lower series resistance and poor bifaciality. Optimization of the B/P co-diffusion process and simultaneous fine-tuning of p^+ and n^+ contact formation will be needed to improve the output of bifacial cells.

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