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Influence of contact firing conditions on the characteristics of bi-facial n-type silicon solar cells using Ag/Al pastes

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Abstract

In this study we investigate metal spike formation of screen-printed Ag/Al pastes during contact firing in an infrared belt furnace and its influence on the characteristics of n-type bi-facial silicon solar cells. The boron emitters are formed in a co-diffusion step using boron doped PECVD layers. It is demonstrated that the formation of Ag/Al spikes results in strong FF and V_{OC} losses limiting the solar cell efficiency. This can mainly be attributed to an increased saturation current density of the second diode which is strongly increasing with increasing set peak firing temperature. A detailed scanning electron microscopy analysis reveals that this j_{02} increase can be attributed to an increasing area density and depth of the Ag/Al spikes for increasing peak firing temperatures.

Keywords: boron emitters; metallization; screen-printing; bi-facial; n-type silicon; scanning electron microscopy

1. Introduction

Contact formation on B emitters with screen-printing (SP) of metal pastes has been intensely investigated in the last years by several groups [1-7]. It has been shown, that the use of pure silver (Ag) pastes can lead to high contact resistance (R_C) [1, 2] resulting in high power losses due to series resistance (R_S). Therefore, new pastes have been developed by adding a small amount of aluminum (Al) into the Ag pastes resulting in reduced R_C [1-3].

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However, the usage of Ag/Al pastes leads to several disadvantages like formation of metal spikes which can penetrate the space charge region (SCR) [2, 3, 7] and higher line resistivity (R_L) compared to pure Ag pastes.

This work is mainly focused on the influence of the firing conditions on Ag/Al spike formation during contact firing in an infrared (IR) belt furnace. The set peak firing temperature (SPFT) is varied in a wide range and the metal spike induced recombination due to deterioration of the SCR is observed to get a deeper understanding of ideal firing conditions necessary for fabrication of highly efficient n-type bi-facial solar cells.

Furthermore, a detailed scanning electron microscopy (SEM) analysis will be given to determine the evolution of the Ag/Al spike depths with increasing SPFT.

2. Experimental

Bi-facial solar cells are fabricated on n-type Cz-Si (6 Ωcm) according to Fig. 1. The wafers obtain an alkaline texture on both sides and co-diffused B emitters from doped plasma-enhanced chemical vapor deposition (PECVD) layers. The B emitter and the P front surface field are formed in one high temperature diffusion step (co-diffusion) in a $POCl_3$ tube furnace using a two-step process similar to the one described in [7–9].

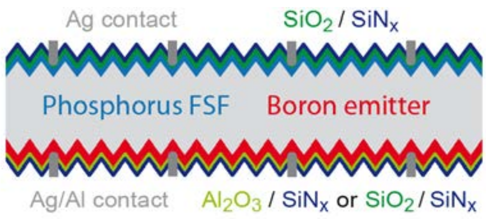

Fig. 1. Cross-section: n-type bi-facial solar cell with PECVD B emitter and P FSF. Contact formation is conducted via screen-printing of Ag paste on P FSF and Ag/Al paste on the B emitter. Two different passivation layer stacks (Al_2O_3/SiN_x and SiO_2/SiN_x) are used for emitter passivation.

Four different co-diffusions for emitter formation are conducted to investigate the impact of the Ag/Al spikes on the solar cell characteristics for different emitter profiles. Sheet resistances R_{SH} measured by a four point probe setup are in the range of 40–70 Ω/sq. The doping profiles measured by an electrochemical capacitance voltage (ECV) setup are shown in Fig. 2 revealing emitter depths of 500-700 nm and surface concentration of $3\text{-}4 \cdot 10^{19}$ cm^{-3}. Contact formation is realized by SP of commercial available Ag paste on the P FSF and Ag/Al paste on the B emitter. To investigate the influence of the dielectric passivation layers on Ag/Al spike formation, two different layer stacks (Al_2O_3/SiN_x and thermal SiO_2/SiN_x) are used for emitter passivation, whereas the FSF is passivated by a stack of thermal SiO_2/SiN_x.

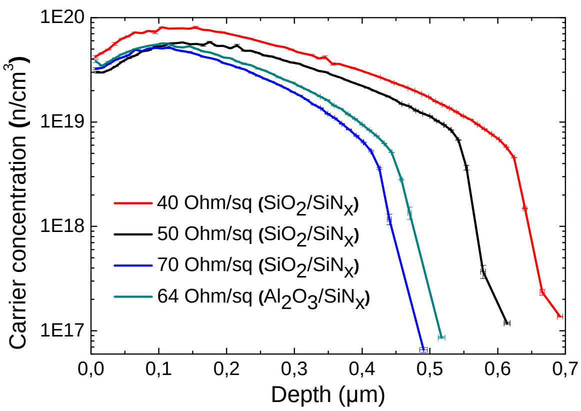

Fig. 2. Doping profiles of the PECVD B emitters measured by an electrochemical capacitance voltage setup.

Contact firing is conducted in an IR belt furnace with SPFT in the wide range from 720-960 C at belt speed of 6 m/min. The solar cells are characterized using an h.a.l.m flasher with an absorbing black rear side to determine the IV characteristics. Non-metalized samples are processed similar to the solar cells to investigate the influence of the SPFT on passivation quality.

Ag/Al spike formation and thereby induced deterioration of the SCR are additionally investigated by SEM. To determine the depth of the Ag/Al spikes, cross-sections of the contact spots were prepared by focused ion beam (FIB).

3. Results

3.1. Solar cell results

The IV characteristics of the bi-facial solar cells are shown in Fig. 3. The short circuit current density (j_{SC}) is nearly independent of the SPFT (see Fig. 3a) except for SPFT below 760°C (due to an inappropriate contact formation leading to high R_C) and above 920°C (due to melting and agglomeration of the paste leading to high R_L).

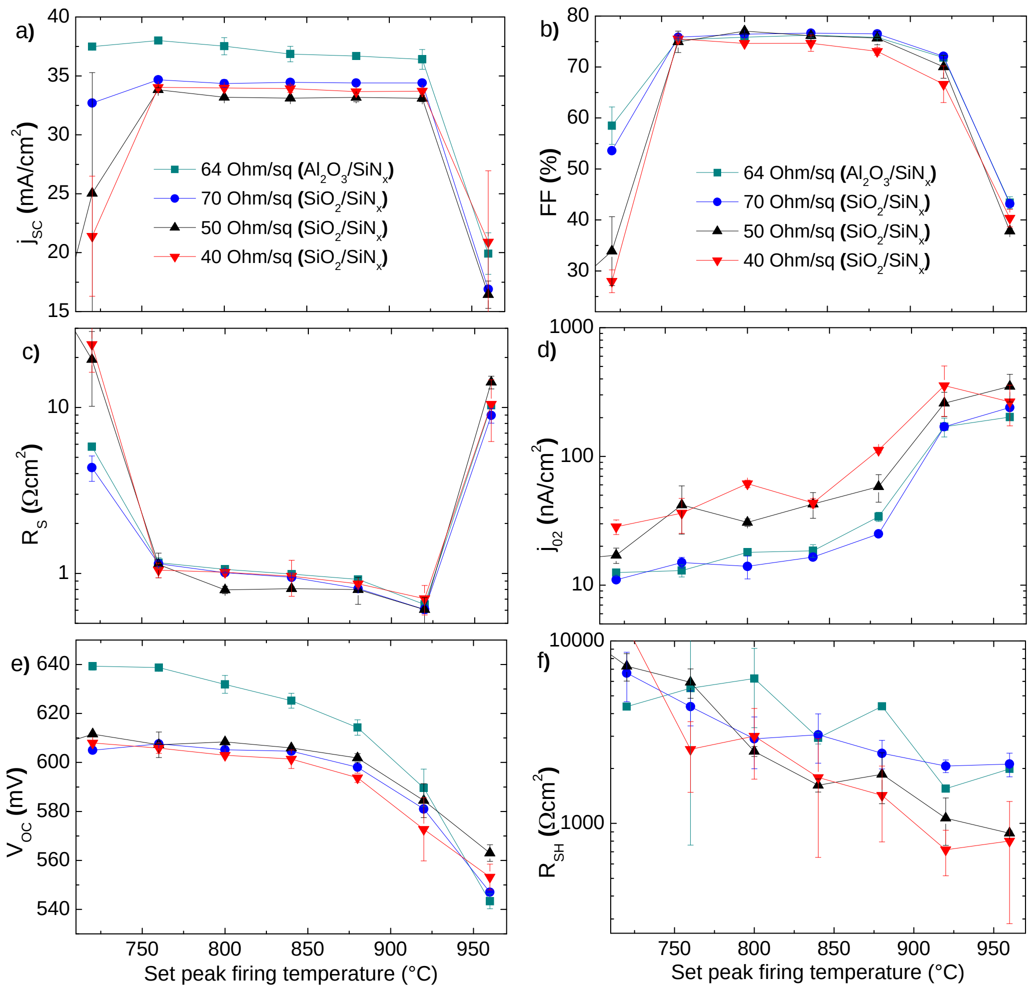

Fig. 3. IV-characteristics of the bi-facial solar cells measured with a h.a.l.m flasher.

The fill factor (FF) is directly linked to R_S. Despite of a decreasing R_S with increasing SPFT due to decreasing R_C, which should lead to an increase in FF, a slight decrease in FF with increasing SPFT can be observed (see Fig. 3b/c).

This can be mainly attributed to an increasing saturation current density of the second diode (j_{02}) as depicted in Fig. 3d, which is generated by Ag/Al spike formation and thereby induced deterioration of the SCR leading to an increased recombination activity in this region. Though the main influence of an increased j_{02} is a reduction of FF, it also leads to open circuit voltage (V_{OC}) losses. Fig. 3e shows that V_{OC} is a monotonously decreasing function with increasing SPFT. Since the shunt resistance (R_{SH}) is above 1 kΩcm^2 for all SPFT (see Fig. 3f), its influence on V_{OC} and FF is of minor importance. The influence of the Ag/Al contacts on the evolution of all IV parameters with increasing SPFT is nearly independent of the dielectric passivation layer stack (compare cyan square and blue circle symbols in Fig. 3).

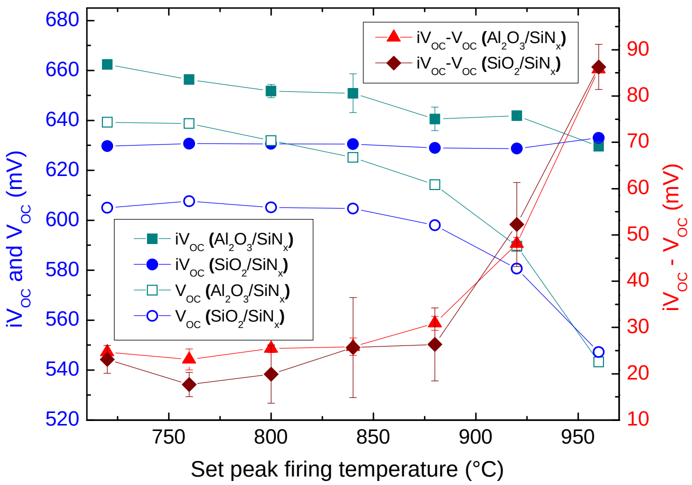

Fig. 4. Evolution of V_{OC} and implied V_{OC} as well as the difference iV_{OC}-V_{OC}, which is attributed to the metal induced losses. The metal induced losses are strongly increasing with increasing set peak firing temperatures and independent of the passivation layer stack.

Fig. 4 shows the evolution of V_{OC} and implied V_{OC} (iV_{OC}) as well as the difference between them which is attributed to the metal induced losses. This assumption can be made since the non-metalized iV_{OC} samples are processed similar to the solar cells. The difference in wafer temperature between iV_{OC} samples and solar cells during firing can be neglected due to the low metallization fraction of the solar cells of around 5% per side.

Al_2O_3/SiN_x passivation layer stacks degrade strongly with increasing SPFT whereas SiO_2/SiN_x passivation stacks are almost stable on a lower level (see iV_{OC} curves, filled cyan square and filled blue circle symbols in Fig. 4). Therefore, V_{OC} of the bi-facial solar cells decreases even stronger for Al_2O_3/SiN_x passivation stacks. Total losses due to metallization are in the same range (20-90 mV) for both passivation layer stacks and follow the same trend (see filled red triangle and filled brown diamond symbols in Fig. 4).

3.2. SEM analysis

In our previous publication, we demonstrated that the area density of the Ag/Al spikes increases strongly with increasing SPFT leading to an increasing contact area with increasing amount and size of the Ag/Al spikes [7]. This coincides with the observed decrease of R_S due to a lowered R_C. It could also be shown that the contact depths are in the range of 1–3 µm for the investigated temperature range of the previous experiment. This led to the assumption that, even for low temperatures, the Ag/Al spikes might be deep enough to short circuit the SCR.

To proof this assumption and to get a deeper understanding of the Ag/Al spike formation and the observed impact on solar cell parameters, a detailed SEM analysis was conducted in this experiment.

The contact fingers were etched back in HF to reveal the silicon surface with the Ag/Al spikes. To determine the depth of the spikes, cross-sections of the contact spots were prepared by FIB. Fig. 5 shows SEM images of the cross sections for different SPFT. The depths of the Ag/Al spikes are marked with red lines. The area density and average depth of the spikes are increasing strongly with increasing SPFT which leads to high j_{02} values resulting in strong reduction of FF and V_{OC} on bi-facial solar cells, as could be shown in the previous section.

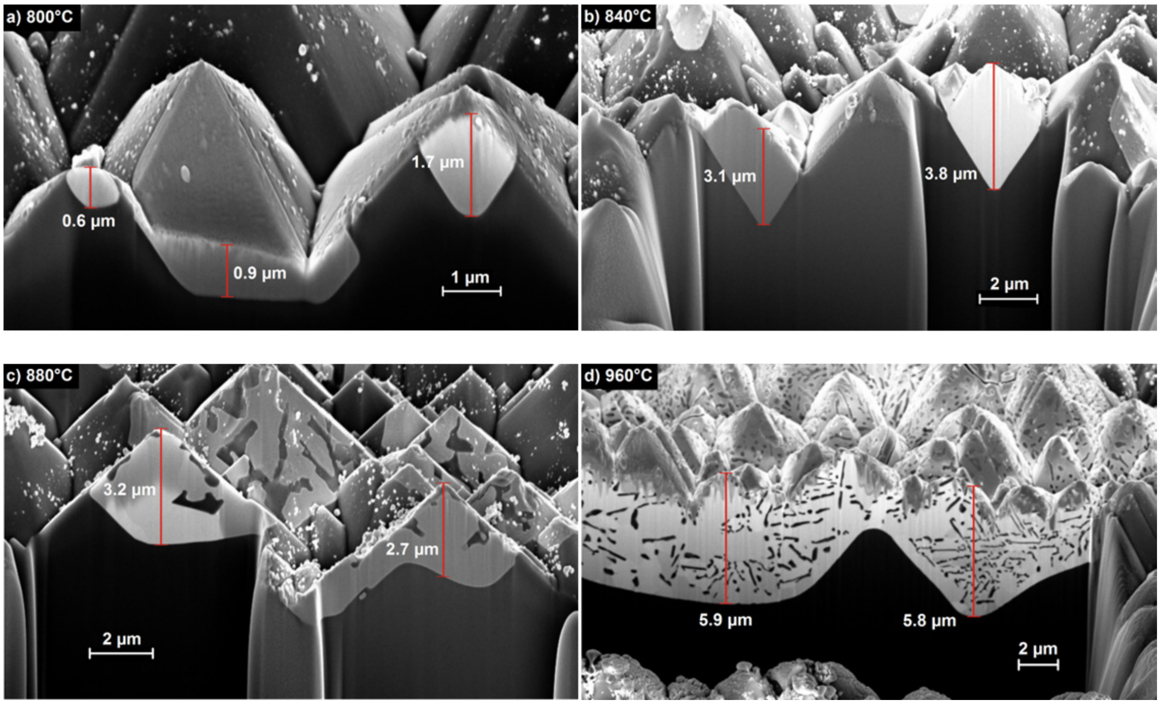

Fig. 5. SEM images of FIB cross sections of the contact spots for different SPFT (given in the upper left corners). The depths of the Ag/Al spikes are marked with red lines. Area density and average depth of the spikes are increasing strongly with increasing SPT.

Fig. 6 depicts a boxplot of the spike depths determined from SEM images of several FIB cross-sections for each SPFT. The mean spike depths as well as the deviation are strongly increasing with increasing SPFT. The spike depths are >600 nm even for the lowest SPFT of 800°C which means that they are already deep enough to short circuit the SCR. Lowering SPFT causes decreasing spike area densities and therewith less metal induced losses. On the other hand, lowering SPFT leads to an increase in R_C.

Therefore, a compromise in the firing conditions between appropriate contact formation in terms of R_C and density of Ag/Al spikes has to be made. Best solar cell results were obtained for SPT of 800°C or lower.

4. Discussion

It was demonstrated that the formation of Ag/Al metal spikes results in detrimental recombination losses on the fabricated n-type bi-facial silicon solar cells leading to strong FF and V_{OC} losses on n-type bi-facial solar cells. This can mainly be attributed to an increased j_{02} contribution which is strongly increasing with increasing SPFT. SEM analysis revealed that this j_{02} increase can be attributed to an increasing area density and depth of the Ag/Al spikes for increasing SPFT. The penetration of the spikes into the silicon of more than 600 nm, even for the lowest SPFT of 800°C, is deep enough to short circuit the emitter. The best solar cell results can be achieved for low SPFT of 800°C or lower.

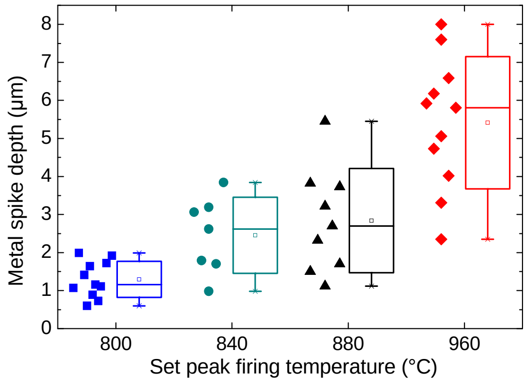

Fig. 6. Depths of the metal spikes determined by SEM images of FIB cross sections of the contact spots.

Engelhardt *et al.* reported that contacting B emitters through the CVD-BSG led to contact resistivities of 1 mΩcm^2 [10]. However, since Fritz *et al*. demonstrated recently that state-of-the-art Al-free Ag SP pastes are capable for contacting of B emitters reaching specific contact resistances ρ_C<1 mΩcm^2 [11], the CVD-BSG was not, as suspected, the cause to support the contact formation. Furthermore, it could be shown that the crystals below Al-free contacts show only a shallow penetration into the silicon surface. However, metal induced losses of 30 mV were also observed for the Al-free Ag SP pastes. This behaviour is not understood yet and under further investigation.

Acknowledgements

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