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Optimization of front metal contact firing scheme to achieve high fill factors on screen printed silicon solar cells

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Abstract

For widespread implementation of silicon PV, the module cost must be reduced by a factor of 2 to 4. A combination of high throughput belt line processing, screen-printed (SP) contacts and mc-Si material offers an opportunity for significant cost reduction. However, most cell manufacturers who use the above combination are only able to achieve fill factors (FF) in the range of 0.68-0.75 with cell efficiencies in the range of 10-14%. In addition, there is considerable scatter in the fill factor of the SP cells in the literature with no clear guidelines for achieving high fill factors. This paper shows that proper understanding of loss mechanisms and optimization of SP paste and firing cycle, can lead to fill factors approaching 0.77 and 0.79 on mc-Si and single crystal silicon, respectively, on a 45 Ω/□ rapidly formed belt line emitter with a shallow junction depth of ~0.25 μm. It was found that, proper combination of paste and firing cycle can produce same high FF value of ~ 0.77 on deep and shallow emitters on mc-Si.

1. Introduction

High fill factors (FF), ≥0.78, can be achieved routinely on screen-printed mono-crystalline silicon solar cells if the following requirements are met: junction depth ≈ 0.5 μm on 40 Ω/□ emitter, $J_{02} \approx 10^{-8}$ A/cm^2, $R_s \leq 0.5$ Ω-cm^2 and $R_{sh} \geq 1$ kΩ-cm^2 [1]. However, inr low-cost mc-Si solar cells, where the emitter is formed rapidly in a belt furnace, junction depth is only ~ 0.25-0.35 μm. This makes the device junction more susceptible to contact induced degradation. In addition, non uniform defect density and paste/defect interaction could further complicate the process, so that even if the 0.5 μm junction depth criterion is met, the FF would still be lower than 0.78. To investigate these issues, a study was conducted on mc-Si, CZ and FZ silicon using both rapid belt line and conventional furnace processing of the emitter in conjunction with screen-printed contacts.

In this paper, we report on the effect of two different Ag pastes and firing cycles on the FF of screen-printed shallow junction solar cells on multi and mono crystalline silicon. These pastes, (A and B, obtained from Ferro Corporation), have the same frit content but different frit composition. In addition, effect of firing cycle for paste B on FF of shallow and deep junction cells is also presented.

2. Cell fabrication

A rapid cell fabrication sequence was developed which involved emitter formation by spin-on, bake, and a 6-min belt line diffusion at 925°C. This resulted in a 40-45 Ω/□ emitter with a junction depth of ~ 0.25 μm and peak concentration of 2.6x10^{19}. After the phosphorus glass removal and DI water rinse, a single layer PECVD SiN antireflection coating was deposited on the front at 300°C. This was followed by screen-printing of Al on the back and a 2 min drive-in at 860°C in the belt furnace to form a very effective Al back surface field. A silver grid was screen printed on top of SiN and then fired through SiN for various times and temperatures to optimize the firing cycle for each paste. Even though 45 Ω/□ emitter with a junction depth of only 0.25 μm reduces the heavy doping effects, it makes the emitter more vulnerable to junction shunting and leakage. Frit composition or impurity in the paste can also degrade junction quality if they can migrate to the junction. That is why a compatible firing cycle needs to be established for each paste. Firing cycles involving a belt speed of 15-30 inch/min in conjunction with low firing temperatures (700-800°C) are referred to as slow firing and belt speeds of 60-75 inch/min with firing temperatures of 750-900°C are referred to as spike firing in this study.

3. Results and Discussion

<u>3.1. The effect of slow and spike firing cycles on FF of shallow junction cells</u>

Since the primary fill factor loss mechanism associated with SP metallization are contact/series resistance (R_s), shunt resistance (R_{sh}), and junction leakage (J_{o2} and n), detailed dark I-V measurements were performed to decouple R_s, R_{sh}, J_{o2} and n values by the measured I-V fit to the double exponential model. Change in fill factor was assessed and explained on the basis of above parameters for various pastes, firing cycle and silicon materials used in this study.

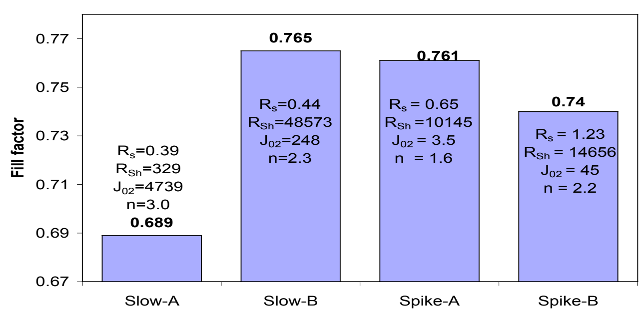

Fig. 1: Effect of paste and firing cycle on fill factor of screen-printed solar cells on mc-Si with 0.25 μm deep emitter.

Figure 1 shows fill factors and the corresponding values of R_s, R_{sh}, J_{o2} and n for the two pastes fired under slow and spike firing conditions. These cells were fabricated on 1 Ω-cm mc-Si from Eurosolare. There are several noteworthy features: slow firing condition gave a very low FF (Fig.1) for paste A primarily due to low R_{sh} and high J_{o2} . This suggests that metal or impurities from this paste are able to get to the depletion region and give rise to generation/recombination centers. On the other hand, the contaminant resistant paste B gave decent fill factor of 0.765 with reasonable R_s and R_{sh} but slightly higher J_{02} with an n factor of 2.3.

Figure 1 shows that a fill factor of ~ 0.76 was also achieved for Euroslare mc-Si cells using paste A when spike firing is used. However spike firing gives higher R_s, 1.23 Ω-cm^2 for paste B and 0.65 Ω-cm^2 for paste A. Thus spike firing arrested the migration of contaminants to the junction but resulted in inadequate etching of Si for good contact. Thus slow firing works well for contaminant resistant paste B while spike firing gives better result for paste A.

3.2. Effect of contact firing temperature on FF of shallow junction cells.

In an effort to achieve even higher fill factor we decided to raise the slow firing temperature gradually from 730 to 770°C using paste B. In this experiment cells were fabricated on Solarex mc-Si, CZ Si from Siemens Solar and a FZ silicon. Figure 2 and shows the result of this study. We observed a slight increase in the fill factor for CZ and mc-Si materials, with the exception of FZ, which remained same, when the firing temperature was raised from 730 to 750°C. This is because R_s decreased below 0.7 Ω-cm^2 and J_{02} improved slightly. It was found that for single crystals, FF value peaked at a firing temperature of 760°C while the peak temperature for mc-Si was 750°C. Dark I-V analysis showed that, beyond the peak temperature, FF begins to degrade due to high J_{02} current. This indicates that mc-Si are somewhat more vulnerable to junction leakage due to the defect/paste interaction.

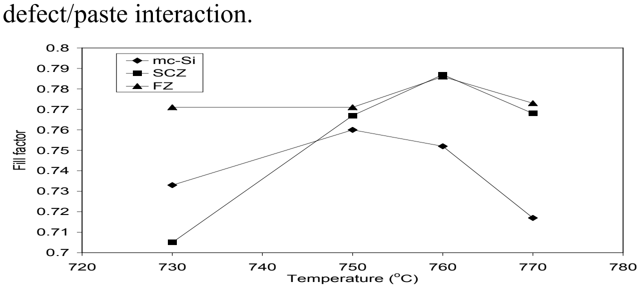

Fig. 2: Effect of temperature cycle and paste B on fill factor.

Figure 2 shows that in this study, the best FF value of ~ 0.77 was achieved on mc-Si cells with efficiency of ~ 15%, while single crystal cells gave a FF of ~ 0.79 with an efficiency of 16.5%. These FF are much higher than what is currently achieved on industrial cells.

3.3 Effect of contact firing temperature on FF of deep junction cells

In order to assess the impact of paste/defect interaction on FF in mc-Si, a conventional furnace was used to form the emitter at 890°C for 20 minutes. This resulted in a 45 Ω/□ emitter with a junction depth of ~ 0.5 μm and peak concentration of 4x10^{19}. After the diffusion, the cells were fabricated by the same process sequence outlined in section 2. Paste B was used and the slow firing temperature was gradually raised from 730°C to 770°C. The idea was that deeper junction may permit higher firing temperature [2], without excessive junction leakage due to paste/defect interaction.

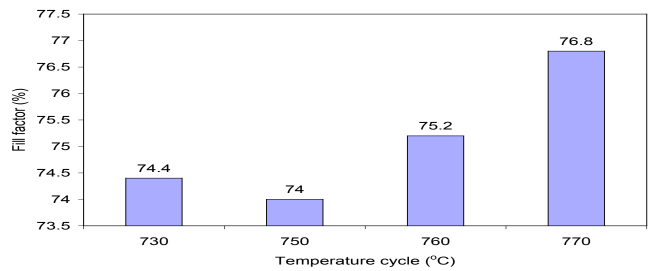

Fig. 3: Effect of contact firing temperature on fill factor of 0.5 μm deep emitters formed by CFP.

Figure 3, shows the results of this study. We observed a slight increase in the fill factor of mc-Si cell when the firing temperature is raised from 730°C to 770°C. Firing time was maintained at 30 seconds. It is interesting to note that the highest FF value was achieved at a firing temperature of 770°C for the deep junction while 750°C was optimum for the shallow junction (Fig. 2). However, in both cases FF of ~ 0.77 was achieved. This suggests that, even for the deep junction, low FF can result from increased junction leakage due to paste/defect interaction at weak spots.

4. Conclusion

The understanding and optimization of SP paste, firing cycle, and loss mechanisms resulted in high FF approaching 0.77 and 0.79 on mc-Si and single crystal silicon, respectively, on a 45 Ω/□ rapidly formed belt line emitter. It was found that, for mc-Si, even the deep emitter of ~0.5 μm does not guarantee high fill factor because of the paste/defect interaction at some weak spots which tend to increase the junction leakage current. However, it was observed that, the deep junction could stand higher temperature firing cycle than the shallow junction. The shallow junction FF peaks at 750°C firing temperature, while the FF peaks at 770°C for deep junction for a firing time of 30 seconds. Even though we have demonstrated high FF for SP cells, further research on frit content and composition and firing cycles is necessary to achieve FF in excess of 0.78 repeatedly on mc-Si.

Reference

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