EFFICIENCY IMPROVEMENT WITH LESS SILVER CONSUMPTION BY DEEPER EMITTER WITH LOWER SHEET RESISTANCE FOR UNIFORM EMITTER

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ABSTRACT

Lower sheet resistance for uniform emitter improved the conversion efficiency by 0.3%$_{abs}$ by doping profile manipulation. It also enables fewer front contact fingers with wider spacing due to the larger lateral conductivity in the emitter, which leads to the reduction of Ag paste consumption. 0.2%$_{abs}$ efficiency gain was achieved for 8% less front Ag paste and 0.1%$_{abs}$ efficiency gain for 11% less front Ag.

1. INTRODUCTION

Phosphorus emitters are known to have a heavily doped n^{++} layer on the surface side and a highly doped n^{+} layer underneath whose border is where the phosphorus concentration (N_P) is ~ 3e19 cm^{-3}, because the phosphorus diffusivity at N_P = 1e19 cm^{-3} is 5~7 times larger than that at N_P = 1e20 cm^{-3} [1]. Our recent works demonstrated manipulation of the emitter doping profile by independent control of those two layers of n^{++} and n^{+} [2] and clarified the role of each layer [3]. In that work, a deeper n^{+} was shown to contribute to higher V_{oc}, and the reduction of inactive phosphorus in the n^{++} layer also resulted in higher V_{oc} while it did not have a negative effect to *FF* as long as N_P is larger than 5e20 cm^{-3} at the depth of 25~50 nm from the surface. The sheet resistance (R_{sheet}) was lowered down to 51~56 Ω/square from the reference 66Ω/square without increasing the processing time or the number of processing steps, resulting in an efficiency gain of 0.3%$_{abs}$.

On the other hand, a reduction of silver consumption for solar cell production is strongly demanded due to the recent steep rise of the silver price [4]. In this study, an emitter with lower R_{sheet} as described above is employed for front contact patterns with fewer fingers to save the amount of silver paste with the expectation that the larger lateral conductivity in the emitter would enable wider finger spacing.

2. EXPERIMENT

An industry-scale $POCl_3$ tube furnace Tempress TS81003, equipped with 400 slots for loading 156×156 mm² wafers in its temperature flat zone was used for diffusion. The doping profiles were characterized with secondary ion mass spectroscopy (SIMS).

In order to investigate the controlled variation of the doping profiles of n^{++} and n^{+}, more than twenty groups of different phosphorus diffusion processes were tested including the reference group with the conventional process currently used by the industry. The total process times of all groups are comparable. A process with the highest average R_{sheet} (7×7 points in a wafer) was selected to optimize the Ag paste process so as to achieve the highest *FF*.

Polished CZ Si wafers out of a single lot were used for characterizing the doping profiles. 156×156 mm² multicrystalline silicon (mc-Si) wafers were used for manufacturing solar cells of which the process is almost identical to industrial production process except in the degree of automation. Except for the phosphorus diffusion process, all other process steps —like texturing; SiN_x deposition; Ag paste; etc.— were identical for all samples and processed in one time to the utmost. Neighboring wafers were equally distributed to each group whose size was 10-12 completed cells. More details are described in [2].

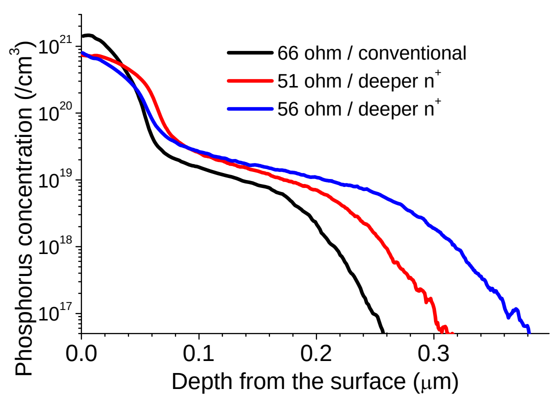

Fig. 1 Phosphorus doping profiles of 51 and 56 Ω/sq. emitters with deeper n^{+} and lower N_P in the n^{++}, and 66 Ω/sq. emitter made of conventional process.

3. RESULTS AND DISCUSSION

Figure 1 shows the representative two doping profiles (51 and 56 Ω/square) with the deeper n^{+} and lower N_P in the n^{++}, with the one from the conventional process (66 Ω/square). As shown in Table I, the emitters with lower R_{sheet} (51 and 56) have 5-7 mV higher V_{oc} than the conventional one and the comparable J_{sc} and *FF*, resulting in efficiency gain of 0.3%$_{abs}$.

In general, lower surface N_P causes higher contact resistance with Ag as the front contact. But phosphorus atoms over 5e20 cm^{-3} are not electrically active [5], and the N_P reduction down till 5e20 cm^{-3} at the depth of 25~50 nm where the penetrated Ag paste contacts with silicon [6] does not increase the contact resistance [3]. Therefore, *FF* does not decrease as shown in Table I. On the other hand, the reduction of inactive phosphorus does not increase R_{sheet} but the deeper n$^+$ which contributes to raising V_{oc} decreases R_{sheet}, resulting in reconciling higher efficiency and lower R_{sheet}.

Table I. Solar cell properties of 156×156 mm² mc-Si solar cells with R_{sheet} = 66 Ω/sq (conventional process), 51, and 56 Ω/sq (deeper n$^+$ and lower N_P in n^{++}), respectively.

R_{sheet} (Ω/sq.)	J_{sc} (mA/cm²)	V_{oc} (mV)	*FF* (%)	efficiency (%)
66.2 ± 1.9	34.4 ± 0.2	612 ± 1	77.6 ± 0.1	16.3 ± 0.1
51.3 ± 2.5	34.5 ± 0.1	617 ± 1	77.9 ± 0.2	16.6 ± 0.1
55.6 ± 1.3	34.6 ± 0.2	619 ± 1	77.6 ± 0.2	16.6 ± 0.1

This concept suggests the possibility for fewer contact fingers with wider spacing, expecting larger J_{sc} by less shadow loss and reduction of Ag paste consumption without losing *FF*.

We tested contact patterns of 54 and 50 fingers, with the conventional pattern of 58 fingers, and weighed the consumed Ag paste on each wafer before and after screen-printing. The average weight of each pattern was 224, 207, and 199 mg for 58, 54, and 50 fingers, respectively. The paste consumption is reduced by 8% for the 54-finger pattern and by 11% for the 50-finger pattern.

156×156 mm² mc-Si solar cells were fabricated using these screen patterns and the two emitter processes targeting 66 and 56 Ω/square profiles shown in Fig. 1. Table II shows the solar cell properties where resulted R_{sheet}'s were 63 and 53 which were a bit lower than each target. As expected, J_{sc} increases and *FF* decreases with the decreasing fingers for 53Ω/square emitter. Similar trend is seen for 63Ω/square emitter, but J_{sc} of 50 fingers is not larger than that of 54 fingers.

Efficiencies of fewer fingers are not higher than those of the conventional (58) fingers for both 63 and 53 Ω/square emitters, but the decreasing trend is weaker for 53 Ω/square one. As a consequence, 54 fingers (8% less Ag) with 53 Ω/square shows 0.2%$_{abs}$ efficiency gain from the conventional one (58 fingers, 63 Ω/square) and 50 fingers (11% less Ag) still shows 0.1%$_{abs}$ gain. This will lead to direct and significant cost reduction in large-scale production.

Table II. Solar cell properties of 156×156 mm² mc-Si solar cells with different R_{sheet} and different number of contact fingers with showing consumed Ag paste weight. The conventional process (63 Ω/square with 58 fingers) is shown at the top row as the reference.

R_{sheet} (Ω/sq)	finger / weight (mg)	J_{sc} (mA/cm²)	V_{oc} (mV)	*FF* (%)	efficiency (%)
63±2	58 / 224±2	34.3±0.1	611±1	77.8±0.1	16.3±0.1
63±2	54 / 207±2	34.5±0.1	611±1	77.1±0.2	16.2±0.1
63±2	50 / 199±2	34.4±0.3	609±2	76.4±0.2	16.0±0.2
53±1	58 / 224±2	34.2±0.1	617±1	78.2±0.1	16.5±0.1
53±1	54 / 207±2	34.4±0.1	616±1	77.6±0.2	16.5±0.1
53±1	50 / 199±2	34.5±0.1	616±1	77.0±0.2	16.4±0.1

4. CONCLUSIONS

Deeper n$^+$ and lower N_P in the n^{++} were shown to be effective to improve the efficiency by 0.3%$_{abs}$ without increasing the total process time or step. This also leads to lower R_{sheet} which enables fewer contact fingers with wider spacing without losing *FF* significantly due to the larger lateral conductivity in the emitter. The cells of fewer fingers with 8% less Ag paste showed 0.2%$_{abs}$ efficiency gain from the conventional fingers and emitter, and that with 11% less Ag still indicated 0.1%$_{abs}$ efficiency gain. These simple modifications without changing the process flow itself clearly demonstrated the possibility of cost reduction in large-scale production.

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