A COMPREHENSIVE STUDY OF THE PERFORMANCE OF SILICON SCREEN-PRINTED SOLAR CELLS FABRICATED WITH BELT FURNACE EMITTERS

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ABSTRACT: In this paper we report on the screen-printed solar cells fabricated on three types of silicon materials; float zone (FZ), HEM multicrystalline and EFG ribbon with $POCl_3$ and belt furnace diffused emitters. The belt furnace diffused emitters involved one- and two-side phosphorus spin-on to assess the contaminating effect of the IR belt. The solar cells with $POCl_3$ emitters and co-firing of screen-printed contacts produced efficiencies of 17.3% on FZ, 16.4% on HEM and 15.5% on EFG ribbon silicon. Solar cells with two-side phosphorus emitters diffused on the belt furnace, produced efficiencies of 17.2%, 16.0%, and 15.1%, respectively, on FZ, HEM and EFG ribbon silicon. However, appreciably lower efficiencies of 15.5%, 15.5%, and 14.1% were obtained, respectively, on FZ, HEM and EFG ribbon silicon for belt-diffused emitters with only one-side phosphorus spin-on with the other side on the belt. This difference in efficiency is reflected in V_{oc} loss for the belt-diffused emitters compared to the $POCl_3$ emitter cells. The IQE measurements supported that solar cells with belt-diffused emitter with two-side phosphorus spin-on and $POCl_3$ emitter cells had comparable J_{sc}. However, the cell with phosphorus spin-on on one-side gave much lower IQE because of poor bulk lifetime or the contamination due to direct contact with the belt. These results indicate that the belt emitters can account for appreciable loss in the performance of the many current commercial cells; however, this loss can be regained by applying phosphorus dopant to both side of the wafer.

Keywords: spin-on, belt-emitter, screen-printed, solar cell, EFG, HEM

1.0 INTRODUCTION

The silicon solar cell performance is controlled by the quality of the p-n junction and its impact on the bulk lifetime during the phosphorus deposition and drive-in. Phosphorus emitters for solar cells can be formed by spray, spin or print deposition of dopant followed by a belt furnace drive-in, or by a liquid source using $POCl_3$ in a conventional tube furnace. Although belt emitters are simple and cost-effective, they can lead to performance degradation due to contamination from the metal belt and junction leakage. In order to quantify the contamination due to direct contact of silicon with the belt during belt-diffusion on solar cell performance we fabricated solar cells using a) belt-diffused emitters with one-side phosphorus spin-on, with the back of the wafer in direct contact with the belt during drive-in b) belt-diffused emitters with two-side phosphorus spin-on, where the back of the wafer is separated from the belt by the phosphorus glass and c) the conventional tube furnace $POCl_3$ emitters where phosphorus is diffused on both sides of the wafer. Also, in each case end lifetime in the finished devices was assessed through photoconductance measurements. This study was performed on three different materials including float zone (FZ) silicon, multicrystalline silicon (mc-Si) grown by the heat exchanger method (HEM) and edge defined film fed growth (EFG) ribbon silicon.

2.0 Experimental

Three types of silicon materials, including six FZ wafers, six HEM mc-Si and six EFG ribbon, were cleaned in 1:1:2 H_2SO_4:H_2O_2:H_2O for 5 minutes, followed by a 3-min rinse in de-ionized (DI) water. This was followed by a clean in 1:1:2 HCl:H_2O_2:H_2O for 5 minutes and a 3-min rinse in DI water. Next the wafers were etched in 15:5:2 HNO_3:CH_3COOH:HCl for 5 minutes followed by a 5-min rinse in DI water. A final dip in 10% HF for 2 minutes was performed, followed by a 30 second rinse in DI water. After the cleaning, the wafers were divided into three groups (A, B, C as depicted in Table 1) of six wafers including two FZ, two HEM and two EFG in each group. The Group A wafers were spun with phosphorus on the front side only and Group B samples had spin-on phosphorus on both sides followed by baking at 200°C for 20 min in an oven, and a 6-minute belt furnace diffusion at 925°C. This resulted in a 40-45 Ω/square emitters with a junction depth of about 0.25 μm and peak concentration of $2.6x10^{19}$ atom/cm^3. The Group C emitters were formed in conventional tube furnace using $POCl_3$ at a set temperature of 877°C, which resulted in a 40-45 Ω/square emitter. After the phosphorus glass removal and DI water rinse, a single layer low frequency PECVD SiN anti-reflection coating was deposited on the front at 400°C. Next, the Al back contact was printed and dried at 200°C. The wafers were separated into groups for the study of lifetime and solar cells. This was followed by front Ag grid printing (for the solar cell samples) and dried at 200°C. Next, the two groups of samples were subjected to the same co-firing cycle in the IR belt furnace. The solar cells were isolated using a dicing saw to define an active area of 4 cm^2 and annealed in forming gas at 400°C for 18 minutes.

After the co-firing step, the Al metal was removed from selected samples for lifetime measurement in an Al-etch solution followed by the silicon nitride etch in hydrofluoric acid. The samples were etched in buffered hydrofluoric acid to remove the n^+ region from the front and the p^+ region from the back. Each sample was placed in the iodine-methanol containing zip-lock bag to perform the lifetime measurements.

Group Number	Emitter type & process
A	Belt-Diffused and one-side phosphorus spin-on
B	Belt-Diffused and two-side phosphorus spin-on
C	Conventional tube furnace using $POCl_3$

Table 1: Summary of experimental design

Table 1 gives a summary of the group numbering according to the emitter type and process. In this paper we will use the group number as well as the emitter type and process interchangeably.

3.0 Results and Discussion

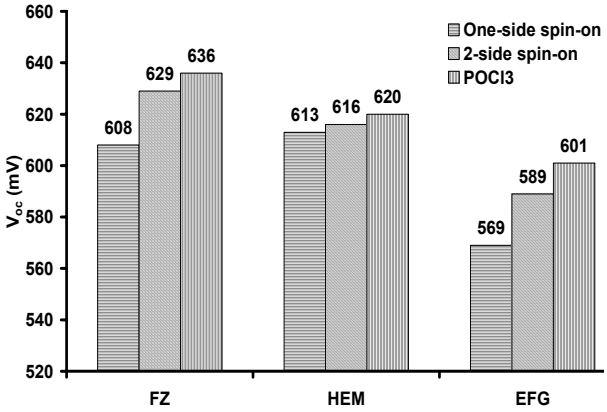

Figure 1: Open circuit voltage as a function of material and type of emitter.

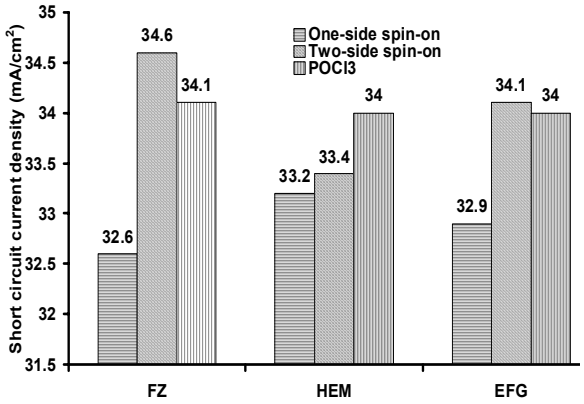

Figure 2: Short circuit current density as a function of material and type of emitter.

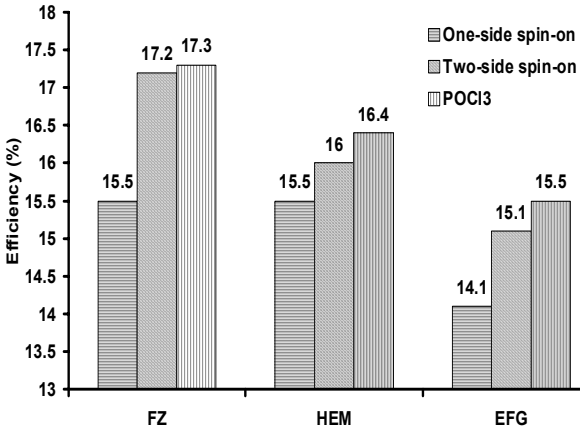

Figure 3: Solar cell efficiency as a function of material and type of emitter.

Figures 1-3 show the open circuit voltage, short circuit current density and the efficiency of the cells as a function of material and the type of emitter. In all three materials, the $POCl_3$ emitter cells (Group C) showed superior open circuit voltage to the belt-diffused emitters with two- (Group B) and one-side (Group A) phosphorus spin-on emitters. In the case of float zone silicon cells, a 7 mV and 28 mV loss in V_{oc} was observed, for the two- and one-sided phosphorus spin-on belt-diffused emitters, respectively, compared to $POCl_3$ diffused emitter cells. The loss in V_{oc} for the HEM multicrystalline cell was only 4 mV for the two-sided phosphorus spin-on and 7 mV for the one-sided phosphorus spin-on emitter cells. However, the EFG material showed the highest loss in V_{oc} of 32 mV for the belt-diffused emitter with one-sided phosphorus spin-on and 12 mV for the two-side phosphorus spin-on emitter, compared to $POCl_3$ diffused emitter.

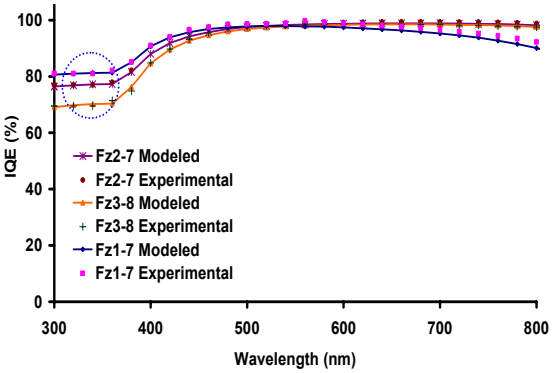

Figure 4: Simulated and experimental short wavelength IQE for FZ cells from Groups A, B, and C.

Figure 4 shows the modeled and experimental blue response for FZ cells with Group A, B, and C emitters. The cell from Group A showed the best blue response followed by Group B and then Group C. The improved blue response for belt-diffused cells may be due to the very shallow junction that normally results from the belt diffusion. Also, since the measured reflectance was used in the PC1D simulation to match the IQEs, differences in the thickness of SiN may be responsible for the observed discrepancies.

From the IQE measurements, we found that the FZ solar cells with belt emitter formed with two-side phosphorus spin-on was slightly superior corresponding to 0.5 mA/cm^2 higher J_{sc}. This is primarily due to better blue response (Figure 4) of the belt emitter cells compared to the $POCl_3$ emitter cell. However, the solar cells with belt-diffused emitters with one-side phosphorus spin-on suffered a severe loss in J_{sc} (1.5 mA/cm^2, 0.8 mA/cm^2 and 1.1 mA/cm^2, respectively for FZ, HEM and EFG) due to poor long wavelength response and the overall lower finished lifetime, as shown in Figure 5. This decrease in J_{sc} was attributed to the contamination due to direct contact with the belt. This was further confirmed by the direct end lifetime measurements shown in Figure 5.

Figure 5 shows the dependence of the end of process lifetime in the device on the type of emitter used. This lifetime was measured on those wafers, which did not have the Ag front grid before co-firing. The $POCl_3$ diffused emitter showed the highest carrier lifetime in all the three materials with FZ Si reaching ~290 µs after cell processing. Belt diffusion with spin-on dopant on one

side reduced the lifetime in the FZ Si to ~16 µs. This is due to impurity contamination from the belt. The lifetime in FZ Si improves to ~198 µs when spin-on dopant was applied to both surfaces, which indicated that the spin-on glass on the back is able to block some impurity contamination from the belt. A similar trend was observed in HEM multicrystalline Si and the EFG ribbon silicon.

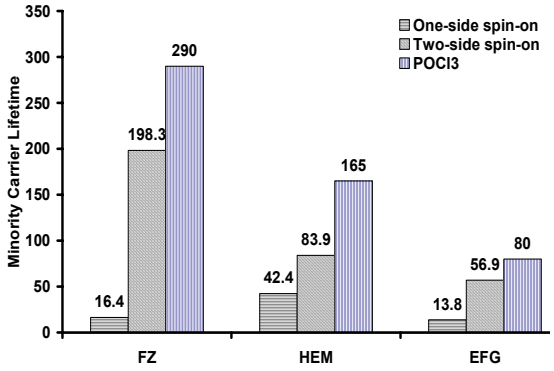

Figure 5: Dependence of minority carrier lifetime as a function of material and emitter type after cell processing.

Table 2 shows the effective diffusion lengths extracted from PC1D simulations of FZ cells from Groups A, B, and C. The back surface recombination velocity (BSRV) value used for the simulation of each cell was the same but the bulk lifetimes were different due to the difference in the short circuit current densities. The smallest effective diffusion length value was obtained for the belt-diffused emitters with one-side phosphorus spin-on. This is due to the belt contamination as a result of direct contact through the back of the cell. Model calculations (matching of the long wavelength IQE above 1100 nm) gave a back surface reflectance (BSR) value of 60% for FZ and HEM, and 70% for the EFG cell.

Cell ID	BSRV (cm/s)	L_{eff} (µm)	Emitter Type
Fz3-8	350	512	$POCl_3$
Fz2-7	350	900	Two-side phosphorus spin-on belt-diffused
Fz1-7	350	105	One-side phosphorus spin-on belt-diffused
H3-8	450	500	$POCl_3$
H2-7	450	325	Two-side phosphorus spin-on belt-diffused
H1-3	450	230	One-side phosphorus spin-on belt-diffused
EFG3-8	220	500	$POCl_3$
EFG2-9	220	600	Two-side phosphorus spin-on belt-diffused
EFG1-3	220	150	One-side phosphorus spin-on belt-diffused

Table 2: Extracted BSRV and the corresponding L_{eff} from IQE measurements and PC1D calculations for the cells from Groups A, B, and C.

Figure 6 shows the long wavelength response of FZ cells from Groups A, B, and C. The long wavelength IQE revealed a similar trend in lifetime as observed in Figure 5 for the witness wafer. Again, $POCl_3$ emitter cells were superior followed by the two-sided phosphorus spin-on cells and one-side phosphorus spin-on cells. These results indicate that the belt contamination is more severe in cells fabricated on FZ material, which had a higher as-grown lifetime than the other materials.

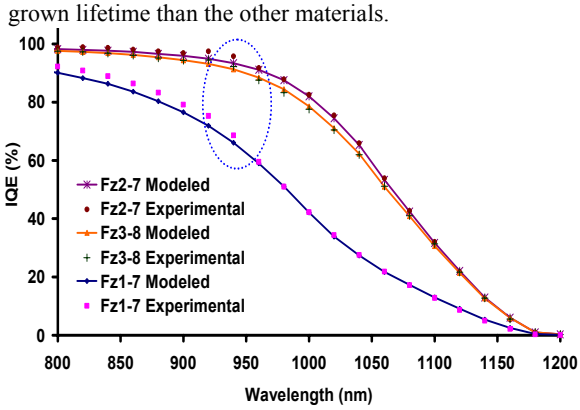

Figure 6: Measured and simulated long wavelength IQE for the three FZ cells with Group A, B, and C emitters.

Although the IQE measurements in the blue region showed a higher short circuit current density for the belt-diffused emitter cells with two-side phosphorus spin-on emitter, the solar cell showed 0.1% and 0.4% higher cell efficiency for FZ and EFG, respectively, in favor of $POCl_3$ emitter. This slight efficiency advantage for Group C cell was due to the higher fill factor (FF) and the open circuit voltage (Figure 1) of $POCl_3$ emitter. This may be due to decreased shunting of the deeper $POCl_3$ diffused emitter. For the HEM material, the efficiency difference between the Group B and Group C cells was reflected in the short circuit current density and the open circuit voltage. The Group A cells had a lower short circuit current density than cells from both Groups B and C due to lower bulk lifetime and open circuit voltage. It is interesting to note that even though the shallow emitter resulting from belt-diffusion favors higher short circuit currents in Group B cells, the high open circuit voltage due to slightly deeper junction from Group C cells and the fill factor tend to balance out, so that the overall performance of cells from the two groups are comparable.

4.0 Conclusions

Screen-printed solar cells were fabricated on three different materials including float zone, HEM multicrystalline and EFG ribbon silicon using belt-diffused and $POCl_3$ emitters. Two types of belt-diffused emitters were formed a) one-side phosphorus spin-on in which the back of the cell was in direct contact with the belt furnace, and b) two-side phosphorus spin-on where the back of the cell was protected by the phosphorus glass during diffusion. These two sets of belt-diffused emitters along with $POCl_3$ emitters were used to assess the impact of belt contamination on the performance of solar cell on these three materials.

Solar cells fabricated with belt-diffused emitter cells with one-side phosphorus spin-on showed 1-2% absolute lower efficiency compared to cells with a $POCl_3$ emitter.

We found that this performance loss can be recovered to a large degree if phosphorus spin-on is applied to both sides of the wafer before belt furnace diffusion. The remaining difference in performance between belts diffused cells with two-side phosphorus emitters and $POCl_3$ diffused cells may be due to lower fill factor and open-circuit voltage resulting from junction shunting because of shallow belt emitter. The short circuit current in the float zone and EFG ribbon cells were slightly higher with two-side phosphorus spin-on than $POCl_3$ emitter cells due to the shallower junction depth of the belt emitter.

Both the lifetime and the IQE measurements indicated significant contamination from the belt. The belt contamination was more pronounced in float zone cells, which had higher as grown lifetimes (greater than 200 μs) than the HEM and EFG ribbon cells. From these results it can be inferred that the poor performance observed in many commercial cells that normally use one-side phosphorus spin-on or spray-on emitters, could be due to the belt contamination. However, our results suggest that the deposition of phosphorus dopant on both sides by spin-on or spray-on can eliminate this loss. The shallow emitter that results from the belt-diffusion produces higher short circuit currents in cells with two-side phosphorus spin-on. However, the deeper junction in $POCl_3$ emitter cells results a higher open circuit voltage and fill factor. This makes the efficiency of cells with emitters formed on both sides in belt furnace very similar to that of cells with $POCl_3$ emitters.

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