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SELECTIVE EMITTER BY LASER DOPING FROM PHOSPHOSILICATE GLASS

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ABSTRACT: In the industrial fabrication of silicon solar cells, lowly doped emitters offer an opportunity to increase cell efficiency by improving blue response as well as lowering the saturation current density of the device. However, conventional approaches of metallization, like screen-printed contacts, combined with shallow emitters result in the problem of firing through the emitter and thus shunting the cell. Employing a highly doped region underneath the front contacts, a selective emitter, can avoid such shunting. Laser doping offers the possibility to tailor a diffusion profile by a simple laser process and create a selective emitter. J_{0E} values of lowly doped emitters are presented and their impact on cell performance is shown. Two solid-state laser systems have been used to fabricate a laser doped selective emitter. Two different kinds of metallization are employed in the solar cell process and compared. The internal quantum efficiency shows an improved response in the short wavelength region. Cell efficiencies of >17.7 % on 50x50 mm² cells with *FF* over 80 % using a shallow 120 Ω/sq emitter and a laser doped selective emitter have been achieved in an industrially feasible process.

Keywords: Laser Processing, Laser Doping, Selective Emitter

1 INTRODUCTION

Current research in crystalline silicon solar cells is focussed on improving the cell efficiency as well as lowering the costs of production, thus reducing the costs per W_P. A conventional crystalline silicon solar cell is metalized by screen printed contacts, which implies certain restrictions to the emitter.

The introduction of lowly doped emitters yields the potential for a higher open circuit voltage, as the recombination in the emitter is reduced. However, industrially fabricated lowly doped emitters are generally shallow (~150-200 nm) and thus pose difficulties in contacting the solar cell with industrially established metallization, such as screen printing. The introduction of a selective emitter [1] can overcome this handicap.

Several approaches to industrially fabricate a selective emitter have been presented up to date [2-4]. Laser doping [5] offers the possibility to selectively vary the doping profile on a substrate. Prior to the laser treatment a doping source is applied to the substrate. A laser locally melts the substrate and diffusion takes place in the liquid phase, which is up to 10 orders of magnitude faster than solid state diffusion [6], thus enabling deep junctions. This allows tailoring of the doping profile to a certain degree by adjusting the laser parameters.

Solar cells with selective emitters have several advantages: they show less recombination in the emitter, feature an improved quantum response at short wavelengths, can yield better contact resistances and are thermally more stable to the contact firing process.

2 IMPROVEMENT OF THE STANDARD PROCESS

2.1 Laser doping of phosphosilicate glass

Figure 1 shows the process flow for a conventional crystalline silicon solar cell. By introducing a single process step after $POCl_3$ furnace diffusion, it is possible to fabricate a selective emitter. The remaining phosphosilicate glass (PSG) on the wafer serves as a dopant source. The laser selectively melts the silicon and locally increases the amount of phosphorus in the emitter as well as drives it deeper into the wafer, thus lowering the emitter sheet resistance underneath the contact fingers.

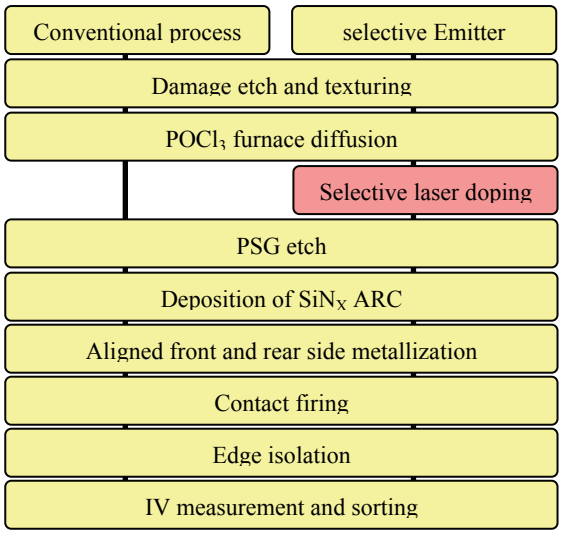

Figure 1: Process scheme for a conventional and selective emitter design solar cell using laser doping. For the formation of the selective emitter, only one additional step is included in the scheme, as highlighted.

2.2 Reducing the emitter saturation current density J_{0E}

In order to estimate the efficiency gain of a selective emitter design, one has to take a careful look at the pn-junction. The goal is to reduce recombination and to improve the quantum efficiency in the short wavelength region in the photoelectric active area, while maintaining a good contact to the metallization by heavily doping underneath the contact fingers.

Three different lowly doped emitters were fabricated in a $POCl_3$ tube furnace aiming at sheet resistances of 120, 160 and 210 Ω/sq respectively. For comparison, a typical industrial emitter with a sheet resistance of 65 Ω/sq was also included in the experiment. 1 Ωcm, p-type, shiny etched FZ wafers were used for this experiment to exclude excessive influence of material quality and texturisation effects. After diffusion, the

samples were submitted to a PSG etch and immediately coated with a PECVD SiN_X anti-reflection coating on both surfaces. After a fast firing step, the effective lifetime of the symmetrical samples was measured by means of quasi-steady-state-photo-conductance decay (QSSPC). This allows determining the emitter saturation current density J_{0E} as proposed by Cuevas [7]. The results are shown in Table I and an upper limit of the attainable open circuit voltage is also included, calculated through

$$V_{OC,\max} = \frac{kT}{q} \ln\left(\frac{J_{SC}}{J_{0E}} + 1\right) \qquad (1)$$

where the recombination in the FZ bulk was neglected. A temperature of 25 °C and a short circuit current density of J_{SC} = 34 mA/cm² were assumed, which is a reasonable value for a planar FZ surface. This process sequence allows the look at J_{0E} values, as they can occur in a typical solar cell structure in the unmetalized areas.

Table I: Emitter saturation current densities and potential open circuit voltages of lowly doped emitters on planar FZ surfaces determined from QSSPC measurements

Emitter [Ω/sq]	65 (ref.)	120	160	210
J_{0E} [fA/cm²]	565	253	195	147
$V_{OC,max}$ [mV]	635	656	662	670

2.3 Effect of the selective emitter

In order to estimate the gain in efficiency by employing a selective emitter, a crude estimation can be made using the 2-diode model. Although much more sophisticated simulations of selective emitter structures can be conceived, a simple calculation model can give an impression of the advantage of the selective emitter compared to a conventional cell design. Three different regions of the solar cell are considered: (i) illuminated, un-metalized emitter region with low doping (i.e. high sheet resistance), (ii) illuminated, unmetalized emitter region with high doping and (iii) metalized emitter region with high doping under no illumination, as indicated in Figure 2. Region (ii) has to be taken into account, as certain alignment tolerances for the metallization are required.

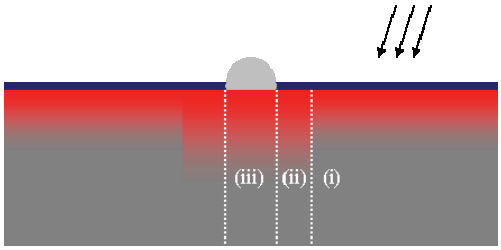

Figure 2: Scheme of a front side for a selective emitter design solar cell.

For each region, J_{0E} and sheet resistance values are taken, area weighted means for J_{0E} and series resistance R_S were calculated and the resulting values are used to calculate the cell performance by the 2-diode model. Values for J_{SC}, J_{0B}, parallel and contact resistances were held constant for the calculations, as the impact of the sheet resistance and J_{0E} on the cell performance is of interest. The finger spacing was chosen to be 1.8 mm, contact fingers were 100 µm in width and the above mentioned region (ii) was held constant at 100 µm. The sheet resistance for the heavily doped region (ii) and (iii) was 25 Ω/sq for all emitters, with exception to the 65 Ω/sq emitter, which was assumed to be homogeneous. J_{SC} values for the 65 Ω/sq cell are taken from reference cells. Table II summarizes the results of this comparison.

Table II: Comparison of the impact of different lowly doped emitters. As a reference, an emitter with a sheet resistance of 65 Ω/sq is also shown.

Emitter [Ω/sq]	65 (ref.)	120	160	210
V_{OC} [mV]	628	635	637	639
J_{SC} [mA/cm²]	33.8	34.3	34.3	34.3
FF [%]	79.0	78.6	78.2	77.7
η [%]	16.8	17.1	17.1	17.0

It can be expected, that the open circuit voltage will be augmented by up to 1.7 % by using a selective emitter structure. The fill factor is expected to decrease by up to 1.6 % due to the increased series resistance induced by the high sheet resistances. However, an overall gain in conversion efficiency of about 0.3 $\%_{abs}$ can be expected.

3 PROCESSING OF SOLAR CELLS

3.1 Experimental setup

For the processing of solar cells, an emitter with a sheet resistance of R_{sheet} = 120 Ω/sq was chosen. As a reference, solar cells with a R_{sheet} = 65 Ω/sq emitter were also processed. For each emitter, an optimized grid was used. Two different laser systems were used to fabricate a laserdoped selective emitter. *Laser I*, a frequency tripled Nd:YVO_4 DPSSL, has a wavelength of λ = 355 nm and a pulse length of approximately τ_{Laser} = 25 ns. *Laser II*, a Yb:YAG disc laser in the spectral ground mode, has λ = 1030 nm and τ_{Laser} = 2 µs, respectively. Two types of metallization were employed, screen printing and aerosol jetting [8]. The latter allows finer contact fingers and thus also a reduction of the highly doped region on the wafer. For this kind of metallization, no 65 Ω/sq reference was included in the experiment.

The cells with a size A = 50x50 mm² were processed on 1 Ωcm, 250 µm thick FZ wafers with a shiny etched surface. The process sequence was identical to that shown in figure 1. However, the batch of wafers that were metalized with Aerosol jetting were submitted to silver light induced plating (Ag-LIP) prior to edge isolation.

3.2 IV results

Tables III and IV display the results of the processed solar cells. With a conventional metallization such as screen printing, summarized in Table III, a strong difference between the two kinds of laser can be observed. The laser doped selective emitter generated with Laser I performs quite satisfactory; an overall gain in efficiency of 0.6$\%_{abs}$ compared to the reference can be

reached. However, solar cells with a laserdoped selective emitter generated with Laser II perform, due to very low fill factors, poorly. As shown below, this low FF is caused by high specific contact resistances. For all cells, the pseudo fill factor (PFF), acquired by means of a $SunsV_{OC}$ measurement, is above 81 %. This indicates that the laser process does not inflict any significant damage. Obviously the disadvantageous distribution of the phosphorus induced by Laser II is hindering a formation of a good semiconductor-metal contact. Hence, only selective emitter cells done with Laser I are considered and discussed.

Table III: Results of the processed solar cells with selective emitter and *screen printing* as metallization. The mean value and standard deviation for the best five cells is given. The best cell was done with Laser I.

	Laser I	Laser II	best cell reference	
V_{OC} [mV]	632.5±0.9	627.2±0.8	633.1	627.1±1.4
J_{SC} [mA/cm²]	34.4±0.2	30.3±2.0	34.8	34.3±0.2
FF [%]	78.7±0.3	36.1±1.7	78.2	76.9±0.8
η [%]	17.1±0.1	6.9±0.7	17.2	16.5±0.2

The advantage of the selective emitter originates predominantly through the rise in V_{OC}. Compared to the reference, the open circuit voltage is about 0.9 % higher for the lowly doped emitter. The increase in the short circuit current density is marginal and in the scale of this experiment not ascertainable. This has two reasons: first, compared to the reference, a larger percentage of the cell is metalized for the selective emitter cell. This is intentioned, as the finger spacing was reduced to maintain a high fill factor for the emitter with higher sheet resistance. Second, the emitter with a sheet resistance of 65 Ω/sq has undergone several optimisations, where as the $POCl_3$ furnace process for the 120 Ω/sq emitter still has the potential for further improvement. This is also visible in the small increase in quantum efficiency compared to the reference, see figure 5.

For the two-staged metallization, aerosol jetting and subsequent Ag-LIP, results look different. Both lasers yield good results, but overall Laser I performs better. An overview is given in Table IV. Note, that no references with sheet resistance of 65 Ω/sq were processed with this kind of metallization, as it does not represent a yet widely employed form of contact formation and is still under development. Due two the fine structures of this tech-nique (seed layers < 40 µm in width), the finger spacing was adjusted and thus high fill factors were the result.

Table IV: Results of the processed solar cells with selective emitter and *Aerosol jetting* + LIP as metallization. The mean value and standard deviation for the best five cells (laser I) and the best three cells (Laser II) is given. The best cell was done with Laser I.

	Laser I	Laser II	best cell
V_{OC} [mV]	633.9±1.0	633.6±0.2	635.1
J_{SC} [mA/cm²]	34.6±0.0	34.3±0.0	34.6
FF [%]	80.9±0.7	79.4±0.6	81.2
η [%]	17.7±0.1	17.2±0.1	17.8

3.3 Enhanced stability in the contact firing step

One of the advantages of the selective emitter is the reduced sensitivity to temperature variations during the contact firing process step. This has been experimentally verified and is shown in Figure 3.

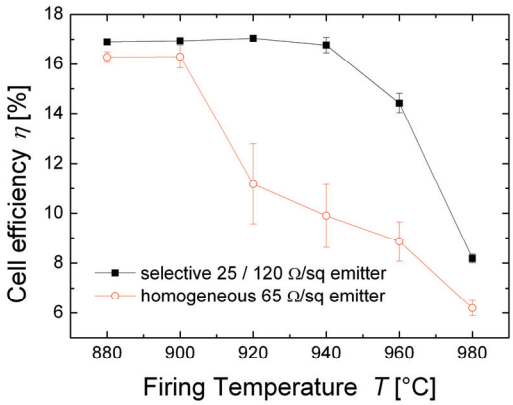

Figure 3: Cell efficiency over firing temperature for the cells with selective emitter done with Laser I and the reference cells for the *screen printed* cells. The cells with selective emitter are less sensitive to the firing temperature variations and exhibit a good stability over a wide temperature range. Each data point represents the mean and the standard deviation of five solar cells.

The solar cells with selective emitter show an improved thermal stability compared to the reference cells. The drop in efficiency at 920 °C for the reference cells and at 960 °C for the selective emitter cells is due to a decrease in the fill factor. The loss in FF has its origin in the worsening of the contact formation, visible in series and specific contact resistance at high firing temperatures.

3.4 Enhanced contact resistance

Figure 4 shows the comparison of the specific contact resistances for the selective emitter solar cells and the reference cells measured by means of the "transfer line modelling" (TLM) [9], for screen printing metallization. Again, cells with selective emitter show a superior performance compared to the reference cells. However, overall values are moderate and the error in measurement is relatively high. This is partly due to the polished surface, as in the absence of the random pyramids the area for contact formation is reduced. Nonetheless, a comparison between the two types of emitters is reasonable, as both types of cells have the same material and surface.

Solar cells processed with screen printing and selective emitter done by Laser II had specific resistances in the range of 0.05 up to 1.1 Ωcm². These high values prevent high fill factors and thus an acceptable cell performance.

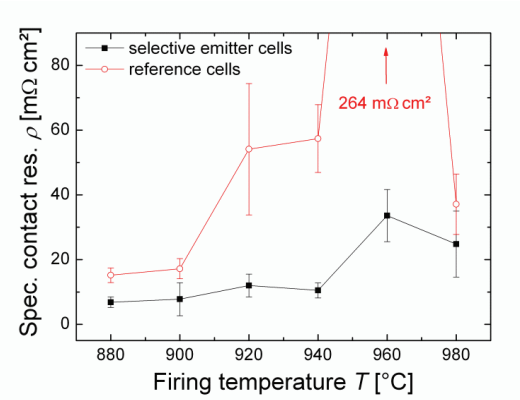

Figure 4: Comparison of the specific contact resistances for the reference and the selective emitter cells, acquired by TLM measurements.

3.5 Improved blue response

In reducing the overall content of phosphorus in the emitter, the quantum efficiency in the short wavelength region, the so-called blue response, is improved. This can lead to a significant gain in short circuit current density. However, this significant gain can not be observed in this experiment. As stated above, the maturity of the 65 Ω/sq. reference emitter is much higher than for the lowly doped emitter with $R_{sheet} = 120$ Ω/sq, leaving only a slight advantage for the latter one. This minimal gain is visible in figure 5. With further optimisation, this advantage is expected to become more significant.

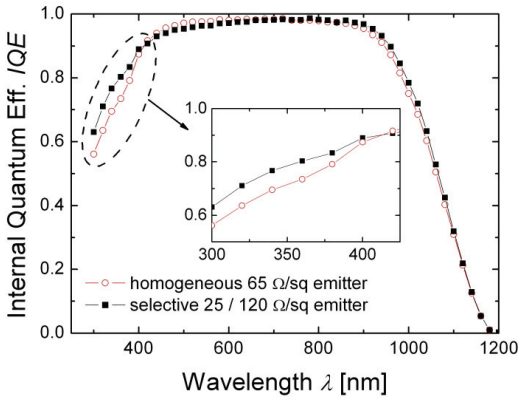

Figure 5: Comparison of the Internal Quantum Efficiency (IQE) for a screen printed reference and a selective emitter cell. Although little, an improvement for the selective emitter in the IQE is visible.

3.6 Comparison to the 2 diode model

The previous shown calculations underestimate the advantage of the selective emitter. This is partly due to the neglected effects of enhanced contact resistivity. This value was not predictable, as solar cell structures are required for TLM measurements and thus a variation in ρ_C was not included in the calculation. However, the increase in V_{OC} was predicted to be 1.0 % and was measured to be 0.8 ± 0.3 %, giving a reasonable agreement.

4 SUMMARY

The implementation of a selective emitter allows the improvement of the cell conversion efficiency by decoupling the requirements of the emitter for light conversion and metallization. Laser doping from phosphosilicate glass after $POCl_3$ diffusion offers the possibility to fabricate a selective emitter in a single additional processing step.

High ohmic emitters feature lower emitter saturation current densities as conventional emitters, thus enabling higher open circuit voltages. Simple calculations employing the 2-diode model show, that an estimated gain up to 0.3 $\%_{abs}$ in efficiency can be expected.

Solar cells with selective emitters have been fabricated and yielded a gain of 0.6 $\%_{abs}$ compared to the reference. Employing a novel metallization technique, conversion efficiencies of almost 18 % are possible on planar solar cells. The improved thermal stability, an improved contact resistance and a better blue response have been experimentally verified as advantages of a selective emitter with screen printed metallization.

5 ACKNOWLEDGEMENTS

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