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STUDY ON LASER PARAMETERS FOR SILICON SOLAR CELLS WITH LCP SELECTIVE EMITTERS

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ABSTRACT: In this paper Laser Chemical Processing (LCP) is used for high local doping of selective emitters. In order to find influencing laser parameters on LCP selective emitters, high-efficiency Si solar cells with size of 2x2 cm^2 cells were processed. The highly doped emitters were processed with different laser powers to see the influence on grooving form and pulse energies. In order to find out if there is a contact resistance problem because of an isolating PSG layer, solar cells with and without PSG etch after the LCP selective emitter formation were compared. Laser induced damage is investigated for low and high pulse energies with TEM. This shows no dislocations for low laser power and small regions of dislocations for high laser power.
Keywords: diffusion, doping, laser processing, selective emitter, Laser Chemical Processing, high efficiency solar cells.

1 Introduction

Recently an intensive research has been done on laser processing as an important application for fabrication of silicon solar cells, as e.g. edge isolation, buried contacts [1] or laser fired contacts (LFC) [2]. It has also been demonstrated that laser doping is a good possibility to produce a selective emitter structure [3], [4]. The contact resistance between the metal fingers and the emitter is reduced with the selective emitter structure [1]. Thus, the efficiency of the solar cell is increased. Since the increasing of sheet resistance of the emitter makes it difficult to contact via screen printing because of the low doping concentration in comparison to a standard 40 Ω/sq emitter, other contacting methods have to be considered. For a standard laser system a phosphorus containing layer is deposited on the wafer and due to strongly increased temperatures by the local laser heating, the phosphorus diffuses into the molten silicon.

Within our group intensive investigations on laser doping with Laser Chemical Processing (LCP) [5], [6] have been done. LCP is based on the liquid-jet guided laser (called LaserMicroJet/LMJ®), patented and commercialized by the company Synova® S.A., Switzerland. Since 2002, Fraunhofer ISE and Synova® cooperate in the development of this new process and its applications. This method combines a laser with a liquid doping source which acts as a liquid laser guide. No photolithography or second high temperature diffusion are required in this mask-free process. There is no need for deposition of the phosphorus containing layers and for the removal of this layers after the process. Selective emitter formation with Laser Chemical Processing is a very simple and elegant method solving this problem.

In this paper the influence of laser fluence on the doping process and on the cell performances is presented. Solar cells are characterized with IV-measurements, TLM measurements for contact resistance and TEM measurements for laser induced damage.

2 Experiments

2.1 Sample preparation

High-efficiency laboratory scale (2x2 cm^2) solar cells were processed on 4 inch FZ(B) wafers with 0.5 Ω cm base resistivity and random pyramids texture. LCP process was applied for formation of the selective emitters structure. For this we used an ISE standard process sequence with thermal oxide (105 nm) passivation and performed the LCP step right after the 120 Ω/sq emitter diffusion and oxidation. Directly after the selective emitter formation, a PSG etch (HF-solution) was carried out on selected wafers to remove a possibly existing isolating layer generated during the laser diffusion process at high temperatures. Then a 2 µm thick aluminium layer was deposited. After a photolithography step for structuring of the front side metal fingers, TiPdAg layers were evaporated as a seed layer on the selective emitter locations. Before the Ag light induced plating (LIP) [7] was performed to thicken the front contacts, the rear side was contacted with LFC.

The laser grooves with selective emitter were produced using a 532 nm laser from Spectra Physics. The laser fluences were varied in the range of 0,2 – 3 J/cm². This fluence is measured in the phosphoric acid jet which means, that this is the real power reaching the solar cell surface. The experiment was performed for two different water jet nozzles having diameters of 60 µm and 80 µm resulting in effective jet diameters of 50 µm and 66 µm. To investigate also if it is possible to achieve the same results with other laser repetition rates but leaving the pulse overlap constant by adapting the driving speed of the axis, for the 60 µm nozzle 35 kHz and 40 mm/s or respectively 80 kHz and 90 mm/s was used. And for the 80 µm nozzle 35 kHz and 50 mm/s was used.

2.2 Results

In figure 1 the solar cell results as a function of the applied laser paramenetrs are presented. On top the cell efficiency η followed by the fill factor *FF* and at the bottom the open circuit voltage *Voc* and the short circuit current *Jsc* are plotted versus average fluence of the laser. All results of varying repetition rate and nozzle diameter are plotted in the same graph and follow the same general trends, which show that the fluence is a dominant parameter in this process. Highest values of η, *Voc* and *FF* are delivered for the lowest fluences of the laser. They nearly stay at the same level with increasing fluence until a sharp drop in performance in the range of 0,9 – 1,3 J/cm². This sharp drop is not observed with *Jsc*. For all curves shown in this graph high values are obtained with a slight decrease of *Jsc* with fluence. This may due to the fact that at higher fluences the groove width is slightly enlarged. This causes an increasing region next to the metallization finger which has no passivation and anti-reflection layer. Below will be shown (figure 5) in this paper that the series resistance *Rs* has no high influence on the cell performance. So *Jsc* is not affected negatively by *Rs*. This is also confirmed by the comparison of *FF* and *pseudoFF* of the cells. The *pseudoFF*, measured using the Suns-Voc measurement method [8], shows the same sharp drop at the same fluence range This shows that *Rs* is not a dominant source of performance decrease.

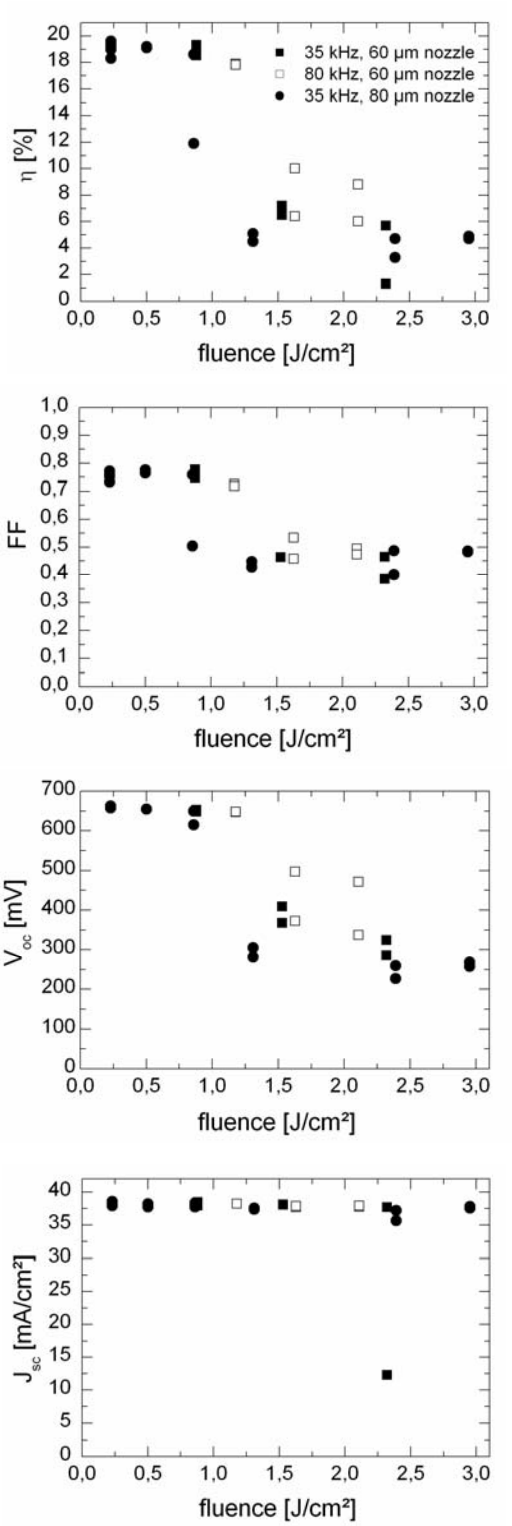

Figure 1: Efficiency, FF, Voc and Jsc results for solar cells with LCP and evaporated contacts plotted versus laser fluence (before additional annealing step).

The decrease of *Voc* can be related to recombination in the base, emitter or space charge region. And the *FF* can be affected by recombination in the space charge region or high *Rs*. Since it will be shown below, that *Rs* has not an important role in this case, it seems that the recombination current density J_{02} in the space charge region is mainly affected by the laser fluence.

One possible reason for this could be the evaporation of silicon which starts at even lower fluences than 0,9 J/cm² in the case of the used laser system and the beam profile. The real beam profile used in this experiment was not homogeneous. It has local maxima and minima which are significantly higher/lower than the average measured intensity. The evaporation of silicon and hence the resulting recoil pressure increases with fluence. It is possible that in the lower fluence region the ejection and removal of molten silicon takes place only at the first few hundreds of nanometers of the solar cell surface within the pn-junction (the depth of the applied emitter diffusion profile is 1,5 µm) and the recoil pressure is not strong enough to induce much laser damage which would influence the cell performance. So the space charge region is not negatively affected by the laser process. In contrast to that the melting depth becomes deeper for higher laser fluences and the ablation depth of silicon could be in the range of emitter depth or even more. Also caused by the increasing recoil pressure more damage could be induced into the silicon. If the laser induced damage is limited to the space charge region, it is shielded by the emitter on the front side. Does the damage exceeds the pn-junction depth and is also deeper than the doping depth of the selective emitter it is not shielded anymore and causes shunting (figure 2).

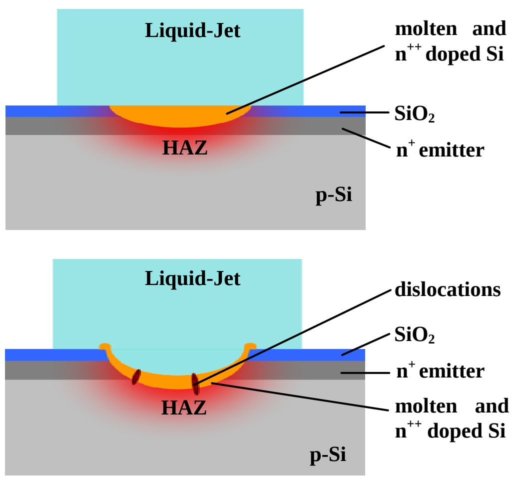

Figure 2: LCP doping for low fluence (upper picture) and high fluence (lower picture). HAZ: Heat affected zone.

Since simulation of melting depth and evaporation depth is a very complex system it is not possible to confirm this theory with exact simulation results.

One evidence for the damage theory are TEM pictures which were taken from cells with low (0,2 J/cm²) and high fluence (2,4 J/cm²). Figure 3a depicts a TEM measurement of a solar cell produced with 0,2 J/cm². Only the top of the pyramid was molten. Part of the passivation layer can still be seen on the pyramid surface. The picture shows no dislocations which would be an evidence for laser induced damage.

Figure 3b shows a TEM picture of a solar cell produced with 2,4 J/cm². The pyramid structure disappeared completely. Local dislocations can be found which indicate laser induced damage for high fluences. The picture is only a small section of the whole laser groove. These kinds of dislocations are found at 2-3 places distributed over the whole widths of the laser groove (approx. 80 µm for the 80 µm nozzle at high laser powers).

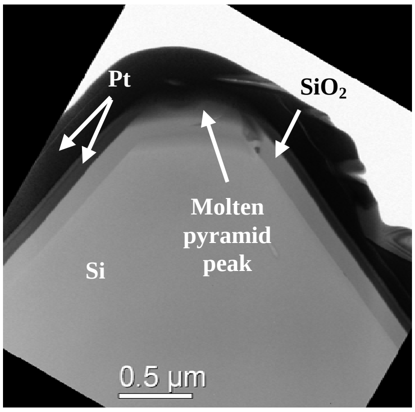

Figure 3a: Pyramid with molten and doped peak showing no dislocation into the silicon crystal for low laser fluence: 0,2 J/cm².

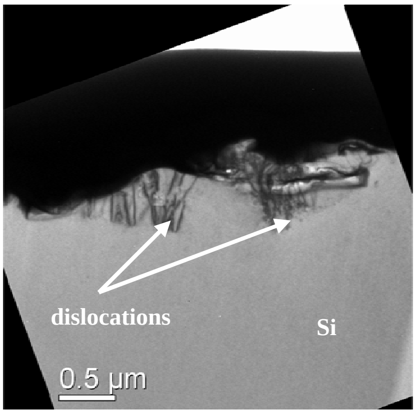

Figure 3b: Doped laser groove with molten surface showing local dislocations into the silicon crystal for high laser fluence: 2,4 J/cm².

The best performing cells were further improved by an additional annealing step. The final cell results for 60 and 80 µm nozzles are listed in table 1. For approximately the same fluence the 60 µm nozzle has higher *Voc*, *Jsc* and *FF* in comparison to the 80 µm nozzle. An explanation for this is the decreasing line width for smaller nozzles, which can result in less shading and removal of passivation layer and therefore lead to a decrease of losses.

Figure 4 compares IQE curves of solar cells with LCP parameters 0,2 J/cm² and 2,4 J/cm². For the cell with

Nozzle diameter [µm]	Fluence [J/cm²]	Voc [mV]	Jsc [mA/cm²]	FF	η [%]
60	0,88	654,4	38,19	0,783	19,6
80	0,86	650,5	37,73	0,771	18,9
80	0,23	664,4	38,51	0,78	**20,0**

Table 1: Comparison of solar cell results for 60 and 80 µm nozzles at constant laser fluence and best cell result of batch.

higher laser fluence a drop at the lower wavelength region is found. Shorter wavelength light is absorbed very close to the front side of the solar cell because of its high absorption coefficient in silicon and therefore its low penetration depth. This drop in IQE indicates that only a problem at the surface of the cell occurred and the bulk remains unaffected. Such a drop can be caused by laser induced damage which generates recombination. Especially green laser light is absorbed within the first µm of the silicon crystal and for high fluences more damage could be induced, which is an explanation for the drop only at high fluences. This is confirmed also by the TEM picture of figure 3b which shows a damage depth of around 0,5 – 1 µm.

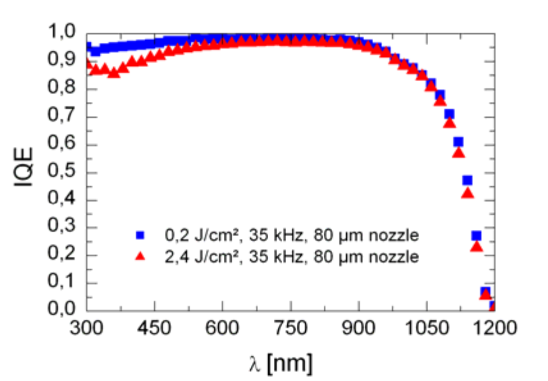

Figure 4: IQE measurement of solar cell with low (0,2 J/cm²) and high (2,4 J/cm²) laser fluence.

Additional to TEM, electrical and IQE characterization, the specific contact resistance ρ_c of the cells were measured with the Transfer Length Measurement (TLM). For this purpose a 3 mm long silicon strip was cut out of the solar cell and the contact resistance was measured directly on the contact fingers. Results are shown in figure 5. A minimum of contact resistance at approximately 0,5 J/cm² is found with increasing specific contact resistances at higher and lower fluences. One have to note that evaporated contacts are optimized to create a good contact between silicon and metallization finger. This means for low fluences where the pyramid structure is still visible and only the peak is slightly molten that also doping exists only on top. Actually it could be possible that only the passivation layer was opened without significant doping for low fluences. However this would also end up in low contact resistances because for high efficiency cell structures with evaporated seed layers a selective emitter is not necessary. On the other hand this cell structure is very sensitive to disturbances of the pn-junction which can be induced e.g. by laser processing. The increase in contact resistance for higher fluences could be caused by the fact that melt dynamic of recoil pressure or liquid jet becomes more important. This could lead to not optimal dopant distribution into the silicon because of convection caused by ejection of molten silicon by recoil pressure of evaporation on the one hand. On the other hand slight removal of doped silicon melt out of the contact region by the liquid jet momentum could take place. So the contact resistance would be increasing. Since melt and doping dynamics of the LCP process are not yet fully understood, the explanations given above have to be investigated further.

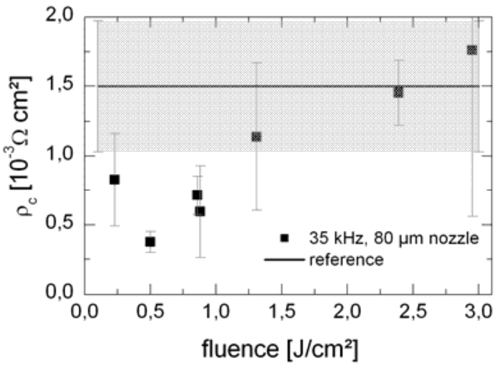

Figure 5: Contact resistance for different laser fluences and reference cell without LCP (grey area: error of reference line).

2.3 Phosphor Silicate Glass (PSG) etch

One question concerning selective emitter formation with LCP has not been answered satisfactorily yet. Is an isolating PSG layer being formed during the LCP doping process and how does it affect the cell performance? For this reason a few solar cells processed with same laser parameters as presented above received a PSG etch directly after LCP step. Since PSG etch also reduces the thickness of the thermal oxide layer on the front side, the electrical parameters will not be compared here, because it is obvious that *Jsc* and *Voc* will drop down.

Fluence [J/cm²]	ρ_c no PSG etch [10^{-3} Ω cm²]	ρ_c with PSG etch [10^{-3} Ω cm²]
0,23	0,83 ± 0,34	1,12 ± 0,33
0,5	0,37 ± 0,08	0,75 ± 0,14
0,86	0,71 ± 0,14	0,19 ± 1
Reference	1,50 ± 0,47	-

Table 2: Comparison of specific contact resistances of solar cells with and without PSG etch.

Only the measured specific contact resistances are compared in table 2. Except for 0,86 J/cm² the resistances of cells with PSG etch are higher than those without PSG etch. If an isolating layer is created during the LCP process on the surface of the molten and solidified silicon one would expect that the contact resistance will be improved by removing this layer. The results do not show a clear tendency. Since good solar cell results and contact resistances can also be obtained without PSG etch, it is concluded that this is not a necessary process step.

3 SUMMARY

In this paper it is shown that laser fluence applied in the LCP process is a dominant factor influencing solar cell performance. The same trends are found for the 60 µm and 80 µm nozzle diameters and also for pulse repetition rates of 35 and 80 kHz. Best results were obtained for lowest fluence reaching 20,0 % efficiency with evaporated seed layer and plated contacts. A sharp decrease in cell performance is observed between fluences of 0,9 – 1,3 J/cm² which could be related to the evaporation of silicon, which becomes more important and more influencing in this fluence range. A possible explanation of the decrease for the device performance at the higher pulse energies could be that the laser induced damage is deeper than the depth of the applied emitter or the selective emitter (depending on which of them is deeper). This increases the recombination current density in the space charge region. This is confirmed by TEM measurements.

Contact resistance is found to be in the range of good contact formation for all investigated laser fluences. A slight tendency of increasing resistances with fluence is observed with a minimum at approximately 0,5 J/cm² for a 80 µm nozzle. The results of PSG etch show no improvement of contact resistivity. This fact and the good solar cell results obtained lead to the conclusion that no PSG etch is necessary for a good contact formation.

This paper shows already a trend of the LCP laser parameters concerning fluence going down to low laser powers. However the doping process itself is not yet fully understood. Important parameters like dopant concentration, pulse overlap and pulse length have to be investigated in detail further to find out there influence on selective emitter structure and there limitations on the doping process.

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