BEAM SHAPING – THE KEY TO HIGH THROUGHPUT SELECTIVE EMITTER LASER PROCESSING WITH A SINGLE LASER SYSTEM

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ABSTRACT

The fabrication of selective emitters by laser processing has attracted the interest of researchers in recent years. However, narrow foci of Gaussian laser beams limit the throughput and feature an inhomogeneous intensity distribution on the wafer. The use of beam shaping can eliminate this setback. A single laser system delivering < 70 Watt to the wafer is already sufficient to achieve short processing times per wafer. The feasibility of a laser system for a selective laser doping process from PSG is investigated and the potential of eligible beam shaping is assessed. Adequate sheet resistances with a good homogeneity and process stability can be achieved, with minor impact to random pyramid surfaces and no measureable degradation of the material. A diffractive optical element splitting one laser into 10 spots of equal intensity is evaluated and fast processing times are achieved.

INTRODUCTION

Selective emitters offer the possibility to increase solar cell efficiency by suppressing losses on the front side of the solar cell due to high recombination and poor blue response. The industrial implementation of high throughput processing for selective emitter solar cells has been subject to research in recent years [1, 2]. Laser doping from phosphosilicate glass (PSG) [3] offers the possibility to create a selective emitter in a simple process. An increase in efficiency of about 0.5 $\%_{abs.}$ using this approach has been demonstrated on solar cell level using industrial production technology [4, 5]. The inclusion of this process in a PERC structure resulted in efficiencies approaching 19% on large area Cz material using pilot line processing [6].

Gaussian Beams – the bottleneck

Laser beams usually exhibit a spatial Gaussian intensity beam profile, which leads to an inhomogeneous intensity distribution on the substrate and low processing speed for large area. A 156x156 mm² wafer with 70 fingers and 3 bus bars requires, with the inclusion of tolerances for subsequent metallization, approximately 3000 mm² of high doping. Considering a Gaussian beam with a beam waist of 2ω = 40 µm and a repetition rate of 100 kHz, for a 50 % pulse overlap (i.e. pulse distance = beam radius ω), a processing speed of 2 m/s is possible. This leads to a processing time of > 1 min/wafer, an unacceptable high time for industrial fabrication.

Beam shaping – overcoming the limitation

Carlsson *et al*. have demonstrated selective and large area processing using a cylindrical optics to form a linear beam [7], however, scanning only one finger at a time. Thus, the simultaneous processing of several, if not all, fingers is desirable, with each laser spot featuring a top hat profile for a homogeneous intensity distribution.

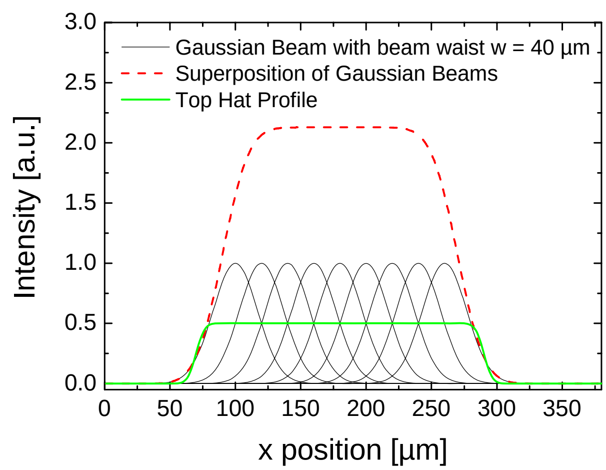

Figure 1: Comparison between nine Gaussian beams and a Top-Hat profile in one dimension; both are illuminating a 200 µm wide spot.

Figure 1 pictures the comparison between scanning a 200 µm wide area with multiple Gaussian beams one after another (beam waist (FWHM) of 40 µm) and a Top-Hat profile. The dashed line represents the superposition of the nine Gaussian beams if they were directed to the wafer at the same time. Assuming that the required intensity for the desired process is 0.5 arbitrary intensity units, both, the 9 Gaussian beams and the Top-Hat profile, dope a line of 200 µm in width. This implies that for the Gaussian beams, each spot on the wafer is illuminated two times (50% overlap as described above) by laser irradiation. Considering only one dimension, integrating according to eq. (1)

$$P = \int_0^\infty I \, dx \quad (1)$$

the required intensity over x, and taking into account that each spot on the wafer is illuminated twice, this would give 383 arbitrary power units for the 9 Gaussian beams and 220 arbitrary power units for the Top-Hat profile. This means, by avoiding the losses in the Gaussian beams above the process intensity, only 57% of the laser power using beam shaping is required for a comparable throughput.

Table I summarizes the advantages of beam shaping by using a single shaped beam and multiple shaped beams compared to a single Gaussian beam. This assessment yields that < 70 W of laser power is sufficient to achieve short processing times for selective doping. This laser power can be supplied by commercially available solid state lasers. Only using a single laser system warrants a low investment cost and cost of ownership for a selective laser doping processing tool.

	Single Gaussian Beam (2ω=40 µm)	**Single Shaped Beam (15x200 µm)**	**Multiple shaped beams (70 beams of 15x200 µm)**
Spot:	Round	Top Hat	Top Hat
Overlap x	50%	N/A	N/A
Overlap y	50%	50%	50%
Scans for single finger	9	1	1
Scans for entire finger structure	9x70 = 630	70	1
Scanning speed at *f*=10 kHz: processing time	0.2 m/s: 500 seconds	0.15 m/s: 80 seconds	0.15 m/s: 1 second
At *f*=100 kHz	2 m/s: 50 seconds	1.5 m/s: 8 seconds	N/A
Required laser power for 3 J/cm²	6.7 W (for 100 kHz)	9 W (for 100 kHz)	63 W (for 10 kHz)

Table I: Comparison of a sigle Gaussian beam, a single shaped beam and multiple shaped beams to achieve short processing times of a 156x156 mm² wafer. An assumed fluence of 3 J/cm² is required for the process.

EXPERIMENTAL

In order to determine the influence of the linearly focussed beam, experiments were conducted to examine the evolution of the sheet resistance, the change in surface morphology and a possible impact on the quality of the silicon due to laser processing. Further, a diffractive optical element (DOE) was fabricated to test a beam splitting into 10 laser spots, each with a homogeneous Top-Hat intensity distribution.

A frequency doubled JenLas® ASAMA laser at 515 nm, *f*=10 kHz and a pulse width of 300 ns was used for the investigation. By using a variable optical attenuator, the pulse energy can be controlled precisely, independent of all other beam parameters.

Sheet resistance, reflectivity and lifetime samples

Two kinds of samples were processed, as depicted in Figure 2:

To determine the evolution and the homogeneity of the sheet resistance, laser doping was performed on 1 Ωcm p-type Cz Si with a alkaline textured surface leading to a random pyramid structure. The remaining PSG following a shallow $POCl_3$ tube furnace diffusion (~ 100 Ω/sq) was used as a dopant source and 20x20 mm² test homogeneously doped structures were fabricated, allowing a simple characterisation. Subsequently, the PSG was etched off and the sheet resistance R_{sheet} was measured on nine spots for homogeneity by a four point probe. Further, the weighted reflectivity R_W was measured. To determine a possible degradation of the material due to laser processing, high quality, p-type, shiny etched 1 Ωcm bulk FZ samples were irradiated with the corresponding fluencies required for doping on large area (40x40 mm²) on both surfaces of the wafer to obtain symmetrical samples. The surface of the samples was cleaned by a wet chemical HNO_3/HF step and passivated by a PECVD Silicon-Oxynitride stack [8]. The effective lifetime of the samples was acquired by means of quasi-steady-state photo conductance (QSSPC).

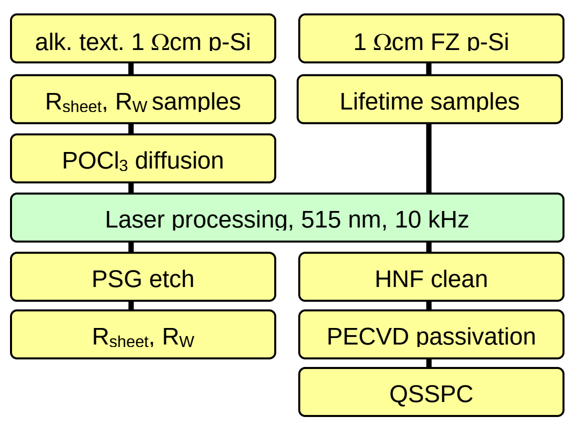

Figure 2: Processing scheme for the determination of the sheet resistance, the change in surface morphology and the lifetime of the processed samples

Diffractive optical element

The optical system consists of a JenLas® ASAMA laser, a variable optical attenuator, a beam expanding telescope, the diffractive beam splitter and an objective. The diffractive beam splitter has been specially designed for the application of selective laser doping. It creates 10 spots, each with a resulting size of 190x70 µm² (FWHM). These spots have a top-hat intensity profile in the long dimension and a Gaussian distribution in the short dimension. The 10 spots are arranged with a distance of 2.2 mm to each other in order to process 10 contact fingers in a single sweep. With this beam splitter, a cell front side pattern of 70 doped regions was processed.

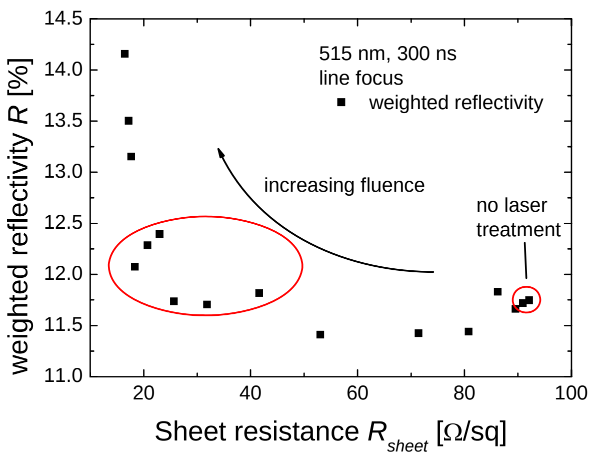

Figure 3: Weighted reflectivity R_W over the measured sheet resistance R_{sheet}. At sheet resistances between 20 and 40 Ω/sq (encircled region), only a minor increase in reflectivity can be ascertained.

RESULTS

Sheet resistance and reflectivity

By setting the laser fluence Φ, it is possible to adjust the sheet resistance between 20 and 40 Ω/sq with homogeneity well below 1 Ω/sq on random pyramid textured surface. The higher the fluence is chosen, the lower the sheet resistance can be set, as more phosphorus is driven into the substrate. At around 20 Ω/sq, all available phosphorus is driven into the substrate; a further increase in Φ leads to deeper melting thus redistributing the phosphorus and resulting a shallow drop of the sheet resistance. Figure 3 displays the minor impact of the laser process on the random pyramid surface: even at sheet resistances around 20 Ω/sq, the increase in weighted reflectivity is small. This is confirmed by scanning electron microscopy, as can be seen in Figure 4. The random pyramids are slightly deformed; however the general shape of the pyramids is preserved. This can beneficial, as reflection losses in areas of illuminated highly doping are avoided. These areas usually are required as some tolerance for a subsequent metallization is mandatory.

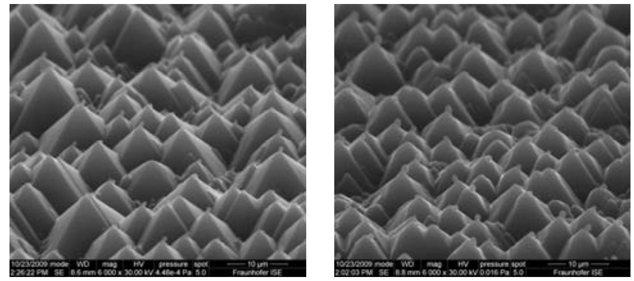

Figure 4: Scanning electron microscope pictures of laser processed samples. Although a slight change of the surface can be seen, the general shape of the pyramids is preserved. Left: random pyramid surface irradiated with 2.0 J/cm²: 41 Ω/sq at R_W = 11.8%; Right: irradiated with 3.5 J/cm²: 18 Ω/sq at R_W = 13.2%

Impact on quality of material

Figure 5 depicts that even at very high fluencies, well above the required fluencies for doping, no degradation of the material can be measured. The difference of the curves is due to a small inhomogeneity across the wafer of the PECVD deposition. This means that after melting the surface recrystallizes without defects, which lower the performance of the silicon device.

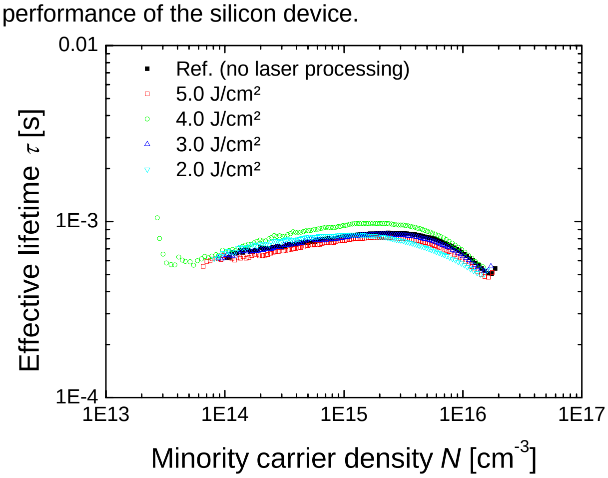

Figure 5: QSSPC measurements of laser processed and passivated bulk FZ. The filled square samples are the area without laser processing, the open symbols represent the samples irradiated with the indicated fluencies, as described in the process flow in Figure 2 right hand side.

Beam shaping with Diffractive Optical Element

A diffractive optical element was fabricated as described above, featuring 10 Top-Hat profiles. The intensity distribution of one such a Top-Hat is exemplarily shown in Figure 6. The profile features a width of about 190 µm (FWHM) and about 70 µm in the scanning direction. This was indented to be kept smaller; however, a mismatch in the design of the DOE and the actual beam quality factor

M² of the used laser prohibited a narrower focus in the scanning direction.

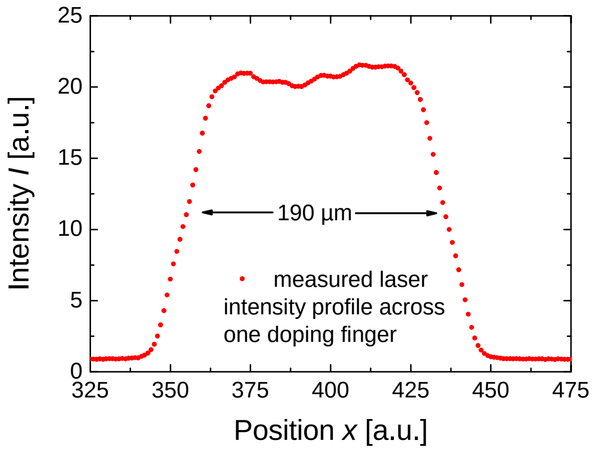

Figure 6: Intensity distribution across one doping finger. The intensity fluctuation across the Top-Hat is < ± 5%. The profile is 190 µm in width (FWHM) and 70 µm in scanning direction.

The entire beam pattern of the optical element can be seen in Figure 7. A scan for a solar cell pattern has been conducted, leading to a processing time of ~ 1 second per 156 mm wafer for 10 fingers, if a scanning speed of 350 mm/s is chosen and all acceleration and deceleration times of the axis are taken into account. This processing time can be kept constant, if the beam splitter generates 70 spots. This requires complex adjustments to the focusing objective, which is currently under investigation.

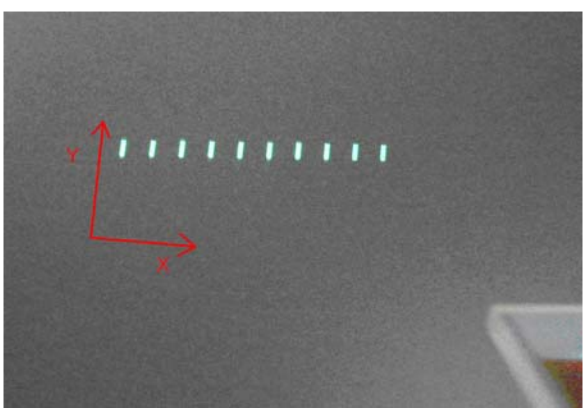

Figure 7: Photograph of 10 Top-Hat Spots on wafer separated by 2.2 mm each. Each spot features a Top-Hat profile in X-direction, transverse to the scanning direction (Y).

Figure 8 displays the doping result for a finger structure on a 156 mm cell. In the photoluminescence picture, the selectively high doped areas have a uniform appearance and constant spacing.

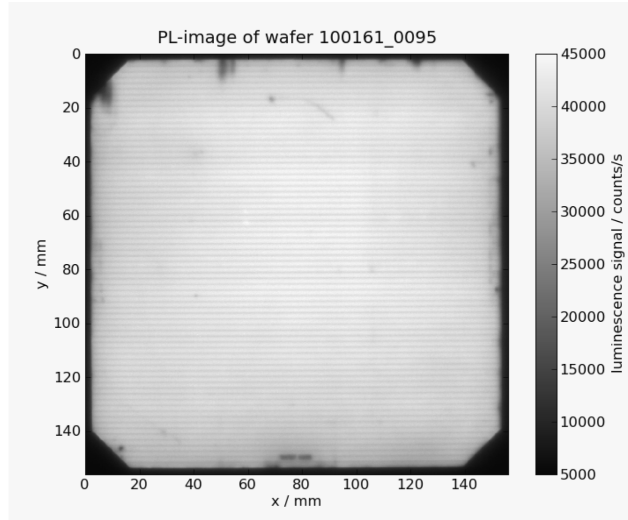

Figure 8: Photoluminescence pictures of the doping on a full 156x156 mm² wafer. The 70 highly doped finger are visible and have a uniform appearance.

CONCLUSION

The feasibility of beam shaping for high throughput laser doping for selective emitter formation is discussed. The drawbacks of Gaussian beams can be eliminated, if an adequate beam profiling is employed. A laser system with 515 nm and 300 ns is evaluated for its capability for laser doping. It is tested together with a diffractive beam splitter for increased processing speed. Doping multiple fingers at one time leads to processing speed of 1 second per wafer for a single scan. The improvement of the beam splitter for up to 70 Top-Hat profiles is currently under investigation. This allows the complete processing of one 156x156 mm² wafer in 1 second.

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