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INSECT: AN INLINE SELECTIVE EMITTER CONCEPT WITH HIGH EFFICIENCIES AT COMPETITIVE PROCESS COSTS IMPROVED WITH INKJET MASKING TECHNOLOGY

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ABSTRACT: The latest results in the application of selective doping structures to inline diffused industrial phosphorus emitters are presented. It was found that the efficiency of the cell can be increased substantially by partially etching back the highly doped layers created during the emitter diffusion. An average gain in the open circuit voltage (V_{oc}) of 19 mV and a rise of the short circuit current density (J_{sc}) of 1.2 mA/cm², resulting from a significant decrease of recombination losses at the front surface of the cell, was measured. Combined with better fill factors achieved by contacting emitters with lower sheet resistivity, an efficiency gain of $1.4\%_{abs}$ was realized. The best cells show 18.1 % efficiency. The processes used for the investigations were performed on equipment used in large scale industrial production.

Furthermore, novel inkjet masking methods were applied and their potential for improving selective emitters was evaluated. Inkjet printing is warp-free, applies no mechanical stress on the wafer and enables a precise structuring of the etch mask with very little lateral tolerances. This increase in precision lowers the areal fraction of low-resistance contact areas, resulting in lower emitter saturation current densities and thus improving the performance of selective emitters produced by inline processes.

Keywords: Selective Emitter, Inkjet, Manufacturing and Processing

1 INTRODUCTION

The rapid growth of production capacities for crystalline silicon solar cells has allowed for a significant decrease of production costs. To further exploit the underlying scaling effects, processes with large throughput that offer competitive cell efficiencies are needed. In recent years the concept of in-line processing has become more attractive with different techniques emerging, suitable to replace methods requiring the handling of large batches of wafers. The in-line diffusion technology has reached a large share of the different doping techniques used today. An inline diffusion system usually consists of a doper that coats the wafers with a defined amount of phosphorus containing dopant before they are transported through a conveyor belt furnace in a controlled ambient at standard pressure.

One of the main advantages of the in-line doping technology, besides being less expensive, is its inherent process simplicity and stability. Whereas a batch process - previously the dominant doping technique for the emitter formation in the production of c-Si solar cells - requires intricate and complex handling systems for a large number of wafers the in-line doping technique can be equipped with a handling system moving single wafers. This leads to less wafer breakage and higher uptimes of the diffusion equipment. Furthermore, the design of the diffusion furnace to drive in the dopant is less complex than its counterpart used in a batch process and offers an excellent stability and remarkable doping homogeneity.

Still, the batch diffusion process features one significant advantage: By controlling the diffusion ambient atmosphere in a tube furnace and the use of comparatively long doping process times the dopant can be driven further into the wafer creating a deeper pn-junction with a lower surface concentration.

Through the application of a selective emitter structure, i.e. removal of the highly doped layers in the areas not intended for metallisation [1], the recombination losses at the front surface can be significantly reduced while maintaining a wide process window for the emitter contact formation during sintering. Key for achieving a minimal areal fraction of highly doped regions to lowly doped regions is the precision of the subsequent printing steps as well as the reliability of their overlay. This is where inkjet printing technology, which is currently under investigation at the University of Konstanz, unfolds its advantages over screen printing.

2 PREPARATORY INVESTIGATIONS

It is well known that during the comparatively short diffusion time applied in the in-line doping process a high dopant concentration remains near the surface of the wafer. Effective lifetime measurements were made using FZ wafers (0.5 Ωcm) with a typical in-line phosphorus emitter on both sides. One group of the samples was passivated with a standard direct plasma PECVD-SiN_x layer with no emitter etching after the diffusion process. The second group of samples underwent an etching of the surfaces, increasing the sheet resistance (R_{sh}) of the emitter from around 40 Ω/□ up to 120 Ω/□. These samples received the same surface passivation layer of PECVD-SiN_x:H. The results of the lifetime measurements taken with a Sinton WCT lifetime tester are shown in Fig. 1.

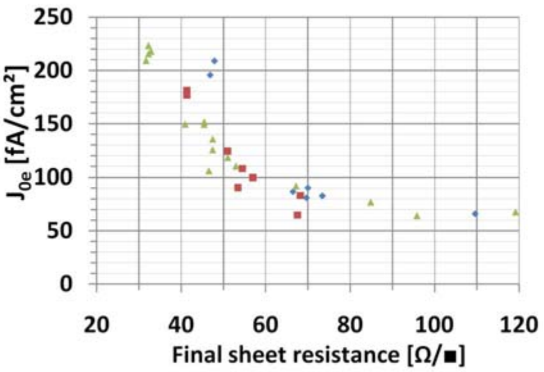

Figure 1: Emitter saturation current density over sheet resistance achieved by etching back from 33 Ω/□ (green), 42 Ω/□ (red) and 48 Ω/□ (blue).

The effective lifetime of the samples was already lowered beneath 100 fA by etching back the highly doped emitter layers, indicating a substantial potential to increase the open circuit voltage of finished cells.

Shirazi et al. have shown [2] that by an adaptation of the properties of the PECVD-SiN_x layer the effective lifetime of etched back emitters can be increased further thus offering the potential for a further increase of V_{OC}.

3 CELL FABRICATION PROCESS AND RESULTS

In order to assess the potential of a decreased recombination at the front surface, 130 cells featuring a selective doping structure (inline Selective Emitter ConcepT, inSECT) were fabricated on monocrystalline 5” Czochralski wafers (1.8 Ωcm, 240 µm, Solsix) using the in-line doping process at the Technology Center Schmid (TCS). The processing sequence of these cells is shown in Fig. 2.

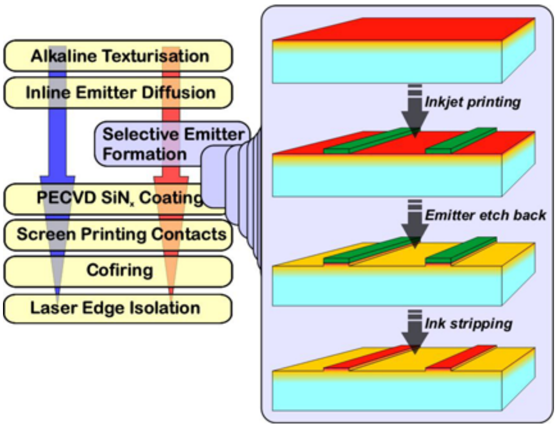

Figure 2: Processing sequence of the 130 selective emitter solar cells (red arrow) and the 60 reference cells with homogeneous emitter (blue arrow). The selective emitter (SE) formation is highlighted. Parameters varied were diffusion sheet resistance, etched back sheet resistance and masking width.

After a wet chemical alkaline texturisation process producing random pyramids, 190 wafers underwent an in-line diffusion step in which different emitters with sheet resistances ranging from 50 Ω/□ to 33 Ω/□ were formed. Subsequently, the areas intended for metallisation were masked with an inkjet printer using a hotmelt wax with the desired acidic resistance properties. The remaining surface of the wafer was etched in a process described in [3]. Afterwards, the mask was stripped, and the wafers were cleaned before being coated with a PECVD-SiN_x AR-film. Metallisation was applied by screen printing and sintering of the contacts. Reference batches of 60 wafers were processed in parallel using the standard processing sequence shown blue in Fig. 3. The results of the IV-measurements of both groups are compared in Tab. I.

Table I: Cell results, averaged over the best batches (brackets indicate batch sizes)

	η	V_{oc}	J_{sc}	FF
Best ref. (6)	16.7%	614	35.4	76.8%
Best SE (3)	18.1%	633	36.6	78.1%
Gain	+ 1.4%	+19	+1.2	+1.3%

4 DISCUSSION OF THE RESULTS

Since values exceeding 18.1% efficiency are unmatched in common inline emitter production environments, and are very high even compared to those relying on the inherently better emitters produced by costly batch doping furnaces, it is instructive to have a look at the origins of such substantial gains.

4.1 Open Circuit Voltage

It is straightforward to assume that the rise in open circuit voltage comes from the better emitter saturation current. This means that less Auger recombination takes place in the emitter region, increasing the overall charge carrier lifetime. The larger number of unhampered carriers allow their quasi-fermi-levels to spread further, this manifests in a higher V_{OC}.

The values of more than 630 mV are consistent with what one would expect from high efficiency lab type emitters formed by prolonged $POCl_3$-diffusion with separate drive-in steps. These emitters have a comparably low surface concentration of phosphorus.

4.2 Short Circuit Current Density

The increased current density originates from the better blue response that is expected when removing the so called ‘dead layer’, the topmost layer of the emitter containing very high quantities of phosphorus in the range of 10^{21} cm^{-3}. Short wavelength photons cannot penetrate silicon very deeply and are usually absorbed within the emitter region. Having lower emitter dopant concentration decreases Auger-recombination within the emitter and the recombination at defects located at the Si-SiN_x-interface. For the minority carriers generated there, holes in this case, this means that they are a lot more likely to reach the pn-junction, drift into the base and contribute to the current.

Indeed, measurements of the external quantum efficiency (EQE) show that selective emitter cells have significantly improved internal quantum efficiencies (IQE) in the short wavelength region (Fig. 3), indicating that the increased current density stems from the emitter.

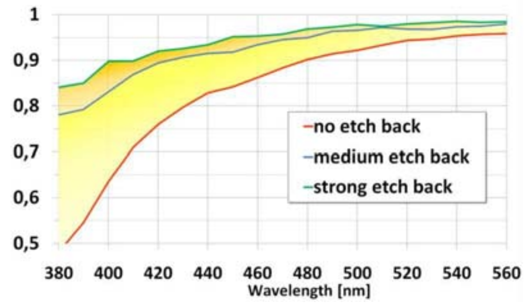

Figure 3: Internal Quantum Efficiency in the short wavelength region. A clear gain in short circuit current is visible for the selective emitter cells compared to the references (yellow). This gain could be increased even further (orange) by etching back stronger to sheet resistances exceeding the 65 Ω/□ suggested by Fig. 1

4.3 Fill Factor

The increase in fill factor stems from the application of a slightly stronger initial emitter diffusion resulting in a higher dopant concentration than used for homogeneous solar cells. These emitters have a lower contact resistance and a significantly broader temperature range for firing, so the selective emitter cells usually have smaller series resistance losses and a very wide process window for contact formation.

5 MASKING TECHNIQUE

5.1 Printing step alignment issues

As in any selective emitter concept the metallisation has to be aligned with the highly doped regions of the emitter.

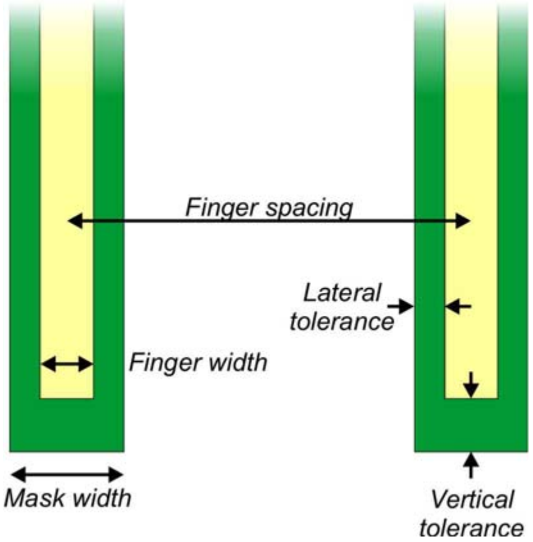

Figure 4: Overlay illustration of metallisation (yellow) and mask (green). The non-metallised area covered by the mask, here indicated by the visible green area, should be kept to the necessary minimum.

Considering the large difference in recombination activity of the highly and lowly doped regions it becomes obvious that the areas with high doping should be limited to a minimum, ideally only the areal fraction covered by the front side metallisation. Thus, it is imperative to use masking and metallisation techniques that allow for an accurate adjustment with minimal tolerances.

On the other hand, if choosing tolerances too low, misalignment of the metallisation may lead to a decrease in fill factor when metallisation paste is printed over regions with low surface dopant content. Since the emitter is very shallow in these etched-back regions, the paste cannot contact the emitter reliably. So it is obvious that if using screen printing for both masking and metallisation, warping of the screen for each step has to be taken into account when designing the mask layout. Thus, its dimensions have to be designed to fit the emitter electrode at all times, regardless of screen wear and overlay tilt. This generally increases the areal fraction that needs to be masked and therefore remains highly doped increasing the emitter and surface recombination (displayed green in Fig. 4)

5.2 Improving Selective Emitters with Inkjet Masking

Considering the large difference in the saturation current density between the initial emitter doping and after etching back of the emitter the benefit of a small alignment tolerance for both the masking and metallisation step becomes obvious. Therefore, inkjet printing has been implemented as a masking technology at the University of Konstanz. One of the main advantages over screen printing is that is does not suffer from any kind of warping effects, so the lateral tolerances can be chosen significantly lower.

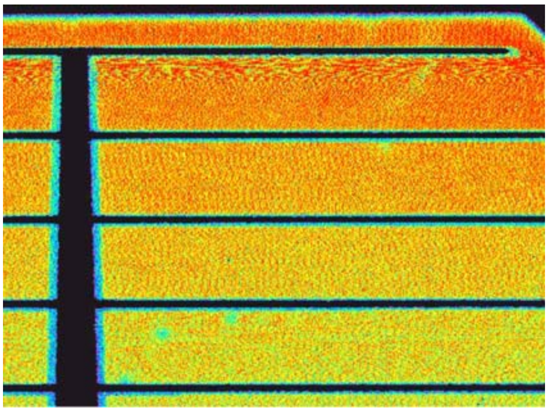

Figure 5: LBIC Image of a well-aligned solar cell at 833 nm. The grid fingers (black) have been printed nicely in the center of the non-etched region, which is visible by its lower IQE of 93% (blue). The etched-back areas show IQEs between 97% (yellow) and 99% (orange).

As can be seen in Fig. 6, this allows for an increase of efficiency. In this experiment, masks with different tolerances were applied, so that a varying fraction of the unmetallised area remained at a low sheet resistance.

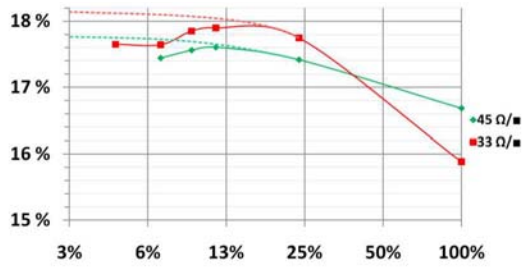

Figure 6: Average cell efficiency plotted over the areal fraction of non-etched back regions. The dashed lines indicate the trends that result from suppressing misaligned cells that impede the statistical average via their poor fill factors.

While screen printing the etch resist mask on an industrial scale usually requires a masking fraction in the range of 20% and more, lines including inkjet masking can be run with masking fractions between 11% and 14%. This is mainly limited by the metallisation step which is still applied by screen printing.

In addition, inkjet technology allows for the deposition of the mask without touching the wafer thus decreasing the breakage rate. Another advantage is that through inkjet technology the amount of masking material that is deposited on the wafer can be greatly reduced simplifying removal of the mask later in the process and keeping consumable costs of the masking and the stripping process very low.

6 SUMMARY AND OUTLOOK

Inline diffused phosphorus emitters satisfy the industrial demand for an easily implementable, low-cost high yield manufacturing process suitable for modern conveyor belt based cell-fabrication lines. The drawback of increased recombination in the resulting emitters compared to emitters diffused in a batch-type process can be more than offset in a convenient and inexpensive way by etching back the highly doped area not intended for metallisation. This way, a selective emitter is formed without implementing another critical and expensive high-temperature process but by masking the surface needed for metallisation, etching back the remaining area and stripping off the etch barrier.

Applying a selective emitter design results in an average efficiency gain of 1.4%$_{abs}$ compared to homogeneous inline emitters, originating from an increase in V_{oc} by 18.6 mV and an increase in J_{sc} by 1.2 mA/cm^2 as well as a fill factor improved by 1.3%$_{abs}$ that originated from the choice of a higher doping level beneath the grid fingers. This massive gain was made possible by reducing the printing tolerances for mask and metallisation since the areal fraction of the highly doped contact region, in which recombination occurs, could be made smaller. For this purpose, a versatile inkjet printing system was established at the University of Konstanz which features a better printing accuracy than conventional screen printing.

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The content of this publication is the responsibility of the authors.

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