IMPROVED EDGE ISOLATION OF SOLAR CELLS APPLYING READILY DISPENSABLE ETCHING PASTE

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ABSTRACT: An advanced and cost effective process for edge isolation of silicon solar cells by strongly local deposition of etching paste isishape SolarEtch® SiD is presented. The deposition of the paste was carried out by deposition technique being free of contact to substrate, namely dispensing. Basic deposition parameters were figured out and later on refined by design of experiment applying elaborated sub-design. In order to evaluate isolation properties of the new process, experimental trials focusing on process step of edge isolation of standard solar cells were conducted by applying different deposition conditions. For this purpose, experimental trials were sub-divided into two phases: firstly, evaluation of new concept and secondly, its validation by applying industrial conditions of mass production. Conventionally isolated wafers, e. g. by laser scribing, were taken as reference. Comparison of paste-isolated batches with reference batches provided clear evidences for improved cell performances after isolation by etching paste over reference batches. The main beneficial factor for improving solar cell's performances was identified to originate from increased values of J_{SC}. Isolation process by paste was supplemented by ES&H considerations which provided evidence for environmentally friendly process conduction being superior to single side etching.
Keywords: etching, shunts, edge isolation, laser

1 INTRODUCTION

Edge Isolation (EI) is a process step of essential importance in course of mass production of conventional industrial silicon-based solar cells. This process resolves the electrical shunt between front and backside caused by state of the art diffusion processes.

The shunting of solar cells is quantitatively described by shunt resistance (R_{SH}) which is for instance, however with some precautions (interference by J_{01}, J_{02}, assumptions for n_1 and n_2, latter being somehow depending on current density), deducible from dark current voltage characteristics applying solar cell's 2-diode-model [1, 2]. In general, values for R_P are tended to be as high as possible in order to effectively suppress parasitic shunting. On the other hand, it was demonstrated that values for R_P being higher than or even equal to 4 kΩ*cm² should be sufficient without affecting performance of solar cell [3]. Too low values for R_P predominantly diminish the Fill Factor (FF) of cells [2].

Currently, EI in mass production is achieved by three dominating technologies: plasma etching, laser scribing or edge isolation (LEI) and single side wet chemical etching (SSE). Besides, several other techniques exist which will be mentioned just briefly: perforating or pre-cutting of a rim circumventing the wafer followed by breaking off this rim, grinding of edges as well as wetting edges by KOH soaked sponges[4]. However, each of predominating technologies mentioned bears their own individual shortcomings from which most are summarized elsewhere [3], [5]. The major drawback of LEI is addressable, however, to laser-induced reduction of the active area which in total might amount to ~0.5% of total cell area.

In this work an advanced concept for improved EI by deposition of a local wet chemical etchant, an etching paste is described (cf. fig. 1). The etching potential of paste can be triggered selectively by controlled activation due to input of heat. The new approach is sketched as follows: local deposition of etching paste free of contact by dispensing on wafer's rear side in order to overcome potential area-losses of 'sunny' side'. Afterwards, the paste has to be activated to achieve etching and paste residues are removed by simple water rinse. However, since dispensing is determined by several process parameters, Design of Experiment (DoE) was used to evaluate deposition parameters. The concept of EI by etching paste isolation performance was proven by manufacturing of standard solar cells: mc and Cz, as in the case of evaluation of the concepts, and Cz for large-volume trials applying industrial production conditions.

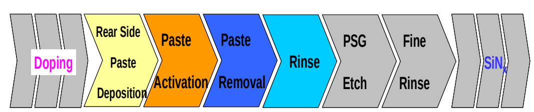

Figure 1: Process sketch for process of paste isolation. Coloured: paste isolation related process steps.

2 EXPERIMENTAL DETAILS

Unless otherwise mentioned, experimental work associated with paste deposition was conducted using following equipment and standard operating procedure: etching paste was deposited using a camera-guided lab-dispenser (Asymtek Dispensemate® 583) equipped with a time-to-pressure valve. Etching profiles were acquired either by tactile surface profiling (Alpha Step IQ, KLA Tencor) or by an optical profiler (FRT CWL 600 µm). Etching figures were examined by optical microscopy (OM; Axio Imager.A1 m, Carl Zeiss). Curing of the etching paste was achieved either on a conventional lab hot plate or by exposing printed wafers in a conventional convection oven or by let them passing an IR-driven inline belt furnace comprising four zones for heat transfer. After curing, the wafers were transferred into a one-lane inline wet bench being equipped with modules for paste removal, rinsing and drying, respectively. A 10 second rinsing step is sufficient for complete removal of residues.

Environment, safety and health (ES&H) investigations were performed in addition. These were mainly focused on tap water analysis from step of paste removal. Those revealed when cleaning paste-cured wafers either 3 or 20 in 2 L water for paste removal, that for instance both, total organic carbon and biological oxygen demand amounted to only 1 ppm each as well as metal contents (Hg, Cu, Cd etc.) were even below limit of quantification (typically: 5 ppb), respectively. Furthermore, paste cured did not set free harming and corrosive vapours like those comprising chlorine- or fluorine-containing compounds as well as nitrous and nitric oxides.

2.1 Design of Experiment

Since several parameters - for instance movement velocity of dispense head, diameter of dispense needle, distance of tip of needle to surface of substrate as well as pressure lasting on dispense reservoir - influence deposition result and interfere each other, most significant ones as well as parameter interactions were identified by DoE (cf. Fig. 5).

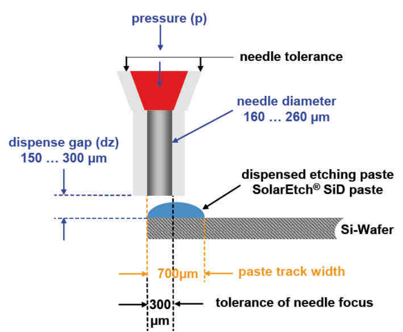

Figure 2: Sketched set-up of lab dispensing system.

2.2 Evaluation and Validation of the Concept

For evaluation and validation of the new concept, the following schematic set-up (cf. fig. 3) applies: the concept was evaluated in collaboration with Fraunhofer Institut für Solare Energiesysteme, henceforth abbreviated as ISE, whereas validation was performed in collaboration with Bosch Solar Energy AG (formerly ersol Solar Energy AG). All paste isolations of wafers were conducted at MERCK.

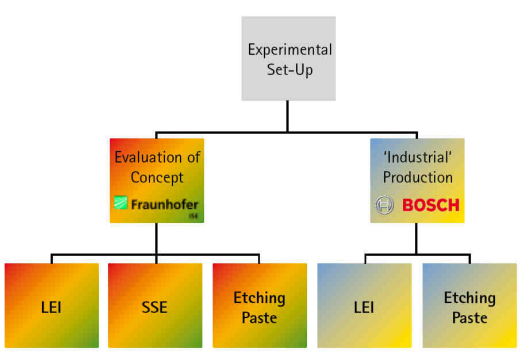

Figure 3: Process sketch for advanced paste isolation process.

The EI experiments applying conventional solar cell layout were performed with iso-textured 6'' mc-substrates in the case of concept evaluation and 6'' CZ-substrates in the case of concept validation. Wafers were double side diffused with an emitter exhibiting a final $R_{\square}$ of 65 $\Omega/\square$ as in the case of mc-wafers and 60 - 70 $\Omega/\square$ in the case of Cz-wafers. After doping, the wafers were divided into different batches, namely such for paste isolation as well as those for reference processing. LEI as well as SSE were taken as references in the case of concept evaluation. In the case of concept validation, LEI was taken as reference. The batches for paste-related isolation process were transferred to MERCK prior to PSG etching in order to conduct the isolation step there. The procedure associated with this step is given in paragraph 2. For this purpose, the wafers were taken as received and the etching paste was deposited directly on the PSG layer applying optimized deposition parameters (cf. fig. 4).

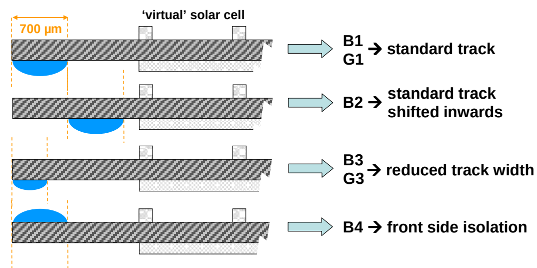

Fig. 4: Sketch demonstrating various dispense parameters and paste depositions.

The curing of the etching paste was achieved by different methods for activation (cf. paragraph 2). Namely, curing was carried out for 2 minutes on a hotplate at 230 °C, for 2 minutes in at 225 °C in convection oven and for ~2 minutes by passing the belt furnace applying constant belt speed of 50.8 cm/s and a peak temperature of 380 °C.

After isolation, all wafer batches were re-transferred either to ISE or Bosch Solar Energy AG in order to finish cell manufacturing process re-commencing with PSG removal and by mixing them up by above-mentioned reference wafers which had remained at manufacturer's site. Cell characterization was carried out according to standard test conditions at either ISE or Bosch Solar Energy AG.

3 RESULTS

3.1 Design of Experiment

Fig. 5 demonstrates an excerpt of typical contour plots obtainable after carefully eliminating parameters as well as interactions of parameters which were found to be of less statistical significance. After refinement of DoE-approach, following process parameters could be identified as being decisive: dispense speed in the range of 200 mm/s, a needle diameter of 250 µm, thus resulting in a wet film track width of paste of about 500 – 700 µm, etching time of about 2 minutes and an etching temperature between 200 °C and 250 °C leading to etching depth of typically 4 µm. Nevertheless, a dispense speed of >400 mm/s was found to be applicable, too. By application of such a fairly high velocity, deposition of paste track following exactly wafer's geometry was somewhat interfered by acceleration and deceleration of the dispense head. However, this is supposed to be quite easily solved by mechanical alignment as well as the use of more sophisticated dispensing valves and will thus be turned into practice by set-up of an advanced pilot plant closely meeting production-related issues.

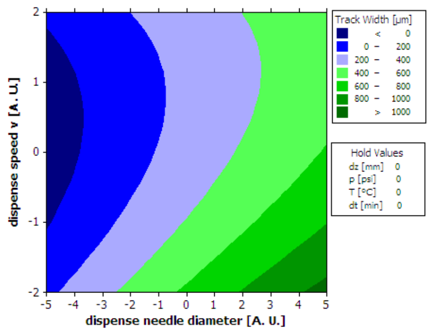

Figure 5: Simplified contour plot, given in coded values, for DoE-related screening of deposition parameters: in this case wet film track width in dependency of dispense needle diameter and dispense speed (v).

Considering results for deposition process, it appears worth to mention that for instance the result for paste track width was superimposed by type of wafers used. On the other hand emitter doping as well as a capping layer of PSG revealed to have rather negligible influences on the etching performance of the paste. Thus, the PSG layer was completely penetrated and stripped due to etching. As a consequence, PSG coating may be used as protective layer during process conduction.

Etching rates of silicon varied in dependency of type of crystalline material used. The etching capacity of paste was found to follow the order: (100)-Si > mc-Si > (111)-Si. The etching rate for mc-Si was determined to be ≥ 1 µm/min on a lab hotplate applying a temperature of 230 °C.

Fig. 6 shows a track of paste deposited directly next to wafer's edge. It was found that paste deposition is reproducible and somehow 'self-aligning' as long as the dispense needle is adjusted to wafer within a so-called region of tolerance which is depicted in the scheme in fig. 2. Especially, if dispense needle overrides its position above the edges of a wafer to a certain extent, however, the paste will not move off the wafer's rear by leaving its intended position and thus for instance wetting the wafer chuck and as consequence thus harming front sides of following wafers. This behaviour of the paste is supposed to be addressable to its properties of wetting as well as to thioxotropy.

3.2 Evaluation and Validation of Concept

Fig. 7 shows a SEM-image of an etching feature derived by exposing a track of etching paste to mc-wafer. The picture highlights the transition between an etched (~500 µm) and non-etched surface region. By comparison between both regions, etched and non-etched ones, it becomes obvious that the attack of etching paste led to the formation of an etching groove as well as to a pronounced smoothening of the surface texture. Latter may also be deduced OM-inspections which are not demonstrated in this context. Shiny and brightly appearing features on the wafer surface were visible after exposure to paste. The shiny appearance may be deduced from smoothening of wafer's surface texture, which gives rise to a local change in silicon's properties of reflection: namely that that extent of diffuse reflectivity becomes reduced by texture wipe out.

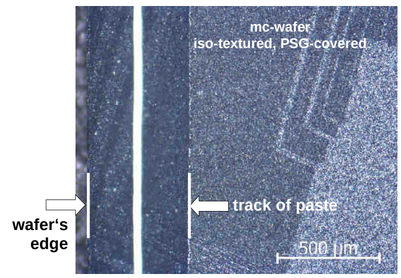

Figure 6: Examples for a dispensed track of paste (width: ~500 µm).

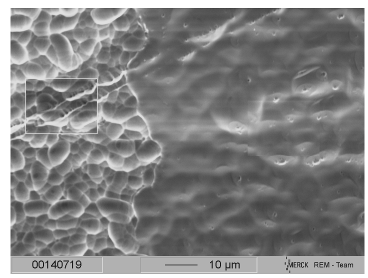

Figure 7: SEM-image of the transition area on a mc-wafer after being etched (right) by a deposited track of paste. The paste was deposited on the rear side directly next to the edge of the wafer.

3.3 Results on Solar Cells

Fig. 8 demonstrates the results from concept evaluation providing average efficiencies and average values of J_{SC} for different batches of paste isolated solar cells as well as for references. References referred, as already mentioned, to LEI as well as SSE. All data were normalized to LEI as sub-batch. Please note that batch numbers, in this case G1 and G3, refer to conditions of deposition applied.

Considering efficiencies, it is obvious that references turned out to exhibit a comparable level, however somewhat surprising, whereas batches edge isolated by etching paste tends towards increased efficiencies. Batches G1 and G3 cured in a convection oven demonstrated a gain in efficiency of +1.2 % relative, which was in turn +0.2 % absolute. Nevertheless, batch G3 which was conducted by assistance of the belt furnace yielded a comparable gain in average efficiency. Just G3, isolated by applying a hot plate as heating method, revealed a somewhat lower performance. This may be attributable to following phenomenon: from sudden heating of very thin wafers on hot plates is known that a pronounced bowing may occur. Due to this deformation, the edges of the wafers are not in tight contact to the heat source underneath so that an isolating layer of air may slightly block the direct heat transfer from source to substrate. As a consequence, a reduced etching depth is obtained. Therefore and due to the fact that hot plates may be overall considered as less favourable as equipment for industrial mass production, the hot plate was excluded as potential heat source for further experimental trials.

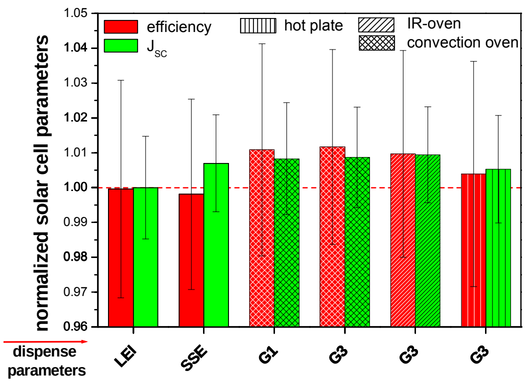

Figure 8: Comparison of average conversion efficiencies as well as of J_{SC} for paste-isolated vs. reference batches processed at ISE.

The gain in conversion efficiencies observed for paste-isolated solar cells over reference batches was accompanied by an increase of J_{SC} which is assumed to be the major contributor to performance gain in general. Latter is deliberately easily conceivable since paste isolation did not reduce the active area of the solar cell as for instance laser scribing does and thus reducing output of J_{SC}. For SSE-batch a gain in J_{SC} was recognized. It is unclear why no gain of performance was observed.

The cut-off of active area during LEI is process inherent. Assuming, that the laser cut makes up an average distance of ~270 µm from wafer's edge (sum of average distance of laser groove to edge and groove itself), the relative loss of surface area available for light incident and therefore for power conversion is about 0.7%. On the other hand, this means that the average performance gain due to paste isolation is about 2 times higher than the geometry related loss of surface induced by laser scribing. Thus providing evidence for potential laser irradiation related crystal damage.

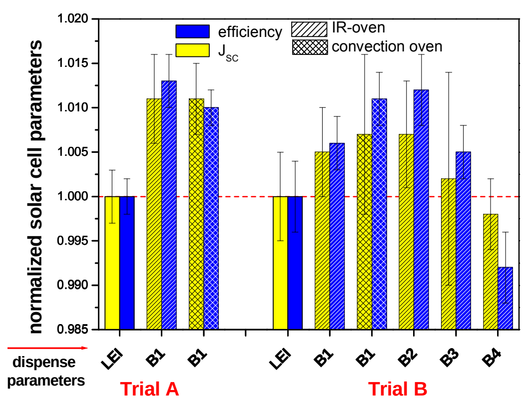

Figure 9: Average values for conversion efficiencies as well as for J_{SC} for different batches of paste isolation vs. reference obtained from validation trials.

Besides, the average value for U_{OC} of mean values over all test batches was 605 mV (± 0.1 %), whereas the average value of R_S over all test batches was 0.73 Ω*cm² (± 2.5 %). In particular the value for U_{OC} demonstrated that paste-isolated wafers did not suffer from potential contamination issues conceivable which might had been caused by handling steps for paste isolation.

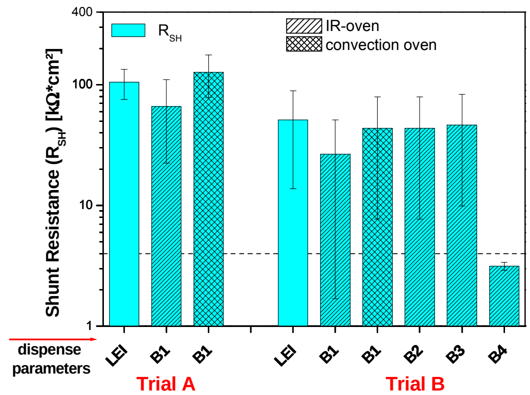

Fig. 10: Average values for shunt resistances for different batches of paste isolation vs. reference obtained from validation trials. Dashed line shows minimal value for R_{SH} required order without significantly diminishing performance of solar cells [3].

Fig. 9 and fig. 10 show typical solar cell parameters after validation trials applying industrial mass production conditions at Bosch Solar Energy AG. Both trials comprised about 900 wafers in total. Validation trials revealed the same results in general: average values for efficiencies as well as J_{SC} of paste isolated wafers were superior to those of reference which corresponded to LEI. The average gain in conversion efficiency amounted to +1 % relative which was, by stressing laser-induced cut-off again and which was in this case lower than that from previously mentioned example, 2 - 3 times higher than geometric loss of active area during reference process. The average gains in J_{SC} turned out to be even superior to average efficiency gain. Results for isolation are somewhat superimposed by method of heat transfer as well as of conditions of deposition applied. So, heat transfer by belt furnace and convection oven yielded comparable results with respect to efficiency as well as J_{SC}, however, the results obtained when using convection oven as activation source revealed a trend for somehow better isolation characteristics – in particular when regarding average value for specific R_{SH} (cf. fig. 10). Furthermore, results apparently revealed a trend for improved isolation performance with respect to device characteristics as well as to material use when applying a paste track with a reduced track width than 'standard' (B3) and when depositing paste by including a 'spacer' between wafer's edge and start of the sidewall of paste track on the wafer's rear (B2). Combinations of those conditions and furthermore triggering etching capability of paste by convection oven should therefore give rise to even more improved isolation performance. Moreover it became apparent by B2 that isolation performance may even be maintained if tracks of paste were not matched exactly next to the edge of wafers. Thus, at least complete space between wafer's edge and beginning of Al backside electrode is accessible for paste isolation and thus providing sufficient tolerance for advanced process control.

On the other hand, depositing paste on wafer's front turned out to be less favourable (B4). However, this finding is supposed to be mainly attributable to track width of paste deposited. The etching groove is too wide to avoid misalignment between etching feature and front side metallization, thus solar cells might have suffered from shunting due to metallization contacting the base directly. However, experimental results clearly provide evidence that the concept of backside deposition of paste is straight forward yielding isolation properties comparable or even slightly superior than LEI and thus making front side treatment unfavourable and less reasonable, since process inherent advantages would be given up by latter approach. Furthermore, the trials from concept validation provided evidence for advanced process robustness.

4 SUMMARY AND CONCLUSIONS

A new advanced method for EI based on the application of dispensable etching paste has been represented. This process has proven the potential to overcome typical shortcomings of common technologies for EI which are mentioned elsewhere. The benefits which have turned out may be summarized in the following:

- free of contact printing by dispensing
- dispensing known as highly reliable and robust production technology (‘workhorse’) from manufacturing of printed circuit boards
- thus, fast and robust deposition
- improvement of conversion efficiency by 1 % relative
- no crystal damage (cf. LEI)
- no process-related contamination of Si
- use of PSG as protective layer
- ‘safe working environment’ (personnel, equipment)
- environmentally friendly due to low level pollution of tap water used

These beneficial effects arising from advanced isolation with etching paste isishape SolarEtch® SiD makes this concept a very attractive and cost-efficient alternative to commonly applied EI technologies.

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