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Impact Of Texture Height And Ozone-Based Rounding On Silicon Heterojunction Solar Cell Performance

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Abstract: In this study, the effect of ozone-based rounding was investigated for three random-pyramid texture height ranges for Silicon Heterojunction (SHJ) at the cell and module levels. In a first experiment, 5 ozone-based rounding process times (0, 2, 4, 6, 8 and 10 minutes) were applied to two texture-height ranges (Small and Medium) to observe variations in the reflection response of the wafers. In a second experiment, 3 ozone-based rounding treatment times (0, 2 and 6 minutes) were applied to three texture-height ranges (Small, Medium and Large) and to observe the results both on the cell and on the module levels. The first experiment has shown that ozone-based rounding increases reflection and has a more pronounced effect for smaller than larger sized texture-heights. An increase in the minimum wavelength of reflection is seen after the Transparent Conductive Oxide (TCO) deposition, indicating that shorter deposition times can be used. The results of the second experiment show that, even though the Short-Circuit Current (Jsc) decreases for the three textures with rounding time, it is compensated by an increase in the pseudo-Fill-Factor (pFF). A maximum is seen at the cell level for 2 minutes of rounding for the small and large texture sizes, but which is leveled at the module. In conclusion, these results indicate that 2 minutes of ozone-based rounding can be beneficial for the cell's final efficiency as the improvement in passivation still compensates the optical losses resulting in a lower J_{sc}.

Keywords: Ozone-based rounding, Silicon Heterojunction, Alkaline Texturing, Reflection.

1. Introduction

Silicon Heterojunction (SHJ) solar cells have been rising to become one of the most important solar cell technologies for its great field performance as for its low-demand processing requirements. Recently, they have attracted the attention of the public by achieving the world record efficiency of 26.81 % Power Conversion Efficiency (PCE) for both contacted c-Si solar cells [1]. Parallelly, intense research is being done on using them as bottom-cells for perovskite/SHJ monolithic tandem devices [2].

With wafers trending to get both thinner and larger, adjusting cell texturing time and results becomes a crucial step in reaching the best efficiencies. Even though a proper cell texturing is expected to reduce light surface reflection, the final texture's size and surface structure can influence other important cell parameters. Therefore, fully understanding how different types and sizes of texture influence cells' and modules' overall performance can lead to important insights on how to save in materials' consumption and improve final efficiency.

In this study we investigated what effect different degrees of Ozone-based rounding (O_3-rounding) have on different texture-height ranges. O_3-rounding is wet-chemical treatment which is performed on wafers after the texturing step. The O_3-based cleaning and rounding can be either conducted sequentially oxidizing the surface in ozonated water and removing the grown oxide layer in hydrofluoric acid (HF) within two baths or simultaneously in one bath adding HF to the ozonated solution [3]. It does so by performing two simultaneous chemical reactions on the Si wafer's surface: first, the growth of oxide by oxidation with O_3 (**Reaction 1**) and the etching of Silicon Oxide (SiO_2) by HF (**Reaction 2**). Pyramid tips and other pointy-features are more intensely etched (and, therefore, taken away) because they have a relatively higher surface area exposed to the solution, therefore suffering more intensely the effect of the oxidation step (**Reaction 1**)

$$2\ Si_{(s)} + 2\ O_{3\,(g)} \rightarrow SiO_{2\,(s)} + O_{2\,(g)} \tag{1}$$

$$SiO_{2\,(s)} + 4\ HF \rightarrow SiF_{4\,(g)} + 2\ H_2O_{\,(l)} \tag{2}$$

The final effect is that the wafers' surface gets smoother by fraction. Previous studies by Moldovan et al. [3] have shown that this smoothening of the surface has two main effects: increasing reflection at the surface and enhancing surface passivation. In terms of the cell's parameters, these effects are reflected respectively in a decrease in the Short-Circuit Current (Jsc) and in an increase in the Open-Circuit Voltage (Voc) and in the Fill-Factor (FF). These factors have opposite effects on the cell's final efficiency and the effect is a trade-off between the two. Further knowledge on the relation between texture, cell and module performance can be found in [4].

2. Experimental

To further assess the effect of the rounding time on the reflective behavior of the wafers, in a first experiment (Experiment 1) we varied the rounding time from 0 to 10 minutes in steps to two minutes for two texture sizes, which we defined to be small and medium, making a total 12 groups. For a second experiment, we decided to recreate and validate Moldovan et al. [3] previous results using 3 conditions: no rounding of the texture (0 minutes of treatment), with the predicted optimal rounding time (2 minutes) and with a too-long rounding time of 6 minutes. To correlate the effect of the rounding time with the size of the texture, we applied these rounding times to 3 texture-size ranges: small (S), medium (M) and large (L), making a total of 9 groups. The processing sequence used to produce our SHJ cells and modules is shown in **Figure 1**, together with the analysis done over the products of each step.

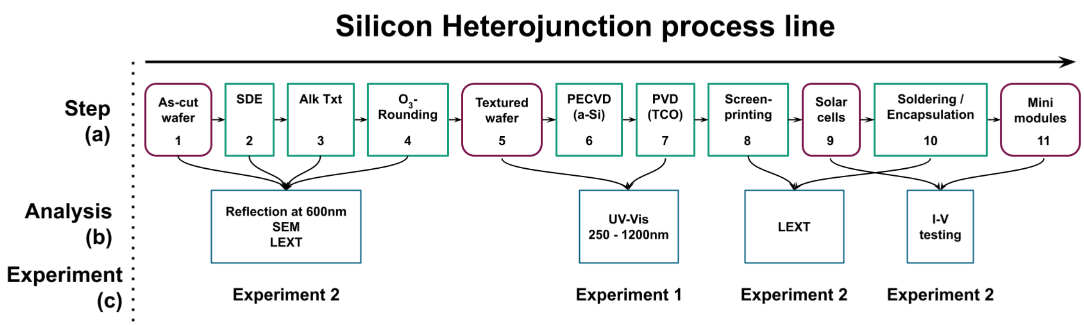

Figure 1: Silicon Heterojunction solar cells process line used in this study in terms of steps and products **(a)**, the characterization methods used at its step **(b)** and the experiment in which these methods were used **(c)**.

2.1. Wet-chemical treatments: Saw Damage Etching (SDE), Alkaline Texturing, Ozone-Based Rounding

For all experiments, we started with M2 (156.75 mm sides, 180 µm initial thickness), Cz, n-type wafers provided by LONGi. The SDE and the alkaline texturing (steps 2 and 3 in the diagram of **Figure 1**) were performed in a Silex II industrial wet-chemistry etching tool (130 l total bath volume, Singulus Technologies AG), capable of etching 2 full carriers simultaneously. During the SDE step, KOH concentration was set to 30 % m/m and the bath temperature set to 80°C with stirring. During the alkaline texturing step, the KOH concentration used was decreased to 3.7 % m/m. For each texture desired, a specific quantity of a commercial texturing additive (Ultra CellTex) was added to the bath. In experiment 1, the quantities were of 800 ml for the S-size texture and 600 ml for the M-size texture. For experiment 2, the quantities used were 100 ml for L, 300 ml for M and 600 ml for S sizes) and the bath temperature was again set to 80°C with stirring. The O_3-rounding step was performed in a bench-sized wet-chemistry etching tool (Ramgraber GmbH), capable of etching one 24-wafer carrier per time. Ozone was continuously generated in situ by an ozone generator (MKS GmbH), where the concentration in the solution is controlled by means of a sensor. The concentrations in the O_3-rounding solution were O_3 30 ppm, HF 2.5 g/l, HCl 5.0 g/l and the temperature of the bath was set to 30°C with stirring. The time of the ozone-based rounding was varied according to the experiment and condition. For experiment 1 (reflection analysis), O_3 -rounding was performed for 0, 2, 4, 6, 8 and 10 minutes for the texture sizes S and M. For experiment 2, O_3 -rounding was performed for 0, 2 and 6 minutes for the texture sizes S, M and L. The O_3 -rounding of the 9 groups belonging to experiment 2 were done over 3 sequential days, in which the pyramid sizes were equally divided in order to randomize the samples and reduce the impact of day and process specific variations (step 5). After each step of wet chemical processing, one of the resulting wafers was observed both under a LEXT laser scanning microscope (Olympus Corporation) and a Scanning Electron Microscope (SEM) for side and top views. Texture sizes were determined by the statistics provided by the LEXT microscope.

2.2. PECVD, PVD, Screen-printing, Soldering and Encapsulation

After the final wet-chemistry step (Ozone-rounding, step 4), deposition of the amorphous hydrogenated silicon (a-Si:H) layers was done by PECVD with an Octopus II tool (Indeotec SA) over 3 consecutive days. During the PECVD deposition, first, on the front-side, an intrinsic a-Si:H(i) layer was deposited on the Si wafer, and over it, a n-doped a-Si:H(n) one. After this the wafers were flipped and a p-doped a-Si:H(p) layer was deposited on the rear side. Indium-Tin Oxide (ITO) was deposited as a Transparent Conducting Oxide (TCO) with a Scala (Von Ardenne GmbH) Physical Vapor Deposition tool, being set to a standard of 75 nm on textured surfaces. In experiment 1, wafers coming from PECVD and PVD were singled out and analyzed for UV-Vis absorption and transmission between 200 and 1200 nm, which did not happen in experiment 2. For experiment 1, screen-printing was done with 20 µm screen opening front-side and 24µm rear-side, while for experiment 2 the size used was 40 µm on both sides.0 µm opening in a 5 busbars configuration. After screen printing, LEXT images were taken from the fingers and busbars to determine their size. Drying and Curing were done at 200 °C and 220 °C for 60 seconds. String soldering was done with Lead/Tin solder alloy at 150 °C. Cell encapsulation and module contact insertion was done with Polyolefin Elastomer (POE) as binder and glass and whiteas outside barriers. Cells and modules were tested in a Halm cell tester from Halm GmbH.

3. Results and Discussions

3.1. Texture Characterization

The images of the tips of representative pyramids after O_3-rounding are shown in **Figure 2**.

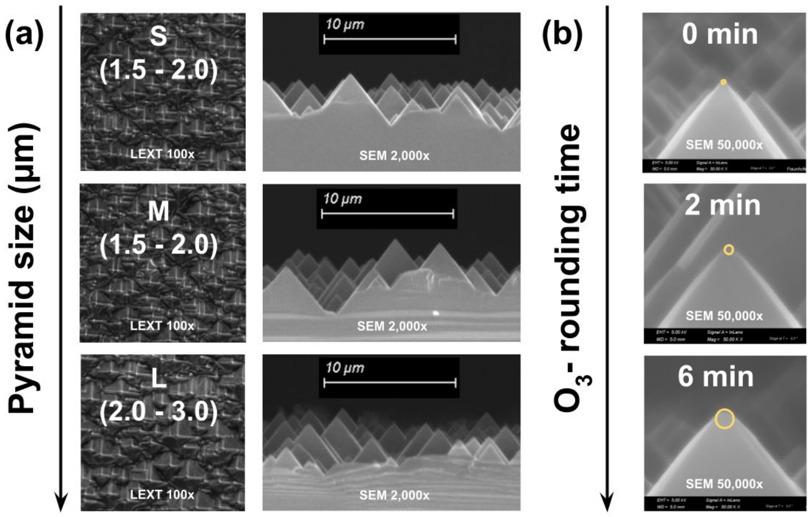

Figure 2: Microscope images of the textures produced. **(a)** Top (LEXT, 100 x magnification, left) and side (SEM, 2000 x magnification, right) views of the textures from each size range (S, M and L) with the respective sizes determined by the LEXT microscope statistics. **(b)** Close-in of the texture's pyramid tips after different rounding times (SEM, 50000 x magnification).

The texture sizes were determined by the statistical analysis provided by the LEXT proprietary software (**Figure 2 (a)**). The fact that the texture height-ranges for the S and M texture sizes were determined to be approximately the same for this method is relevant. Building on knowledge and experimental results of pre-tests, we expected to have these two ranges with a difference in size of at least 1 um. On the other hand, by looking at the LEXT pictures themselves and by considering that the results for other quantities under investigation were different for the S and M texture sizes, we are led to speculate that the results obtained from this characterization method regarding these texture sizes may not be representative of the real texture size, in this case. A further study investigating the accuracy of the different characterization methods on the definition of texture size ranges would be needed to solve this question. The pictures of the pyramid-tips after rounding (**Figure 2 (b)**), nonetheless, clearly show an increase in radius from 0 to 6 minutes of treatment, as expected. This increase in pyramid-tip radius accounts for the increase in flat-surface fraction of the wafer's surface and for the observed increase in reflection shown in the next section.

3.2. Reflective Behavior

The reflective behavior of cells after PECVD (experiment 2) is shown in **Figure 3**.

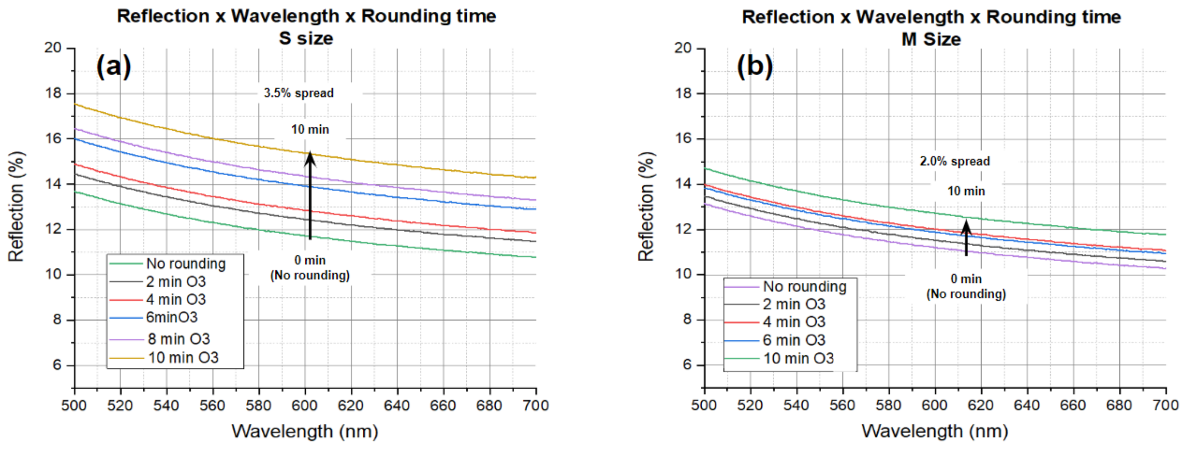

Figure 3: Reflection response obtained for textures of S and M texture-height sizes after texturing from UV-Vis measurements made between 500 - 700 nm (**(a)** and **(b)**).

It can easily be seen that for both texture sizes the reflection increases steadily with O_3-rounding time. A difference between the reflection response for the S and M sizes is observed for the spread though, which is higher for the smaller texture than for the larger one (approximately 3.5 % and 2.0 % respectively). This is explained by the fact that having a texture of smaller size also means to have more pyramids per area, as the whole surface of the wafer is covered by the texture. A higher number of pyramids per area means that a higher number of tips are oxidized during O_3-rounding, thus leading to a higher percentage of flat surface area and, thus, more reflection. **Figure 4 (a)** shows the reflection response for increasing rounding time after PVD deposition of the TCO film, while **Figure 4 (b)** shows the wavelength (λ) where the minimum in reflection happens according to rounding time, for wafers of experiment 1.

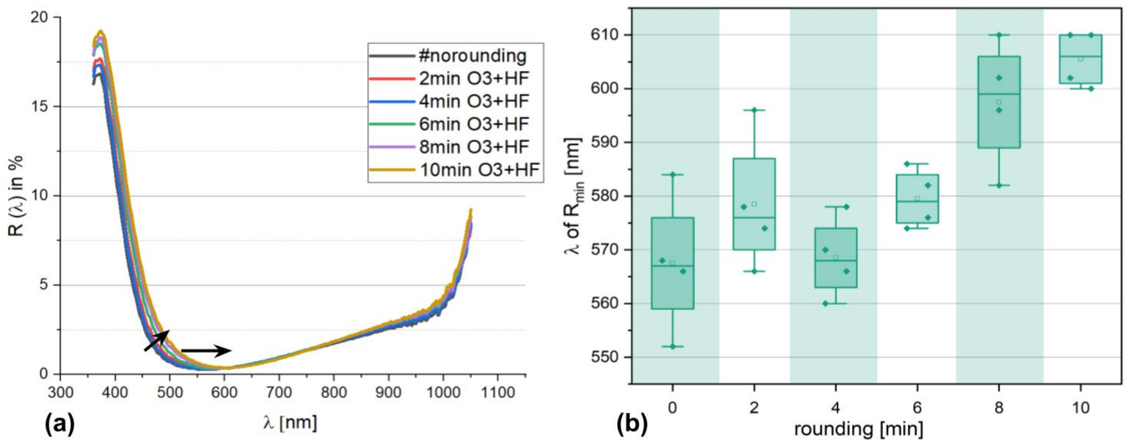

Figure 4: Reflection behavior of wafers after PVD deposition of TCO (in this study, ITO) for wafers of experiment 1 without regard to texture size. **(a)** UV-Vis reflection between 300 - 1050 nm. **(b)** Wavelength (λ) where the minimum in reflection happens according to rounding time.

After TCO deposition the reflection curves changed their shape when compared to that of the wafer after PECVD deposition of a-Si (**Figure 3 (a)** and **(b)**) alone, showing a minimum in reflection at around 575 nm. As can be seen from **Figure 3 (a)**, as rounding time increases, the curves shift themselves from lower to higher wavelengths (left to right). This shift in reflection is quantified in **Figure 4 (b)**, where the wavelength where the minimum in reflection happens is plotted against rounding treatment time. Considering the availability, the current cost, future demand of elemental Indium for solar cell applications, Ozone-rounding might be an effective way to reduce ITO material consumption and, thus, cost reduction.

3.3. Paste Laydown

The results for the amount of paste deposited per texture size are shown in **Figure 5**.

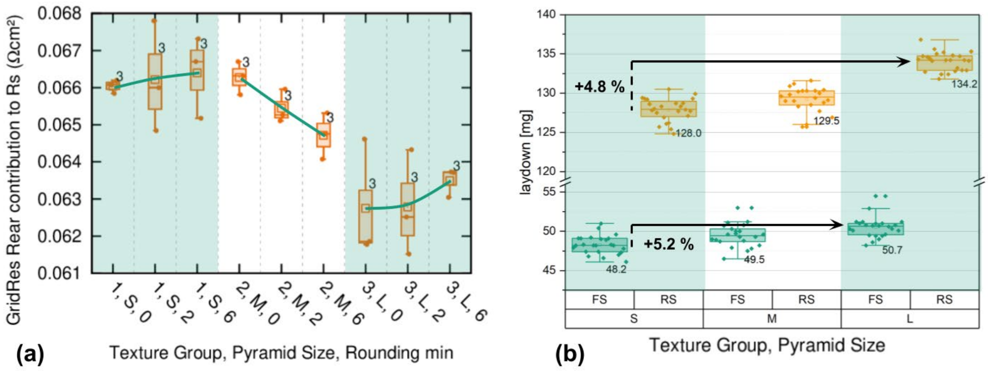

Figure 5: Paste laydown results for cells of experiment 2. **(a)** Rear-side contribution to the series resistance according to texture size and O_3-rounding treatment time. **(b)** Mass of paste laydown according to side (front-side (FS) or rear-side (RS)) and texture size.

Figure 5 (a) shows an expected decrease in paste laydown for decreasing texture height, a result that was also found by other investigations [3]. The material explanation for this is that, as the texture size increases, the silver particles present in the paste matrix can more effectively fill the holes between the pyramids of the texture, leading to an increase in spread.

3.4. Cell and Module Parameters

Results for the cell parameters of cells coming from experiment 2 are shown in **Figure 6**.

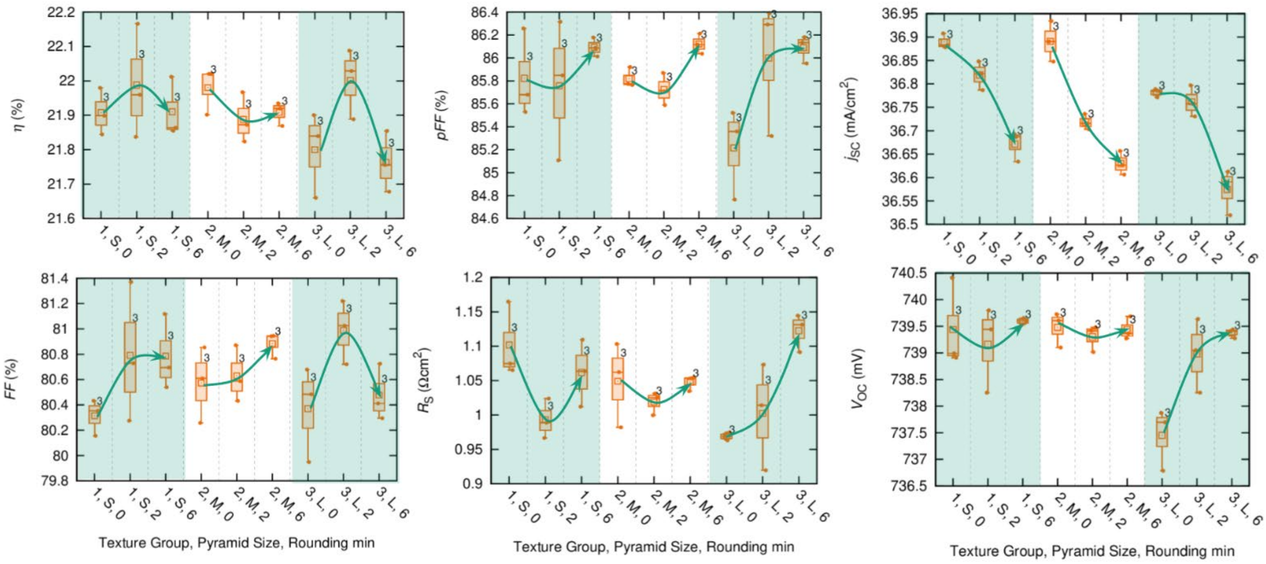

Figure 6: Cell parameters for cells coming from experiment 2.

A clear decrease in the short-circuit current density (J_{sc}) is seen for all 3 texture sizes with increasing O_3-rounding time. This is expected, as the smoother surface delivered by the rounding increases reflection, as shown by experiment 2. For the open-circuit voltage (V_{OC}), we would expect that with increasing rounding time, we would see an enhancement in the cells' surface passivation, leading to an increase in V_{oc} with increasing rounding time. Even though this trend follows for the L size texture, it does not for the S and M sizes, which show a more or less constant trend for the 3 rounding times. This unpredicted behavior may be due to the number of samples analyzed, which was relatively small (3 samples per group). As the trends seen for the V_{OC} do not repeat themselves for the FF, we decided to take the pseudo-FF (pFF) as a figure of merit for the cells' quality. The reason for the difference between the trends for the FF and pFF could not be pointed out. In terms of the cells' efficiencies, a maximum is seen at 2 minutes of rounding for the S and L texture, albeit for this is a minimum for the M size. This goes in accordance with the findings by Moldovan et al. [3].The results for the modules are shown in comparison to those for the cells in **Figure 7** in terms of the difference between the values of the parameters for the two (Cell to module variable differences).

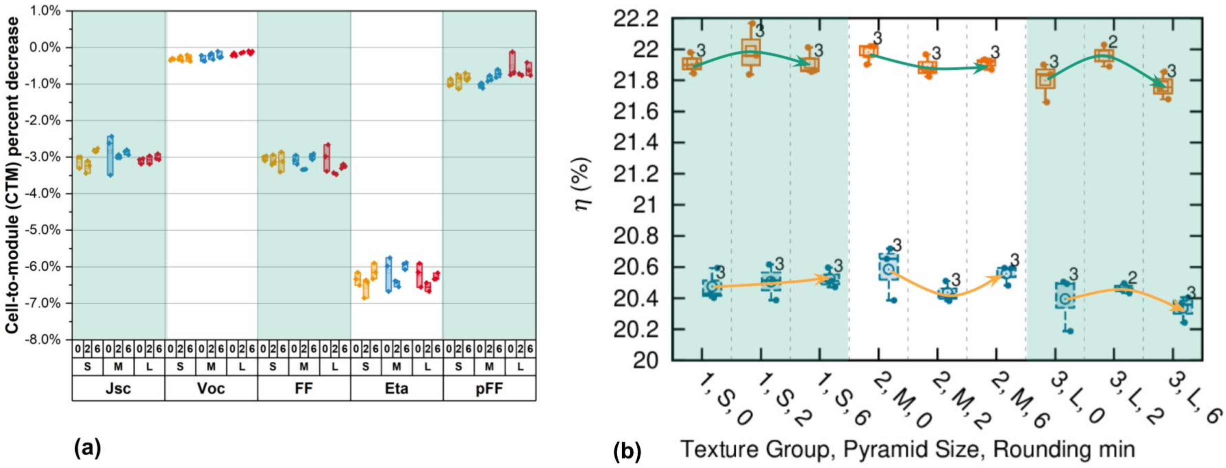

Figure 7: **(a)** Cell-to-module differences between the variables. **(b)** Comparison of absolute PCE (η (%)) for cells (orange) and modules (blue).

For all texture sizes, a decrease of around -3 % in J_{sc} can be seen for all texture sizes. In terms of the rounding time, a small increase can be seen with time, which may or may not be meaningful, but whose contribution could only be better gauged with a higher amount of samples. We attribute the major part of the loss in J_{SC} due to reflection from the module glass. For the FF, we see also a large difference between the two, with the module showing a decrease of around -3 % for all texture sizes. We attribute this decrease to series resistance losses caused by the cells' configuration (5 busbars), which significantly increases the current pathway. Finally, as a cumulation of these effects, the PCE shows a comparative decrease of around -6.5 % for all texture sizes from the cell to the module, a value that represents a -1.6 % loss in the absolute PCE value.

4. Conclusions

In this study, we have investigated the effect of O_3-rounding for different times in different texture sizes. Even though we aimed at obtaining 3 different texture sizes, analysis of pyramid sizes of LEXT images has shown that the S and M ranges were the same. Reflection measurements after PECVD support the conclusion that Ozone-rounding has a more pronounced effect in smaller (S) than larger (M) sized textures. Reflection measurements after ITO deposition, on the other hand, show that TCO thickness and deposition and time could be reduced after rounding. Regarding paste laydown, both grid-line resistance and paste laydown mass show that the amount of paste needed for metallization increases with increasing texture size.

The I-V results for the cells, an expected decrease in J_{SC} is seen for all texture sizes, while the results for V_{OC} varied for different sizes, with L being the only range for which an expected increase was observed. In terms of the efficiency, a maximum in efficiency is seen at 2 minutes of rounding for the S and L texture sizes, with a minimum for the M size at the same time. For the modules, two significant decreases of around -3 % are seen for all texture sizes in J_{SC}, while values for V_{OC} remained approximately the same. For the final energy conversion efficiency, a significant decrease larger than -6 % is seen when comparing the results for the cells to those of the modules. In absolute terms, nonetheless, the decrease in efficiency was of around -1.5 % PCE for all texture sizes.

Data Availability Statement

Data from some but not all experiments can be found in the Fraunhofer repository Fordatis in the link https://fordatis.fraunhofer.de/handle/fordatis/337 or http://dx.doi.org/10.24406/fordatis/276.

Author Contributions

Conceptualization: A.Steinmetz. Methodology:S.Pingel, K.Krieg, A.Steinmetz. Investigation: P.Sansoldo, S.Pingel, K.Krieg, A.Fischer, I.Vulvanean, M.Zimmer. Formal analysis:P. Sansoldo, S.Pingel, I.Vulcanean, A.Fischer. Writing: P.Sansoldo, S.Pingel, A.Steinmetz.

Competing Interests

The authors declare no competing interests.

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