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APPEARANCE OF RIFT STUCTURES CREATED BY ACIDIC TEXTURIZATION AND THEIR IMPACT ON SOLAR CELL EFFICIENCY

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ABSTRACT

For effectively textured silicon surfaces for solar cell applications two sometimes contradicting preconditions have to be met. On the one hand a roughening of the surface which reduces the amount of incident light reflected on the surface and leads to higher short circuit currents and on the other hand a minimization of the total surface area which results in higher open circuit voltages [1]. Acidic texturing of multi-crystalline silicon (mc-Si) wafers often leads to rough surfaces with strong etch attacks (rift structures) especially at crystal defects. However, in this work we come to the conclusion that, besides the rift structures slightly increase surface area and might also decrease parallel resistance, they do not have a significant influence on solar cell efficiency as well as on open circuit voltage, short circuit current and fill factor. Moreover, the rift structures are an indicator for material quality. Furthermore, in this work is has been found that for these acidic created textures surface roughness correlates with weighted reflection and hence only one of these parameters has to be measured.

RIFT STRUCTURES

Acidic texturing of multi-crystalline silicon (mc-Si) wafers often leads to rough surfaces with strong etch attacks (rift structures), especially at crystal defects. These rift structures are very rough, narrow (ca. 3µm) and a few micrometers deeper than ordinary etch pits as shown in figure 1. Because of their rough surface rift structures appear as dark lines on the wafer surface. On a microscopic scale these lines are straight and often parallel to each other (figure 1c). On a macroscopic scale they appear in ball-of-wool-like clusters (figure 1a).
Rift structures are caused by preferred etching at crystal defects such as dislocations and grain boundaries as can be seen in figure 2, where the etching at crystal defects is preferred in comparison to the other sites of the material. Crystal defects are more strongly attacked at a low etch rate than at a high etch rate [2]. So it is possible to reduce the fraction of surface area covered by rift structures f_R. The objective of this paper is to find out if such a reduction of f_R is necessary.

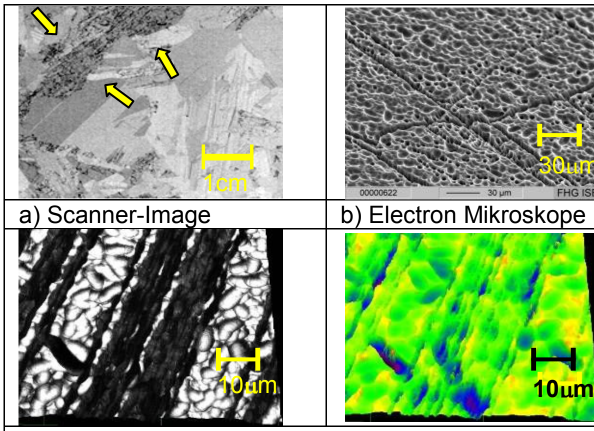

Fig 1: Typical images of rift structures: a) a scanner-image, rift structures are visible as dark lines and their location is highlighted by yellow arrows, b) electron microscope, c) confocal microscope images

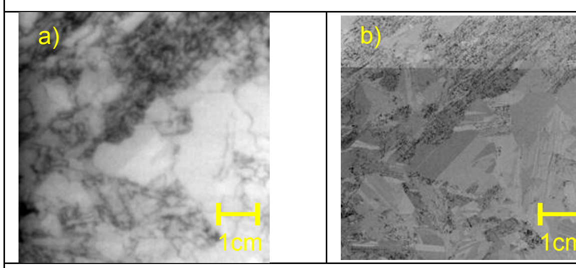

Fig 2: a) a typical photoluminescence image (PL-image) of a 60mm x 60mm part of a wafer in as-cut state. Crystal defects are visible as dark lines, b) scanner-Image of the same sector of the same wafer after texturing. Rift structures are visible as dark lines and lie at the same positions as the crystal defects in the PL-image.

The appearance of rift structures on the wafer surface has already been mentioned in earlier publications and was often recognized as harmful for solar cell performance [3]. Rift structures could lead to shunts after firing because the passivation-layer inside them is thinner. If a contact finger is fired at such a position with thin passivation-layer the used glass frit could etch through the emitter and the finger metal could hence form a contact with the solar cell rear side. Furthermore the solar cell surface area is enhanced by rift structures leading to more surface recombination. Wafer breakage is also increased by the appearance of rift structures [3]. On the other hand rift structures offer an impressive reduction of surface reflection which might compensate some of their negative effects. As rift structures have often sharp tips preferred a hard breakdown under reverse bias can occur in these regions [4]. This is bad for modules but should not have any effect on solar cell efficiency.

EXPERIMENTAL

In this work approximately 150 mc-Si solar cells were fabricated with the standard screen printing process at Fraunhofer ISE. The wafers from different vendors have been selected due to their original material quality (e.g. crystal defects), representing a typical cross-section of industrially available mc-Si materials. The fraction of these recombination active defect areas (f_R) was quantified in as-cut state via photoluminescence (PL) imaging and is, as shown by Haunschild et al. [5], a reliable method to measure the material quality.
Furthermore a texture variation was performed in which three different texturizing methods were used:

1. An acidic texturising-method with $HF/HNO_3/H_2O$ leading to a rough surface (strong texture).
2. A second acidic textrising-method with $HF/HNO_3/H_2O/HOAc$ in high concentrations leading to a high etch rate. This yields a smoother surface which reflects more light (weak texture).
3. An alkaline (KOH) standard damage etching method.

After texturing, images of the wafer front side were made using an inline color vision system [6] (figure 3a). This system meets the requirements of diffuse irradiation which is needed to reduce the disturbance by different grain reflection [7]. With these images and an appropriate computer algorithm, the fraction of rift structure area f_R on the wafer surface was quantified (figure 3b-c). In order to correlate the impact of the texture induced rift structures with the latter solar cell performance, further PL-images and IV characteristics were recorded on the finished solar cells.

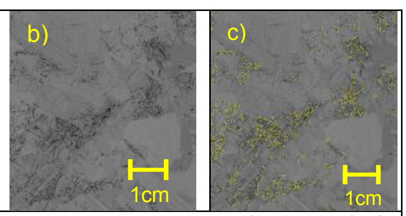

Fig 3: Measuring the fraction of rift structure area f_R: a) the color vision system in the MANZ Zelltester using a line camera, b) a typical image with this camera system, c) rift structures marked in yellow on such an image

To analyze the impact of the texture on the solar cell efficiency two additional parameters have been determined after texturization: Weighted reflection and surface roughness, which is defined in next paragraph. Surface roughness has been determined using a confocal microscope at a magnification of 2160x. The confocal microscope scans are more inhomogeneous for the strong texture (texture number 1) than for the weak texture (texture number 2) as well as for the texture created by the alkaline etch bath (texture number 3). Therefore, the created textures with the strong texture bath (number 1) have been measured three times and their arithmetic average was used for further analysis.

SURFACE ROUHGNESS MEASUREMENT

The RMS roughness of the measured height data points is commonly used to characterize the textured surface. However, it has already been shown by Souren et al. that the RMS roughness is not sufficient to describe the surface roughness completely [8, 9]. For acidic textures the RMS roughness has often more or less the same value and hence cannot be used as the only statistical parameter to describe the surface quantitatively. This can be explained by the fact that the RMS roughness describes only vertical roughness and does not take second order statistics such as lateral correlation length into account. In order to consider also the lateral structure features it is investigated in this work that the best measure for surface roughness is the surface enlargement (E) after texturization compared to a polished surface:

$$E = \frac{\textit{area of a textured surface}}{\textit{area of a same size polished surface}}$$

For isotropic texturing the surface enlargement is theoretically between 1 (for a polished surface) and 2 (a surface covered by half ball like etch pits) [10].

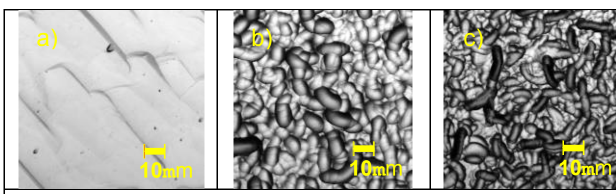

Fig 4: Typical surface structures of a) damage etch, surface enlargement E = 1.0, b) weak texture, E = 1.3, c) strong texture, E = 1.7

In our experiment surface enlargements of ca. 1.0, 1.3 and 1.7 have been determined for damage etched, weak textured and strong textured wafers respectively (figure 4). To get an impression on the surface enlargement due to rift structures, regions with lots of rift structures were also examined. They have a surface enlargement of around 2.5 (,because etching is not isotropic in these regions any more surface enlargement can be greater than 2.0.).
Figure 5 shows that for our experiments surface enlargement correlates with the weighted reflection. This means that for further analysis of our results only one of

these two parameters has to be taken into account. We decided for the weighted reflection, because it has already widely been used for texture analysis. The correlation between the surface enlargement and the weighted reflection only holds for acidic textured surfaces and alkaline damage etched surfaces. A higher reduction of the weighted reflection per surface enlargement is possible for textures with random pyramids (figure 5) which could possibly lead to higher solar cell efficiency. Therefore, new textures can be developed and quantified by determination of the surface enlargement.

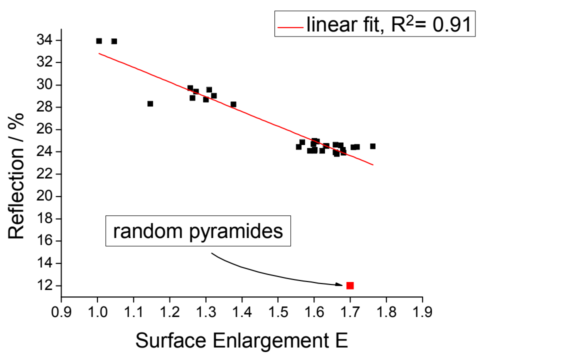

Fig 5: Dependency of weighted reflection after texturizing as function of the surface enlargement after texturing: A linear correlation can be observed for the used acidic and alkaline textures. However, other textures such as random pyramids do not follow this trend.

EXPLAINING SOLAR CELL EFFICIENCY

As a first results it is shown that crystal defects in as cut-material lead to rift structures in textured material at the same positions as the crystal defects (figure 2), which is has already been reported in literature [11], [12]. Many recombination centers in low-quality material lead to many rift structures after texturing with the first method (strong texture). A similar trend can be observed with the second texturing method (weak texture), however, the total fraction of rift structure area f_R is drastically reduced (figure 6).

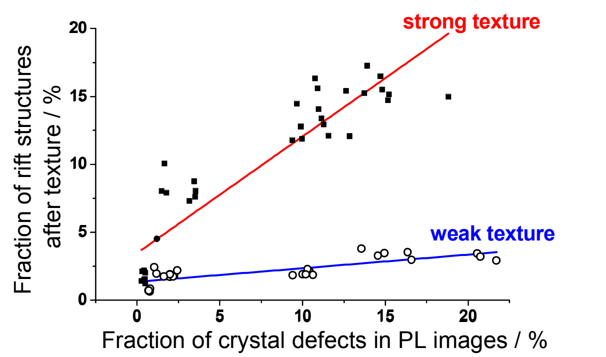

Fig 6: Relation between material quality and texture: The fraction of rift structure area f_R on the wafer surface as well as the fraction of crystal defect area f_{CD} in as-cut PL-images has been quantified using a newly developed algorithm. It is observable that using a material of high quality (low f_{CD}) yields fewer rift structures after texturing. Also the weaker texturing method (marked with open circles) leads to a decrease of f_R.

The fraction of rift structure area (f_R) in low-quality material is determined to be between 3 and 4% for the weak and between 12 and 17% for the strong texture. Assuming a surface enlargement of 2.5 in rift structure areas, as mentioned before, surface enlargement for the weak texture is about. 1.34, instead of 1.30 if you do not take rift structures into account. In case of the strong texture taking into account rift structures leads to a surface enlargement of about 1.81 instead of 1.70. So the surface enlargement due to rift structures is slightly reduced by using a weaker texture.

Besides the assumption that a texture with more rift structures causes more surface enlargement another assumption was that such a texture causes more shunts. In our experiment no shunts have been observed, but as can be seen in figure 7 a significant decrease in parallel resistance is caused by the more rift-structures covered texture 1 (strong texture). The decrease in parallel resistance could be caused by the rift structures and/or caused by the different surface morphology. As can be seen from the relatively high R_p-values, the surface passivation using PECVD a-SiN_x:H, deposited using the Linear Microwave technique, works quite well. With a different passivation method e.g. a sputtered a-SiN_x:H, a strong texture causes is an increase of shunts [13]. Due to a slight increase in surface area and only a small decrease in parallel resistance caused by the rift structures, the rift structures should affect the open circuit voltage (U_{oc}) and the short circuit current (j_{sc}) .

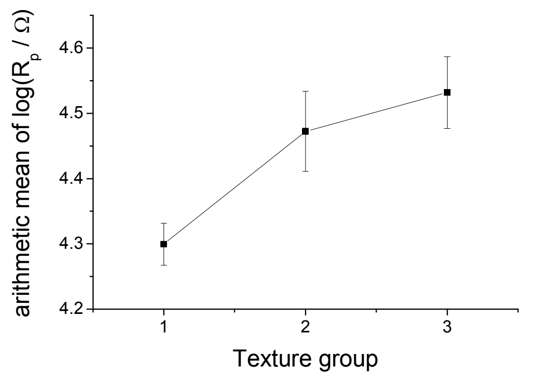

Fig 7: Impact of texture group (1 = strong texture, 2 = weak texture, 3 = damage etch) on parallel resistance R_p: The error bars correspond to the standard error of the mean. It can be seen that a weaker texture (texture group 2 and 3) leads to a reduction of R_p.

From figure 8 it can be seen that within a texturing group a decrease in the fraction of rift structure area f_R leads to an increase in solar cell efficiency. However, the two texturing groups show different behavior. It follows that rift structures after creation of the texture cannot be the only reason for the decrease in solar cell efficiencies. Moreover, they seem to be an indicator for material quality and the low material quality causes the solar cell efficiency losses.

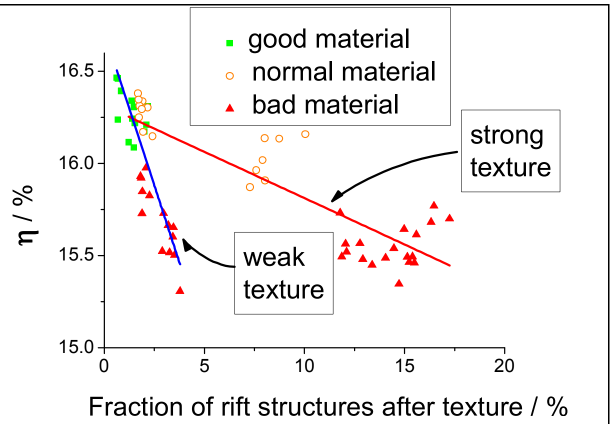

Fig 8: Dependency of solar cell efficiency obtained from IV characteristics on the fraction of rift structure area f_R after texture: The efficiency is decreasing with increasing f_R. However the two different texturizing groups show different behavior. Group 1 is fitted with a red line and group 2 with a blue line. Three different material qualities are marked with different symbols. It follows that rift structures after texture cannot be the only cause for the decrease of efficiencies. Moreover they are an indicator of the material quality.

The hypothesis that rift structures are only an indicator for material quality needs more justification than figure 8. To get more insight in the relevance of rift structures for solar cell efficiency, a detailed statistical analysis was performed where a statistical model, that takes into account quadratic factors as well as linear second order interactions, was used (corrected R^2 = 0.80 for eta). Surprisingly this model needs only two factors: The fraction of crystal defect area f_{CD} on PL images and the weighted reflection of the wafer surface. Figure 9 shows that rift structures are not important to explain the solar cell efficiency. This also holds for the short circuit current j_{sc}, the open circuit voltage U_{oc} and fill factor FF.

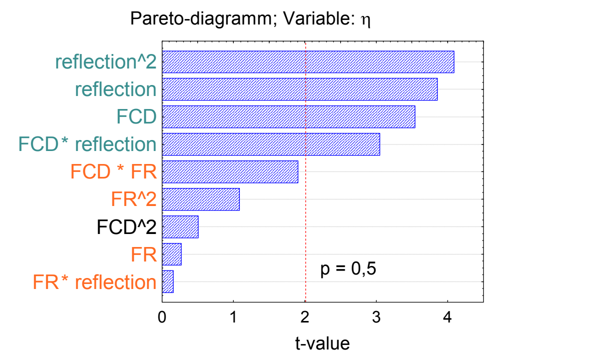

Fig 9: Pareto-diagram for solar cell efficiency η: All parameters that are related to the fraction of rift structure area (FR) are marked in orange. Only weighted reflection and the fraction of crystal defects (FCD) that have impact on solar cell efficiency and are marked in green. It can be seen that rift structures have no significant influence on solar cell efficiency.

Figure 10 shows that solar cell efficiency has its maximum at minimum fraction of crystal defect area (f_{CD}) in PL images and at 27% reflection. A higher weighted reflection than 27% leads to too low quantum efficiency, a lower weighted reflection leads to a too rough surface since surface roughness and reflection are correlated (figure 5). As can already be seen from figure 9 there is an interaction between f_{CD} and weighted reflection. This interaction means that in the case of bad material quality a 0.5% higher reflection increases solar cell efficiency. The reason for this interaction might be that it is better to use a weaker texture on bad material in order to avoid rift structures. However, the improvement in the solar cell efficiency is only small, because at higher f_{CD}, the efficiency is almost independent of the weighted reflection. Even though rift structures play no role in the used model, the interaction of material quality and weighted reflection might be due to rift structures. The influence of rift structures could not be seen, because our algorithm to quantify their amount is still not accurate enough.

The negative effect of surface roughness can also be observed from the model plot of open circuit voltage (corrected R^2 = 0.89). A high weighted reflection leads to higher open circuit voltage which is due to the smoother surface. As short circuit current depends on quantum efficiency as well as on surface recombination velocity, its model plot resembles the plot for solar cell efficiency ($R^2_{corr.}$ = 0.78). The fill factor can not be modeled well ($R^2_{corr.}$ = 0.68). Here other effects from the following process steps might have a significant impact.

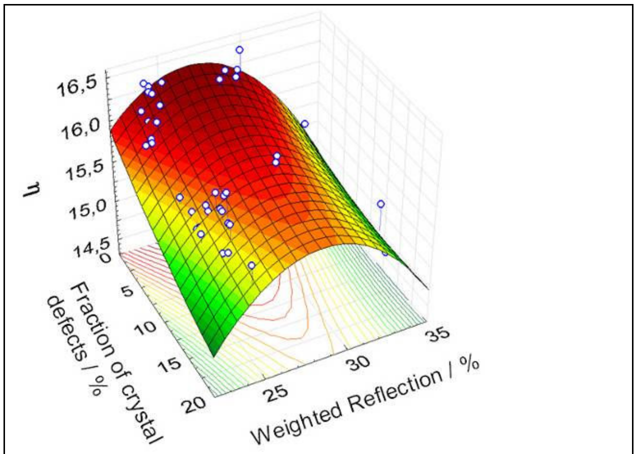

Fig 10: Fitted model for solar cell efficiency obtained from Current-Voltage (IV) characteristics (corrected R^2 = 0.80): Real measured values are marked with blue circles. The solar cell efficiency depends only on the amount of recombination centers in PL-images (material quality) and on the used texturing method. A better material quality leads to a higher solar cell efficiency. This trend is most pronounced for the weak texture where also the best efficiencies have been obtained.

CONCLUSIONS

A detailed analysis was performed on 150 solar cells examining the influence on solar cell efficiency, open circuit voltage, short circuit current and fill factor, as function of the material quality (before texturing) and weighted reflection, surface roughness and rift structures caused by acidic texturing. The surface roughness has not to be taken into account separately, because it correlates to the weighted reflection. The remaining parameters that are taken into account are the weighted reflection, rift structures and the material quality.

The fist result of our analysis is that rift structures are a good indicator for material quality as can be seen in figure 8. Furthermore, in this analysis a good model (corrected R^2 = 0.80 for the solar cell efficiency , $R^2_{corr.}$ = 0.78 for the short circuit current , $R^2_{corr.}$ = 0.89 for the open circuit voltage and $R^2_{corr.}$ = 0.68 for the fill factor) has been determined. This model needs only weighted reflection and the amount of crystal defects from PL images. It predicts the highest solar cell efficiency in the case of a high material quality and a weighted reflection of 27%. In the case of bad material quality it is slightly better to have a 0.5 % higher weighted reflection than the weighted reflection of 27 % in the case of better material quality. This relation between material quality and weighted reflection might be caused by rift structures.

In our experiment rift structures only do not lead to any shunts and only a slight decrease in parallel resistance (from 28kΩ to 20kΩ) is detected by using the strong texture instead of the weak texture. So the PECVD a-SiN_x:H, deposited using the Linear Microwave Plasma technique, works quite well. Surface area is slightly increased due to rift structures. However no statistically significant direct impact of them on any solar cell parameter could be seen in our model and this might be because:

a) The effect of rift structures is negligible.
b) The algorithm to quantify rift structures is not precise enough yet.
c) The negative effects of rift structures are compensated by their reduction in weighted reflection.

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