Mono-cast silicon recently became available in volumes relevant for industrial scale production of solar-cells. One important question in this field is how these wafers can be classified into quality groups and how this can be specified and measured. This paper discusses solar-cell efficiency distributions of mono-cast wafers which were obtained in first tests using an industrial cell process using acidic and alkaline texturing. High efficiencies up to the level of Czochralski mono wafers could be obtained for single wafers. The (optical) classification based on the percentage of \(<100\) oriented area is shown to be insufficient to predict and guarantee a good separation of high quality and low quality wafers, because also \(<100\) oriented grains can contain high defect densities. An analysis of the defects structures in the wafers and cells using photoluminescence, electroluminescence and defect etching reveals that the amount of defects generated at boundaries of seed crystals depends strongly on the alignment of the seeds and that the structural defects can be separated in the same defect classes as observed for standard multicrystalline silicon wafers. For a good sorting and specification of mono-cast wafers in the future, the further development of methods to measure and quantify crystal defect structures will therefore be essential.

Keywords: Multicrystalline Silicon, Mono-cast Silicon, Defects

1 INTRODUCTION

Mono-cast silicon is produced using a conventional directional solidification process with additional seed crystals placed on the bottom of the crucible and an adapted thermal profile for melting of the feedstock material and crystallization of the ingot. In the centre part of the ingot, the material grows monocrystalline with a \(<100\) orientation. Edge and corner areas of the ingot grow partially multicrystalline due to nucleation at the crucible. This detrimental effect is enhanced towards the top of the ingot. The high monocrystalline fraction and the reduced crystal defect density of mono-cast wafers offer the potential of higher solar cell efficiencies.

The development of mono-cast silicon can be considered as another example of a so-called hype cycle describing an emerging technology [1]. This hype cycle is characterized by five phases. Phase 1, the “technology trigger”, was the development of BP Solar’s Mono²-Wafer, details of which were published in 2008 [2,3]. This was followed by an enthusiasm leading to phase 2, the “peak of inflated expectations”, which was reached in the middle of 2011. Several companies launched mono-cast based products yielding high efficiencies and improved performances. Phase 3, the “trough of disillusionment”, was reached rapidly at the beginning of 2012, caused by the understanding that numerous defects are present in the mono-cast material, impacting on the solar-cell efficiencies.

Phase 4, the “slope of enlightenment”, is expected to develop a deeper understanding of the realistic potential and obstacles of the technology, followed eventually by phase 5, the “plateau of productivity”, where the true usefulness of the new technology is demonstrated. On which time scale and to what extent phase 4 and 5 will be realised, is currently an exciting question.

In this paper we will present very promising cell results obtained using mono-cast silicon wafers showing the very high potential, but on the other hand also discuss some of the problems in crystallization and especially the classification of the wafers in different quality classes and the impact of defects on solar-cell efficiencies.

2 EXPERIMENTAL METHODS

Solar-cells were produced in industrial cell production lines using acidic or alkaline texturing. Contacts are formed by screen printing and cells are measured and classified directly after firing furnace using an industrial cell tester.

The structural defect density (SDD) is determined in a simplified matter using defect etching and a flat bed scanner. The so called “red area fraction” used here gives approximately the area of the wafer with a defect density equivalent to dislocation densities above \(5 \times 10^8 \text{ cm}^{-2}\). Details of the method are described elsewhere [4].

Photoluminescence (PL) and Electroluminescence (EL) images were recorded using a BT Imaging LIS-R1 tool. PL intensities reported are corrected for the influence of resistivity for measurements on wafer level, because low injection conditions are assumed [5], averaged over the wafer / cell area, and normalized to the maximum value. Reverse biased EL at -14V (ReBEL) and sub band EL (EL-sub) images were acquired at the Fraunhofer CSP using a Si or an InGaAs charge coupled device (CCD) camera in order to detect band to band and sub-band defect luminescence, respectively. These measurements are then combined to classify the defects found according to [6].

3 CORRELATION BETWEEN \(<100\) FRACTION AND SOLAR-CELL EFFICIENCY

3.1 Optical wafer classification

Mono-cast wafers are commonly classified by the area fraction of the \(<100\) oriented grain using an optical inspection system. The classification scheme differs between the different wafer suppliers but usually three classes are provided (e.g. for wafers in this study class 1: 

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100%-90% <100>; class 2: 90%-70%; class 3 70%-0%.

Examples of wafers according to such classification schemes are shown in Fig. 1.

![Figure 1: Optical images of wafers taken from different mono-cast classes, showing the different area fractions of the <100> oriented grain, (a) class 1; (b) class 2; (c) class 3. The vertical line is a measurement artefact](image)

3.2 Solar-cell efficiency distribution

In order to test the relationship between the optical classification and the solar-cell efficiencies, mono-cast wafers from all three classes were tested in industrial relevant volumes. Fig. 2 shows the comparison of the solar-cell efficiency distributions of standard multicrystalline (mc-Si) and mono-cast materials of different qualities. For class 1, we found a relative increase of the position of the distribution maximum of about 5%; see Fig. 2(a). However, the cell efficiencies are not Gauss-distributed as in the case of standard mc-Si. There is a significant broadening of the distribution to lower cell efficiencies. Whereby class 2 still yields an increase of the distribution maximum of about 2%, class 3 can be regarded as equivalent to standard mc-Si.

Averaging over all three distributions yields a broader efficiency distribution compared to standard mc-Si with a slight shift to higher cell efficiencies. The magnitude of this shift is determined by the relative share of these three classes over the whole ingot.

3.3 Center-, corner- and edge-bricks

In order to get a better understanding of the distribution of the <100> area fraction and its influence on solar-cell efficiency, sorted bricks from the center, edge and corner of a mono-cast ingot were investigated.

As it can be seen in Fig. 3a, the area fraction of the <100>-grain differs considerably between the three bricks as well as over the ingot height. In the center brick, the <100>-area fraction is between 95% and 100%. In the edge brick it decreases from about 95% to 20% and in the corner from about 75% to 0%, i.e. the seeded <100>-grain orientation completely disappears.

The solar-cell efficiencies, normalised to the maximum and plotted against the <100>-fraction are shown in Fig. 4. For the center brick, all wafers would have been in class 1 and also all cells have an efficiency clearly above the level of standard cells. However, for the corner and edge brick, the correlation is really not sufficient for a good sorting.

Considering this relation of <100>-area and efficiency it becomes therefore clear, that the area of the <100>-grain is not the only parameter determining the achievable efficiency.
2.4 Comparison of acidic and alkaline textured cells

The potential of mono-cast silicon was further evaluated by a comparison of acidic and alkaline textured solar-cells. As an example for this comparison a particular brick with a strong variation of the <100> fraction is shown in Fig. 5. Wafers of this brick are 100% <100>-oriented from the bottom up to approximately 40% of the ingot height. In the direction of crystallization, the monocrystalline area fraction decreases to 20% wafer area at the top of the ingot.

Neighbouring wafers of this brick were processed to solar-cells using acidic and alkaline texture. Cell results are depicted in Fig. 6.

Though being 100% monocrystalline, the bottom part yields low efficiencies for both processes due to impurity diffusion from the crucible. Between 15% and 40% of the ingot height, the alkaline textured cells show an efficiency gain up to 7.5% compared to the acidic textured cells. It should be mentioned, that the best cells reach the efficiency of Cz-Si solar-cells produced with the same process. With an increasing multicrystalline fraction, the advantage of the alkaline texture decreases and vanishes completely if the area of the <100> oriented grain is below 60% of the wafer area. This is mainly due to the poor texture on the multicrystalline wafer areas.

4 IMPACT OF DEFECTS ON SOLAR-CELL EFFICIENCY

In this chapter the defects in the mono-cast wafers are analysed in order to understand the observed poor correlation between <100>-fraction and solar-cell efficiency. Firstly wafers are analysed by PL (i.e. non-destructive and therefore suitable for use in solar-cell production and wafer sorting) and secondly by defect etching (i.e. destructive and not usable in solar-cell production). Finally also finished cells are investigated by PL / EL.

4.1. Photoluminescence on wafer level

In order to evaluate crystal defects in the mono-cast wafers firstly PL on wafer level was used. During the investigations one interesting example of defect generation in <100> oriented areas was observed.

Due to the use of a pattern of seed crystals on the bottom of the crucible, the alignment of the seeds is important in order to get a high wafer quality throughout the whole ingot height. As shown in Fig. 5, there are contact planes between perfectly aligned seed crystals (green) and contact planes, that have the potential to cause distorted crystal growth (red). When the seeds are not perfectly matched together these contact planes act as a source of small angle grain boundaries. Once generated, they multiply in the direction of crystallisation, as shown in Fig. 6 and the <100> oriented part of the wafer can have very high densities of structural defects. With an increasing density of these small angle grain boundaries, the advantage of mono-cast wafers reduces significantly. However, with an exact alignment of the seed crystals the contact planes are no drawback for mono-cast silicon.
Figure 7: Development of defects originating from seed joints investigated by PL imaging. Crystallization height: (a) ~ 5% (still in region contaminated by metals); (b) ~ 50%; (c) ~ 95%.

The correlation between cell efficiency and average PL intensity is shown in Fig. 8 for the cells from Fig. 3. As observed in [4] only a poor correlation was found. Reason for this behavior are that the metallic contaminations in the bottom of the ingots are gittered in the cell process and that some structural defects increase their recombination activity strongly during the solar-cell process and are barely visible in the as-cut wafer (see also 3.3).

Figure 8: Plot of mean PL intensity measured on wafer level vs. solar-cell efficiency. Please note that not all cells from Fig. 4 were investigated here.

4.2. Structural defect density

In order to make all structural defects visible independent of recombination activity we applied the simplified method described in [4] to determine the density of structural defects (“red area fraction”) in the wafers.

Figure 9: Defect Density (“red area fraction”) vs. crystallization height.

Figure 10: Defect Density (“red area fraction”) plotted vs. solar-cell efficiency. Cells in red circle are from ingot parts contaminated with metals (“red zone”)

In Fig. 9 and 10 the measured “red area fraction” for the three bricks over brick height and compared to efficiency are shown. The density of structural defects is very low for the center brick. For the edge and corner bricks, the density of structural defects increases strongly towards the top. Comparing “red area fraction” with solar-cell efficiencies (Fig. 10) a much better correlation
than the one found using PL on wafer level. The points in the red circle are wafers from the bottom of the bricks, which have a low defect density, but a reduced efficiency due to metallic contamination.

4.3. Classification of defects

In order to understand the types of defects and the reason for the poor correlation of PL on wafer level and solar-cell efficiencies in more detail, we classified the defects visible in the finished cells according to the scheme proposed in [6] into Type A and B defects combining EL, EL-sub and ReBEL.

The example in Fig. 11 reveals two recombination active defect types in the EL band-band image (Fig. 11a): small angle grain boundaries all over the wafer as well as dislocations clustering in the top part. Both defects show sub-band electroluminescence (see Fig. 11b) which is significantly more intense for the small angle grain boundaries. The ReBEL image at -14V exhibits only a pre-breakdown at the positions of the dislocation clusters (see Fig. 11c).

Figure 11: (a) EL band-band image; (b) EL sub-band image; (c) ReBEL image (-14V)

This result shows that the observed dislocation clusters can be classified as “Type A” defect with a lower defect luminescence and a soft pre-breakdown “Type II” and an increase of recombination activity during the cell process. The small angle grain boundaries originating from the contact planes of the seed crystals in mono-cast Si are so called “Type B” defects, characterized by a low carrier diffusion length, a high defect luminescence and a pre-breakdown behavior of “Type III” (avalanche breakdown).

4.4 Photoluminescence analysis of solar-cells

It was shown in [4] that the best correlation between cell performance and defect density can be observed if photoluminescence on cell level is used. In order to check whether this is also true for the investigated mono-cast wafers, PL on cell level was measured. The result is shown in Fig. 12 revealing a very good correlation between the two dataset.

Figure 12: Plot of mean PL intensity measured on cell level vs. solar-cell efficiency

In summary this shows that the defect types and their behavior in mono-cast silicon can be categorized in the same way as in standard multicrystalline silicon and also the correlation between the different measurements behaves like observed for standard multicrystalline wafers.

5. CONCLUSIONS

We presented the efficiency distributions of solar-cells made of mono-cast silicon wafers classified by an optical determination of the <100>-grain size. A relative efficiency gain of 5% was obtained for class 1, whereas class 3 is equivalent to standard mc-Si. However, the combined distribution of these three classes, representing all wafers from throughout the entire ingot, is broadened in comparison to standard mc-Si. The high potential of mono-cast silicon wafers with 100% <100> area fraction is demonstrated with an alkaline cell process, yielding efficiencies comparable to Cz-Si. It was demonstrated that the optical classification scheme is not sufficient to predict a narrow solar-cell efficiency distribution. Defect analysis revealed that the same defect types as in multicrystalline silicon exist and that small angle grain boundaries are “Type B” defects. As in the case of multicrystalline silicon the correlation between PL on cell level reveals better correlation with cell efficiencies than defect densities determined by defect etching or PL on wafer level, making a sorting of wafers and prediction of
efficiencies based on measurements on wafer level difficult.

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REFERENCES