NARROWER EFFICIENCY DISTRIBUTION FOR MULTICRYSTALLINE SILICON SOLAR CELLS BY DOUBLE-SIDE EMITTER DIFFUSION

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SUMMARY

Multicrystalline silicon solar cells produced with double side emitter diffusion are compared with single side emitter diffused cells. Double side emitter diffusion yields in improved current and voltage for all materials of four multicrystalline silicon wafer suppliers. Poor quality material improves approximately 3% more than good quality material. This results in a narrower efficiency distribution over all material. No relation between substitutional carbon concentration, interstitial oxygen concentration and FeB concentration and improved current due to double side diffusion was found.

INTRODUCTION

A major drawback of multicrystalline silicon (mcSi) solar cell processing is that it results in a very wide efficiency distribution compared to mono-crystalline silicon solar cells. This is caused by a wide distribution in material quality. Solar cell manufacturers handle this issue by demanding from wafer suppliers a certain distribution of material quality measured by effective lifetime, carbon or oxygen content or doping concentration. The wafer supplier then cuts off a certain amount of low quality material, which is not used or sold as a lower classified material. Also, cell manufacturers sell products with a wide range in power output. To avoid these negative aspects, researchers have been looking for improved processing conditions to obtain a narrower efficiency distribution.

During the course of earlier work [1], we discovered such an improvement by using double side instead of single side emitter diffusion. This process improves the low quality material substantially. We do not have a proven theory to explain this improvement.

The objective of this study is to find an explanation of why low quality material is improved. Also, we want to show that this improvement occurs for all kinds of material, independent of supplier. Therefore, we have collected data for mcSi wafers from four wafer suppliers and we have related these data to the solar cell characteristics after single or double side emitter diffusion.

EXPERIMENTAL METHODS

For this experiment 100 cm² mcSi wafers collected from four wafer suppliers are used. The wafers are selected from different positions in the ingot, namely from two columns (one from the middle and one from the edge) and five heights (1%, 25%, 50%, 75% and 99% of the maximum height).

For all experiments the phosphorus source is either applied on one or on both sides of the wafer by spin-coating. Cell processing was performed according to the so-called firing-through scenario (table 1). The I-V-characteristics are measured and the data are analysed with the analysis of variance method for mcSi solar cells as described by Weeber and Sinke [2, 3]. Also, spectral response is measured of selected cells.

Table 1. Scenario for firing through process

<table>
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<th>Firing through scenario</th>
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<tr>
<td>Saw damage etching</td>
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<tr>
<td>Emitter processing</td>
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<tr>
<td>PECVD- Si₃N₄/H</td>
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<tr>
<td>Metallisation (front/back)</td>
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<tr>
<td>Firing</td>
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Furthermore, a selection of neighbouring wafers of the cell experiment has been extensively characterised by lifetime and FTIR measurements. Concentrations of substitutional carbon and interstitial oxygen in wafers are determined by Fourier Transform Infrared Spectroscopy (FTIR). Before measuring, no thermal treatment is applied and the wafers are polished by chemical etching. The calibration constants used for conversion of absorbency to concentration were the ASTM-1995 standards: 1.64 ppma-cm for carbon (at ~605 cm⁻¹), and 6.28 ppma-cm for oxygen (at ~1107 cm⁻¹). The effective thickness of the floatzone reference wafer and the test wafers were matched using the Si phonon bands [4]. Carbon concentrations are systematically underestimated by approximately 10-30% due to the relatively small thickness of the wafer that does not allow a high-resolution FTIR.

Effective lifetime of the minority carriers is measured with the Sinton QSS-equipment [7,8]. The measurements were performed after saw damage etch and applying a Remote PECVD Si₃N₄ layer optimised for surface passivation. Using the lifetime measuring method, the Fe content in the wafer can be estimated by determining the change in lifetime due to FeB pair dissociation after light soaking [5,6]. The change in inverse lifetime is proportional to the number of dissociated FeB pairs (i.e., the interstitial Fe concentration: by far most of the interstitial Fe is paired at room temperature in thermal equilibrium).
RESULTS

Solar cell processing

The average values of the I-V-characteristics of the solar cells with single side emitter are shown in figure 1 (Isc) and 2 (Voc). In figure 3 and 4 the gains in current and voltage for double and single side emitter diffusion (determined as double side minus single side divided by single side times 100%) are presented.

Fig. 1. short current of solar cells with single sided emitters

Fig. 2. open circuit voltage of solar cells with single sided emitters

Fig. 3. gains in Isc for double side diffused emitters compared to single side diffused emitters

Fig. 4. gains in Voc for double side diffused emitters compared to single side diffused emitters

The plotted values in the figures are averaged over four samples (two neighbouring wafers from two different columns). All the data-points have a certain variation that is not plotted in these figures. The current and voltage of wafers from almost all positions is for double side emitter diffusion higher than for single side emitter diffusion. Material from the bottom improves for all suppliers about 3% in current and for supplier A and D about 1.5% in voltage. Material from the top of supplier A is of the same quality as inside the ingots, and shows hardly any improvement. The combined effect of gains due to double side diffusion is that the efficiency distribution becomes narrower because low quality cells improve more than good quality cells. For instance, for material B, the efficiency of cells varies by 14% with single side diffusion and by 10% for double side diffusion, which is a reduction in variation by 40%.

All combined experimental data is analysed using Statgraphics [3]. As indicated by Least Significant Difference (LSD) analysis, double side emitter diffusion improves short circuit current by 2.5% compared to single side diffusion with a probability of at least 95%. It improves open circuit voltage by 1% compared to single side diffusion with a probability of at least 90%. Spectral responses are measured on solar cells originating from bottom and top of a column. Internal quantum efficiencies have been determined from spectral responses and reflection curves. In figure 5, the gain (determined as double side minus single side times 100% and divided by single side) in quantum efficiency due to double side diffusion compared to single side diffusion is shown for bottom materials (for material B, position 25% is used). In figure 6, the gain in quantum efficiency is shown for top material. The gains in quantum efficiency show that the material quality in the bottom of a column improves for double side emitter diffusion compared to single side emitter diffusion for all four suppliers. This is in agreement with the gains in short circuit current. For material in the top of a column, only material A shows less gain in red response due to double side diffusion.
Effective lifetime and FeB concentration

The effective lifetime of the minority carriers was measured on wafers from one column received from all suppliers (figure 7). The measured lifetimes show some correspondence with the quality of the cells, low lifetime material from bottom leads to low quality cells. This is not the case for the top of the ingot, where very low lifetimes do not necessarily lead to poor quality cells.

According to the method explained before, a rough measure of the FeB concentration [ref5] can be calculated from the difference in lifetime before and after light soaking. The estimated FeB concentration for several materials is plotted in figure 8.

All ingots show increased contamination and reduced lifetime at top and bottom. The increased contamination is due to solid state diffusion of impurities from crucible and/or coating (bottom), or back diffusion of the segregated impurities in the top of the ingot. The contamination in the central region of the ingots is due to the contamination present in the liquid silicon during crystallisation, in combination with the limited segregation of Fe. Of course, in addition to the FeB pairs, precipitated Fe and other metallic impurities may be present in the wafers. This will vary from ingot to ingot, depending on aspects such as purity of crucible, purity and effectiveness of crucible coating, and purity of feedstock.

substitutional carbon and interstitial oxygen

The results from FTIR measurements are presented in figure 9 for the substitutional carbon content and figure 10 for the interstitial oxygen content measurement.

sub. carbon (ppma)
Diffusion. Based on the collected wafer characteristics it is therefore not possible to explain the exact reason why double side emitter diffusion improves the current and voltage. Probably additional contamination in the wafers is present, depending on the feedstock and crucible materials used for the crystal growth process. These can be in the form of precipitates, which dissolve during high-temperature processing. Measuring wafer characteristics after solar cell processing, like effective lifetime, substitutional carbon, interstitial oxygen and FeB-content during processing may provide more information on this. Measuring impurity concentration with DLTS, before and after thermal processes, may provide additional information.

CONCLUSION

Double side diffusion narrows the cell efficiency distribution considerable compared to single side diffusion. This is due to the fact that cell efficiency improves more for low quality material than for high quality material due to the change from single side emitter diffusion to double side emitter diffusion. Double side emitter diffusion improves the current from low quality material about 3% in the bottom and 2% in the top. This improvement can not be explained by FeB concentration, substitutional C concentration, or interstitial O concentration.

REFERENCES

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[6] for more extensive description, use, and interpretation of this technique for material and processing analysis, see L.J. Geerligs et al., to be published
[8] Sinton; WCT-100 photoconductance tool, Sinton consulting, Boulder, CO.

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