INCREASED WAFER YIELD FOR SOLAR CELLS IN TOP AND BOTTOM REGIONS OF CAST MULTICRYSTALLINE SILICON

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ABSTRACT: We present lifetime measurements and solar cell results of wafers cut out of the top and bottom region of a cast multicrystalline silicon block. Lifetime profiles of vertically cut wafers demonstrate the effect of two different emitter diffusion processes in the top and bottom region. The solar cell results on adjacent wafers show relatively high values especially for the top of the ingot. By processing solar cells on horizontally cut wafers we investigated the dependence of the cell parameters of the height in the top and bottom of the ingot. In the bottom region a process with a phosphorus-aluminium-codiffusion yields the best results. In the top a modified process with longer time on high temperature increases the cell efficiency further. In comparison with a normal phosphorus-diffusion process, an increased yield of up to 50 wafers per brick is possible by using adjusted processes.

Keywords: Lifetime, Diffusion, Solar Cell Efficiencies

1 INTRODUCTION

Multicrystalline silicon ingots manufactured by a casting process show regions of reduced minority carrier lifetimes in the bottom and top regions as well as in the edge regions. Lifetime measurements exhibit a width of the degraded regions of the order of 2-6 centimeters at the bottom and a usually smaller width at the top and the edges. Investigations in these degraded regions show a variety of defects [1].

An estimation of the solar cell parameters on the basis of the lifetimes found in these regions in the starting material predicts rather poor performance of the finished solar cells. Therefore the material from top and bottom regions with low lifetime is rejected before entering the solar cell process.

In this work we analyse the effect of different diffusion steps of a solar cell process on the minority carrier lifetime in bottom and top regions of a multicrystalline ingot. In parallel solar cells made out of material of the same regions are investigated. On the basis of the resulting solar cell parameters an assessment of the cut off heights of the investigated bricks is given for the applied processes.

2 LIFETIME INVESTIGATION OF TOP AND BOTTOM REGION

2.1 Preparation of wafers

We investigated wafers of the top and bottom region of a Solsix ingot. First two sets of wafers were vertically cut of an edge brick as can be seen in Fig. 1 on the right hand side. The wafer size is 100 mm x 100 mm. The sets cover the bottom region of the cast block down to a 2 mm offset, referred to as wafer set “vertical bottom” (VB), and the top region up to the block cap (VT). Secondly, horizontally cut wafers from a corner brick form another pair of sets. They are cut at around 15 mm, 25 mm and 35 mm distance from the bottom, referred to as wafer set “horizontal bottom” (HB) and in 10 mm, 20 mm and 30 mm distance from the top of the ingot (HT). After applying a wet chemical damage etch to all investigated wafers, reference wafers for each set of starting material were passivated with a PECVD-SiN_x layer on both sides for lifetime measurements.

In each set adjacent wafers were treated with two different phosphorus diffusion processes. The first diffusion consists of a $POCl_3$ diffusion on both sides at a temperature of 830 °C (diffusion 1). For the second process the wafers are coated with a 1 µm thick aluminium layer on the back side before the diffusion at 830 °C is applied (diffusion 2). The resulting emitter has a sheet resistance of around 80 Ω/sq. After the diffusion processes the aluminium layer and the layers of p-doped silicon on both sides were chemically etched and the wafers were passivated with a silicon nitride layer on both sides for lifetime investigations.

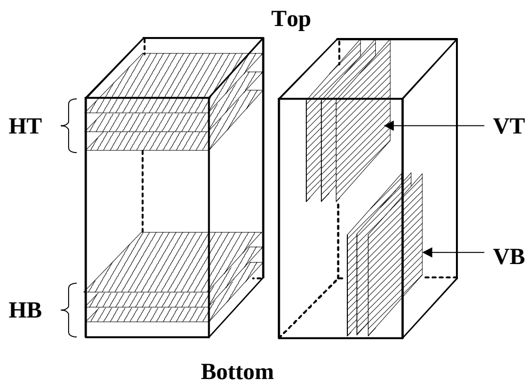

Figure 1: Position of horizontally and vertically cut wafers of bottom and top regions of two adjacent bricks

2.2 Lifetime measurement on vertically cut wafers

For the vertically cut wafers VB and VT images of the minority carrier lifetime were taken with the Carrier Density Imaging (CDI) method [2]. The measurement time was around 15 minutes per wafer. The starting material at the bottom and top of the ingot shows regions of very low lifetime. Assuming a lifetime threshold of 5 µs, the width of the poor lifetime regions is around 35 mm at the bottom and 25 mm at the edge of the wafer in set VB. In set VT the width is about 25 mm at the top and 8 mm at the edge of the wafer, respectively (Fig. 2).

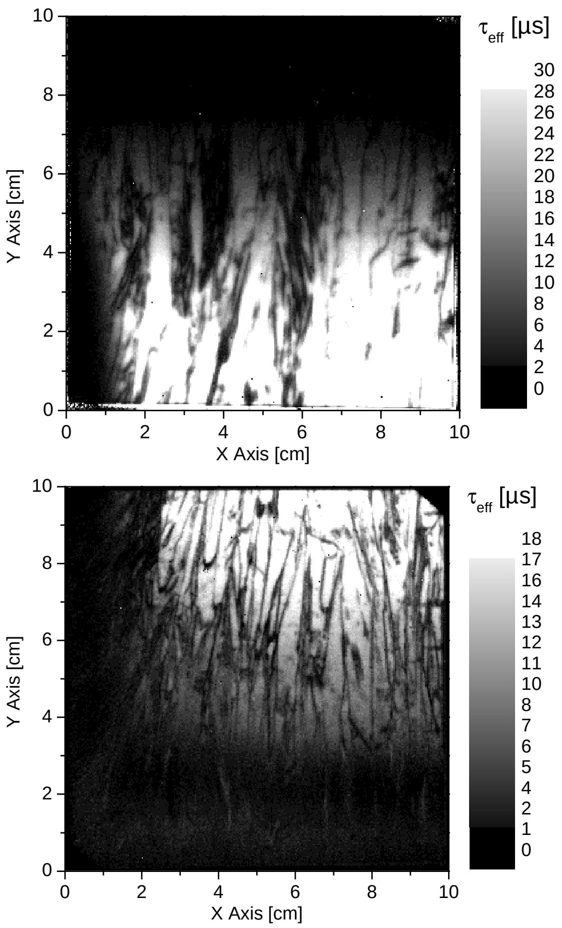

Figure 2: Lifetime images of starting material, vertically cut from top (wafer set VT, above) and bottom regions (wafer set VB, below)

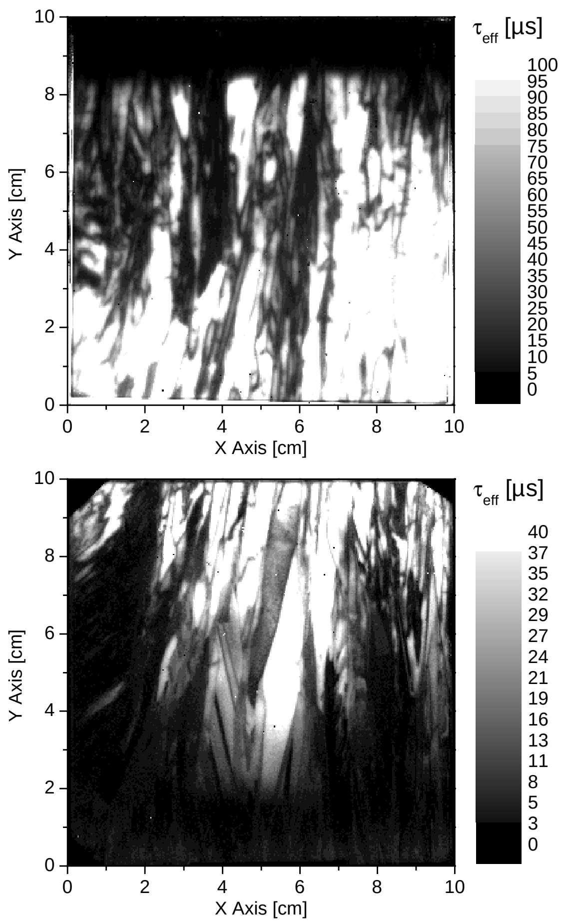

Figure 3: Lifetime images of vertically cut wafers, adjacent to samples of Fig. 2, after P-Al-codiffusion (diffusion 2)

Inside the ingot volume, areas of poor lifetime can be found extending along the growth direction.

Applying diffusion 1 to adjacent wafers of VB, the areas of very low lifetime are diminished by about 15-20 %. The reduction of poor areas after diffusion 2 for the top regions in VT is of the order of 40-45 % as can be seen in Fig. 3 (please note the change in scale). The regions of high lifetime are extended towards the edge of the ingot. Still areas of very low lifetime inside the ingot volume remain nearly unaffected.

For comparison of the material improvements due to the diffusion processes lifetime profiles are calculated for the lifetime samples of sets VT and VB. The lifetime values are averaged over horizontal lines parallel to top and bottom edge. To exclude any influence of the edge of the block, apparent as dark areas on the left border of Fig. 2, the first 4 cm in every line are neglected.

The averaging procedure uses a weighting function for the calculation of the expected solar cell results on the basis of an averaged material parameter, in this case the effective minority carrier lifetime [3]. In case of the applied cell process on multicrystalline material, the inverse of the effective diffusion length $1/L_{eff}$ represents a reasonable weighting function for the lifetime [4]. Assuming a constant mobility of the minority carriers throughout the wafers, the effective lifetime values were weighted by the arithmetic mean over the inverse square root of lifetime τ_i of every pixel i.

$$\tau_{weighted} = \frac{1}{\left(\sum_i \frac{1}{\sqrt{\tau_i}}\right)^2}$$

Fig. 4 and Fig. 5 show profiles of the weighted lifetime over the distance from bottom and top of the brick. In the bottom region (Fig. 4), diffusion 2 results in an overall improvement in lifetime. In comparison to the starting material a shift of the minimum from around 2.1 cm to around 1.5 cm can be observed. The same shift also occurs after diffusion process 1, but on a lower lifetime level. In the region near the bottom the lifetime even falls below the initial values. The shift of the minimum is not due to any obvious change in the crystalline structure between the adjacent wafers. The reason for this effect is still under investigation.

In the top region (Fig. 5) the difference in lifetime between the processes is far more prominent. We again observe a significant improvement after diffusion 2 and a less strong one after diffusion 1. Considering $\tau_{eff} = 5$ µs as a lifetime threshold for solar cell processing, this threshold is shifted from 4.4 cm below the top in the starting material to 2.0 cm after diffusion 1 and 1.4 cm after diffusion 2.

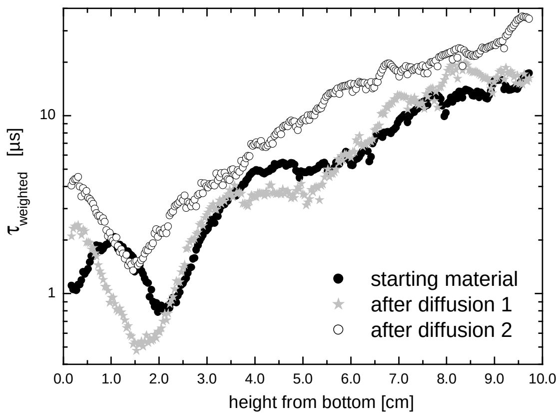

Figure 4: Lifetime profiles of weighted lifetimes of vertically cut wafers in the bottom region (wafer set VB)

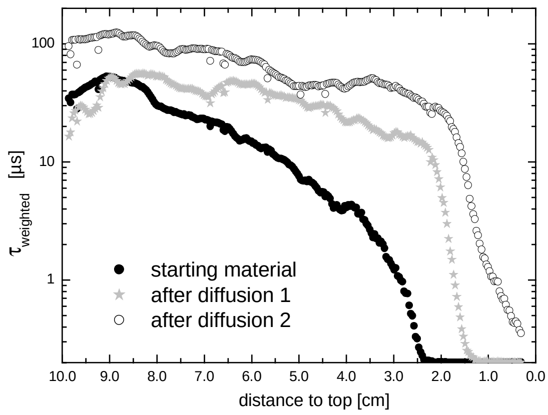

Figure 5: Lifetime profiles of weighted lifetimes of vertically cut wafers in the top region (wafer set VT)

Since the wafers were passivated with a SiN_x-layer on both sides, one should keep in mind that the resulting lifetime values may be influenced by a hydrogen passivating effect during nitride deposition.

2.3 Lifetimes of horizontally cut wafers

Lifetime measurements on horizontally cut wafers of sets HT and HB were performed with the CDI technique and the QSSPC-method [5]. The lifetime images show an influence of the edge of the ingot on two sides. For comparative measurements without any influence of the edges, the measurement area for the QSSPC-measurements was chosen to be centered in the quarter of the wafer opposite the edges. The measurements confirm the ratio of lifetimes after the diffusion processes and the starting material for the chosen distances from the bottom and top of the ingot, measured on the vertically cut wafers.

3 SOLAR CELLS OF TOP AND BOTTOM REGION

3.1 Solar cells on vertically cut wafers

Parallel to the lifetime investigations solar cells were processed on adjacent wafers for all four sets. The emitter diffusion processes used for the solar cells are analog to the processes used for the lifetime investigation. In contrast to the lifetime samples coated with a SiN_x layer, the cells received a TiO_x / MgF_x anti reflection coating on the front side as part of the standard solar cell process.

Table I: Solar cell results for wafer sets VB and VT

		V_{oc} [mV]	J_{sc} [mA/cm^2]	η [%]
Bottom	diffusion 2	577	31.3	13.6
Top	diffusion 1	593	32.3	14.7
	diffusion 2	600	33.7	15.8

The results of the solar cells processed on vertically cut wafers are shown in Table 1. The comparison between P-diffusion (diffusion 1) and P-Al-codiffusion (diffusion 2) for the top region affirms the stronger gettering effect of the latter process. The efficiency of 15.8 % of the cell including the topmost region is relatively high compared to the results of cells on horizontally cut wafers of top regions (Fig. 5). For wafer set VB no cells with diffusion 1 were processed.

3.2 Solar cells on horizontally cut wafers

For the solar cell processing on horizontally cut wafers a third diffusion process, intended to increase the gettering efficiency, was applied. After the coating with aluminium on the back side, the wafers received a light emitter diffusion at a temperature above 800 °C and a subsequent diffusion on a slightly lower temperature to reach the sheet resistance of around 80 Ω/sq. (diffusion 3). The net time on high temperature was about twice as long as in diffusion 2.

The effect of the different diffusion processes on the cell efficiencies strongly differs for top and bottom region. Whereas in the top region the emitter diffusion 3 yields the best efficiencies, in the bottom region it is diffusion 2. This stresses the different influences of the processes for the kind of defects in the bottom and the top of an ingot. Diffusion 1 with subsequent etching of the phosphorus layer on one side results in medium efficiencies for the bottom region, but the lowest efficiencies of these processes in the top region.

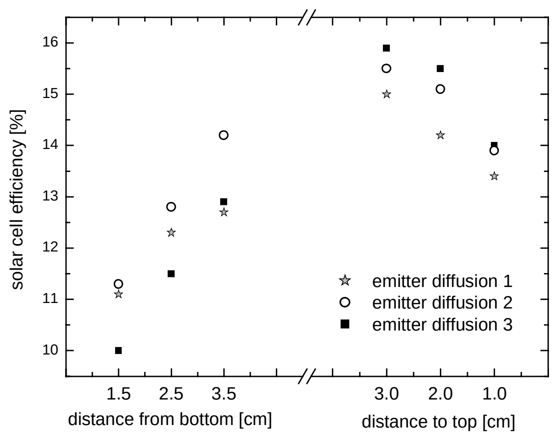

Figure 5: Solar cell efficiencies on horizontally cut wafers of top and bottom region

By the use of diffusion 2 compared to diffusion 1 the cell efficiency improved by up to 1.5 % absolute in the bottom region and 0.9 % absolute in the top region. Applying diffusion 3 with twice the time at high temperature, the gain in efficiency extended up to 1.3 % absolute for the top region. In contrast the efficiencies in the bottom region drop by up to 1.3 % absolute.

4 DISCUSSION

The effects on the lifetime indicate strongly deviating gettering efficiencies of the different diffusion processes, especially in the poor areas at the bottom and top and the regions of low lifetime inside the ingot volume.

Since the horizontally cut wafers from the top and bottom regions are usually not used for solar cell processing, it is necessary to define a quality threshold for separating the usable parts from the material to be rejected. This is mostly done by assessing the minority carrier lifetime of the ingot with e.g. microwave photoconductance decay (MW-PCD).

The value of the lifetime threshold is based on the achievable solar cell results for material with that specific lifetime. As we have shown in the profiles in Fig. 4 and Fig. 5, the lifetime after diffusion processes can considerably differ from the lifetime of the starting material. Therefore a prediction of the expected solar cell results depending on the block height has to take into account the effects of the particular cell manufacturing process.

For diffusion process 2 we have developed a model using the simulation software PC1D [6]. The model has been adjusted to cells processed on high quality floating zone material. As the main input parameter we have used the minority carrier lifetime after the diffusion process. Another important parameter the model has to take account of is the doping concentration varying over the height of the ingot.

We applied the model to the lifetime values of sets HT and HB, measured with the QSSPC-method after the diffusion processes and weighted as described in section 2.2. For a lifetime of 6 µs, the model predicts an open circuit voltage of 595 mV, a short circuit current of 32.1 mA/cm^2 and a cell efficiency of 15.0 %. The weighted lifetimes, measured on sister wafers, predict cell parameters which are up to 20 % higher than the measured cell parameter. Using the latter as input for the model, reverse modelling yields bulk lifetimes up to a factor of two smaller than the measured ones. This effect is most probably due to an overestimation of the measured bulk lifetime caused by a hydrogen passivation during the deposition of the nitride layer used for surface passivation. A thorough investigation of this problem will be in the scope of future work.

The different gettering efficiencies of the emitter diffusion processes, which can be observed in the lifetime investigations, are confirmed in the solar cell results. In the bottom region as well as in the top region the solar cells with a P-Al-codiffusion (diffusion 2) show a better performance than the cells with a P-diffusion (diffusion 1) on both sides. An improvement as well in V_{oc} as in J_{sc} and efficiency can be observed. This applies for the horizontally cut wafers as well as for the vertically cut. The absolute values for V_{oc}, J_{sc} and cell efficiency of the cell on the vertically cut wafer at the top are similar to the cell on the horizontally cut wafer with a distance of about 3 cm from the top.

In contrast the varied P-Al-codiffusion (diffusion 3) with a higher thermal budget, applied on wafers of set HT and HB, shows completely different results for the bottom and top regions. Whereas in the top region the values for V_{oc}, J_{sc} and efficiency exceed the values of the process with the normal thermal budget, they are diminished in the bottom region. This again stresses the different material behaviour in the top and bottom region during emitter diffusion.

5 CONCLUSION

In this work we have shown that different emitter diffusion processes have a significant influence on the lifetime and thus the solar cell results in the bottom and top region of block cast multicrystalline silicon. The prediction of solar cell results depending on the height in the ingot is very sensitive to the assumed diffusion process and the characteristics of the dominant defects in the top or bottom region. This has to be taken into account when deciding which part of the ingot is going to be rejected before the solar process.

In comparison to the applied P-diffusion, the use of a P-Al-codiffusion process can extend the part of the ingot with lifetimes higher than a certain threshold significantly. For an effective lifetime of 3.5 µs, the increase is up to 0.6 cm at the top and 1.8 cm at the bottom of the investigated brick. This is equivalent to an increased yield of around 50 wafers for this brick.

For the top region good cell results have been achieved for vertically cut wafers including the topmost region of poor lifetime of the starting material. Assuming the height of the usually rejected top part of the ingot to be 2 cm, using vertically cut wafers from the top of an ingot for solar cell production would result in an increased yield of around 40 wafers per brick.

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