ABSTRACT: The sensitivity to impurities of the solar cell conversion efficiency is reported for a state of the art (i.e. 18%) and advance device architecture (i.e. 23%). The data are based on the experimental results obtained in the CrystalClear project for the state of the art cell process and extrapolated to a device with excellent front and rear surface passivation. Both device structures are not assumed to work in low injection level as several studies assumed before but real operating conditions are considered. This is a fundamental difference with the past and required for modeling future high efficiency devices. In general advanced devices will be more sensitive to the impurity content than the state of the art cell design. This effect is partly compensated by reducing the base thickness. In high efficiency devices, a large reduction of the impurity impact is visible for impurities with large capture cross section ratio like Fe which reduces its relative difference in comparison with e.g. Cr which has a small capture cross section ratio.

Keywords: Impurities, Silicon, Solar Cell Efficiencies, Photovoltaic, Lifetime, Feedstock, Polysilicon, Solar-grade silicon

1 INTRODUCTION

Energy supply from photovoltaics will dominate the international scene in the next decades. Currently, crystalline silicon solar cells contribute to over 80% of the total supply of PV modules. It is therefore reasonable that the technology which will most probably dominate the supply of PV in the years to come will be based on crystalline silicon substrates. The substrate characteristics, which are the topic of this paper, should not limit the solar cell conversion efficiency and should enable the integration of architectures suitable to obtain high efficiency and optimized cost/performance ratio. The solar cell minority carrier diffusion length is intrinsically limited by Auger and band to band recombination which cannot be avoided [1]. A substrate with resistivity of 1 ohm×cm and injection level (operation condition) $\Delta n = 1 \times 10^{15}$ cm$^{-3}$ is limited by a diffusion length of about 3 mm. In practice substrates are dominated by recombination via extended and point defects like impurities, dislocations and grain boundaries.

2 BACKGROUND

In this paper we discuss the impact of metal impurities on the device performance. Within the framework of the CrystalClear project [2] an extended research was carried out in this respect (CC study). Major impurities were studied by producing several multicrystalline ingots with intentional contamination of known amount of each element. Results of this work were reported in [3]. In addition, in this study the total ingot height, corresponding to 100% of the melt weight, was used for the experiments and the evaluation. Therefore, each ingot provides a broad range of impurity concentration levels in the wafers. For example at 90% of the ingot height the impurity concentration for the majority of metal impurities is about 10 times higher than in the bottom due the segregation of impurities. We aim to gain insight into the impurity contamination level allowed therefore it is of great importance to relate the impact of impurities to the usable fraction of the ingot which is analyzed in the CC approach. An example of this is reported in Fig. 1, where it is visible a degradation of the solar cell performance from the bottom to the top of the ingots. 90% of the ingot height can be considered an intuitive limit to calculate the impact of impurities. At 99% the concentration of impurities is 100 time higher than in the bottom therefore data extrapolation is relatively straightforward. The CC study used a software (PC1D) [4] for the numerical solution of transport equations and the full AM1.5 solar spectrum. The Internal Quantum Efficiency (IQE) was used together with the IV-parameters to model the solar cell with PC1D, considering both the bulk and emitter regions [3]. In this and other studies [12,11,5] as well, the device was considered operating in low injection level. In this paper development were carried out in order to model the device at the operating injection level (no low injection level assumption) therefore opening the possibility to model a future device with excellent surface passivation and with higher efficiency. To our knowledge this has not been reported before.

Figure 1: The product of short-circuit current and open-circuit voltage versus position in the ingot from the bottom, for the ingots contaminated with chromium. The model used is based on the degradation of the base-bulk recombination. The parameter fitting was carried out on the ingot with 40 ppm wt of chromium, obtaining an excellent fitting. The model has been validated using the ingots with 4 ppm wt and 200 ppm wt.

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3 MODEL

In this paper the model developed to predict the behavior of impurities is reported and its impact on current and future device structures is addressed. Here the effect of operation injection level, which became important for high efficiency device, is taken into account. For this is important to know both the majority and minority carrier recombination parameters as in the case of Fe, Ti and Cr. In previous works the solar cell is always assumed to work in low injection level conditions. This is a good assumption for the state of the art industrial multicrystalline p-type solar cells based on screen print, SiN\textsubscript{x} firing through and Al-BSF process. However considering the recent progress on monocrystalline based solar cell, the continuous improvements on cell processes and crystallization for multicrystalline wafers and in general higher efficiency devices this assumption is no more valid. The substrate is also assumed to be not limited by other recombination mechanism than Auger and band to band. Therefore the model can be extrapolated to any type of material mono- or multicrystalline with different level of other defects as crystallographic defects for multicrystalline wafers and boron-oxygen (BO) complex for monocrystalline wafers.

Improperly like titanium, chromium and iron have been reported to reduce the bulk recombination (diffusion length), therefore, the SRH theory is used to model the bulk lifetime in PC1D. The model fitting parameters where extracted by fitting the solar cell performance of the entire ingot for each impurity and ingot studied, as reported in [3]. The model was then applied to both a state of the art 2010 design and an advanced design (see Table I). For a more detailed description of the modeling we refer to [7].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resistivity</th>
<th>Thickness</th>
<th>Front and rear SRV</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of the art 2010*</td>
<td>1.1 Ω·cm</td>
<td>200 μm</td>
<td>400 fA/cm(^2)</td>
</tr>
<tr>
<td>Advanced</td>
<td>1.1 Ω·cm</td>
<td>100 μm</td>
<td>20 fA/cm(^2)</td>
</tr>
<tr>
<td><em>(Typical values for a multicrystalline p-type solar cell)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4 RESULTS AND DISCUSSION

The device model parameters, for the state of the art 2010 design with a p-type substrate and a n-type front emitter, are reported in Table I. In case of absence of bulk defects (device limited only by Auger and band to band recombination) an efficiency of about 17.5% is obtained. The solar cell efficiency calculated at 90% of the ingot height is plotted versus the impurity concentration in the feedstock in Fig. 2.

Note that the efficiency is very sensitive to the presence of Ti. The reason is that Ti, being a slow diffuser, has small or negligible relaxation and segregation gettering [8] effectiveness as expressed from its electrical activity close to one (100% active). On the other hand Fe being a relatively fast diffusing impurity is more sensitive to gettering.

We are interested in estimate the impact of impurities on a device which meet the characteristics [9] of a future solar cell. Therefore we model a device which is not limited by front and rear surface passivation, meaning cells with excellent surface passivation. Most likely the substrate thickness will be reduced as shown by the steep trend in the last several years. In Table I the device model parameters for excellent surfaces and substrate thickness of 100 μm are reported. In case of absence of bulk defects (device limited only by Auger and band to band recombination) an efficiency of about 25% is obtained.

In order to model the minority carrier lifetime for this device we use the same assumption and parameters for the state of the art device. This means that: the impurity global electrical activity is considered the same and proportionality is kept between total impurity concentration and active impurity concentration. In Fig. 3 the efficiency at 90% of the ingot height, for this device, is plotted versus the impurity concentration in the feedstock. One could note that the relative difference between Cr and Fe changed. This is because in this advanced device and especially at relatively low impurity concentration, the solar cell does not operate anymore at low injection level. Actually the smaller the impurity level, the higher the injection level. The effect of impurities like Fe, with a high capture cross section ratio \(\sigma_n/\sigma_p\), therefore with a steep lifetime injection level dependency, benefit from an increasing lifetime since the injection level increases [10]. Instead Cr, with small capture cross sections ratio (flat injection level dependency) is less sensitive to this effect.
impact is visible for impurity with large capture cross section ratio like Fe which reduced it relative difference efficiency devices, a large reduction of the impurity concentration (without considering the injection level dependency effect), shifting the sensitivity curve in Fig. 3 leftwards (rightwards).

Note that the operation injection level is determined by the total recombination in the device. The presence of other defects like other impurities, BO complexes and crystallographic defects reduce the operation injection level and therefore the operating lifetime. This means that in presence of these other defects, the cell performance sensitivity towards Fe will increase.

Note that in general the efficiency sensitivity towards impurity increase significantly with a high efficiency device despite the reduction of half the base thickness which only partly compensates the increased sensitivity. The above assumption on the electrical activity means that in the future device the same optimum gettering and hydrogenation of current device is used in order to have realistic model. Depending on the nature of the device architecture implemented (for example hetero-junction where the temperature employed and gettering effect is low), the electrical activity can increase and consequently the impact of impurities on the device increases as well. On the other hand R&D effort to improve the wafer quality, and optimize gettering and hydrogenation will definitively be implemented in the future solar cell process.

Therefore the predictions in this work should be considered conservative. Note that a more (less) effective gettering and hydrogenation which results in a 10 times reduction (increase) of electrical activity will give similar efficiency as 10 times less (more) impurities concentration (without considering the injection level dependency effect), shifting the sensitivity curve in Fig. 3 leftwards (rightwards).

For a more detailed description of the model, analysis and results we refer to [7].

4 CONCLUSIONS

In conclusion the sensitivity of the solar cell conversion efficiency to iron, chromium and titanium was modeled for a state of the art and an advance device architectures. Contrarily to previous modeling, it is not assumed that the device is working in low injection level but in real operating conditions. This is of fundamental importance for modeling high efficiency devices. In high efficiency devices, a large reduction of the impurity impact is visible for impurity with large capture cross section ratio like Fe which reduced it relative difference with Cr which has a small capture cross section ratio.

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REFERENCES