Temperature dependent suns-V_{OC} of multicrystalline silicon solar cells from different ingot positions

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Abstract **— This paper presents temperature dependent Suns-V_{oc} measurements on multicrystalline silicon cells originating from different ingot positions. The effective lifetime is found to increase for all cells when the temperature is increased from 25 °C to 65 °C. However, cells from the top of the ingot show a considerably larger increase of 40 − 48 % for illumination conditions of 0.1-1 Sun, compared to an increase of 20 − 30 % observed for cells from the bottom. The decrease in V_{oc} with increasing temperature is found to be lower for cells from the top of the ingot compared to cells from the bottom. The temperature coefficient of the V_{oc} is found to vary 5 % along the ingot at 1 Sun, highlighting the influence of ingot position for applications at elevated temperatures.**

B.I. Introduction

Solar cells are usually characterized and compared at standard test conditions (STC) which correspond to an irradiance of 1000 W/m^2, an air mass 1.5 spectrum and a cell temperature of 25 °C. However, under real operating conditions, temperatures rarely resemble the STC and are typically higher [1,2]. An increase in cell temperature negatively affects the power output from most cell types [1,3,4]. It is therefore of high importance to understand and quantify this temperature sensitivity to make proper field predictions and to enable device optimization.

Multicrystalline silicon (mc-Si) wafers made from a polycrystalline silicon (poly-Si) feedstock are often used for industrial production of silicon solar cells because of the cost-effectiveness of the fabrication process. However, mc-Si ingots contain a relatively large amount of crystal defects compared to monocrystalline silicon (mono-Si), resulting in a lower cell efficiency [5]. In addition, these crystal defects are unevenly distributed throughout the ingot causing the efficiency and other cell parameters to vary with cell position, and typically to reduce towards the top [6–9].

Recently, it has been found that the relative temperature coefficients (TC) of mc-Si cells vary along the ingot height and that cells originating from the top show better relative TCs compared to the cells from the bottom [9]. Ref. [10] studied the spatial distribution of mc-Si wafers from different ingot positions and found that wafers from the top of the ingot consisted of a larger number of cell-limiting lifetimes compared to cells from the bottom. These cell-limiting lifetimes were found to improve with increasing temperature, whereas no trend was found for the higher lifetime-areas.

Understanding the physical processes responsible for the reduced temperature sensitivity observed for cells and wafers originating from the top of an ingot is an important step in the process of quantifying the thermal behavior of mc-Si cells. In this work, temperature-dependent Suns-V_{oc} measurements are performed on compensated mc-Si cells originating from different ingot positions. Suns-V_{oc} measurements enables the generation of pseudo light IV curves without the effect of series resistance and therefore allows a better study of the bulk material properties of the cells [11]. The measurements were performed at room temperature and at 65 °C, the latter corresponding to realistic field operating conditions.

B.II. Experimental Details

Seven compensated p-type mc-Si cells were studied, originating from an ingot produced by directional solidification of a mix of 55 % poly-Si and 45 % compensated Elkem Solar Silicon® (ESS®) with a targeted resistivity of 1.25 Ω·cm. ESS® is a tri-doped compensated material where gallium is added to the boron and phosphorous dopants to avoid a pn-changeover throughout the ingot and for better resistivity control along the ingot height [13]. A central brick was cut into wafers which were labelled with the numbers 1-37, representing positions from the bottom to the top of the brick. Seven wafers were then chosen from different ingot positions from the bottom to the top. The 180 μm thick 6” wafers were passivated with a-Si:H at a research laboratory and processed into Al-BSF cells at ISC Konstanz. The cells were then light-soaked for 48 h to ensure full light-induced degradation.

The Suns-V_{oc} measurements were performed under standard AM 1.5G conditions using

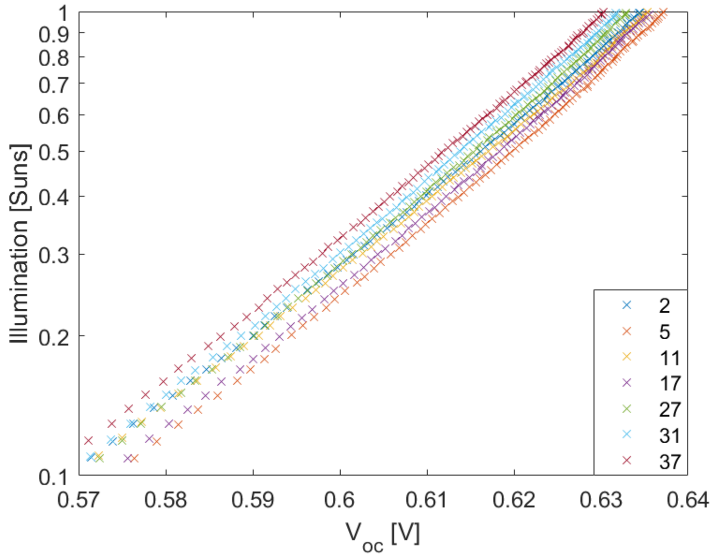

Figure B.1: Open-circuit voltage at different light intensities obtained at 25 °C for cells originating from different ingot positions.

a NeonSee^{TM} AAA sun simulator at the temperatures 25 °C ± 0.3 °C and 65 °C ± 0.4 ° C. Since the cell parameters of mc-Si cells vary approximately linearly with temperature for normal operating temperatures [12], two temperatures are assumed to give a proper representation of the temperature dependence. To ensure repeatability, the same cell was studied several times during the total period of data acquisition.

B.III. Results and Discussion

A. Influence of Ingot Position on V_{oc} and τ_{eff}

Fig. B.1 shows Suns-V_{oc} curves obtained at 25 °C for cells from different ingot positions. For all light intensities, V_{oc} is found to be lowest for the three top cells and highest for cells originating from the middle and near the bottom of the ingot, similar to the findings presented in Ref. [9]. This is illustrated further in Fig. B.2 which shows the V_{oc} as a function of cell number for the light intensities 0.1, 0.5 and 1 Sun. An illumination intensity of 0.1 Sun corresponds to an injection level close to the maximum power point of the cells considered. No substantial difference is observed for the change in V_{oc} with ingot height for the different illumination conditions.

Fig. B.3 shows the effective lifetime as a function of injection level obtained at 25 °C. The lifetime is found to be lowest for the three top cells for an injection level of $2 \cdot 10^{13}$ cm^{-3} and higher. This is illustrated further in Fig. B.2 showing the effective lifetime as a function of cell number for the light intensities 0.1, 0.5 and 1 Sun. The lifetime at 0.1 Sun seems to be most sensitive to ingot position.

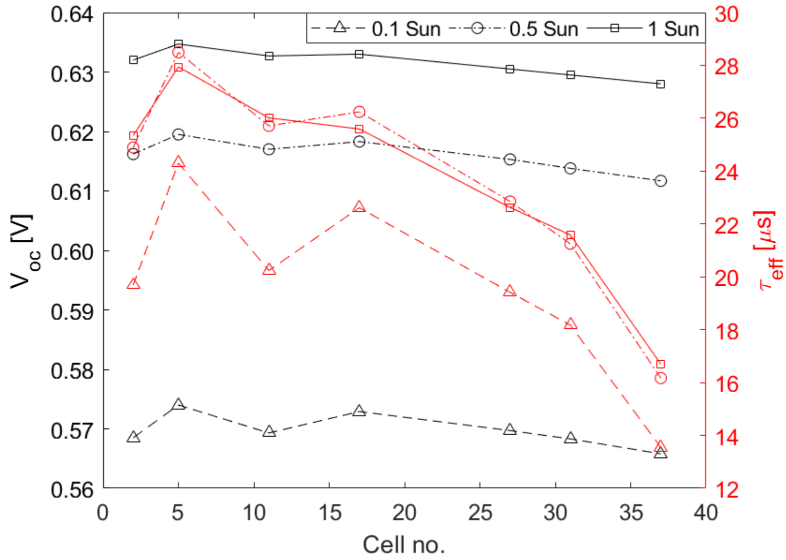

Figure B.2: Open-circuit voltage and effective lifetime as a function of cell number at 25 °C for the light intensities 0.1, 0.5 and 1 Sun.

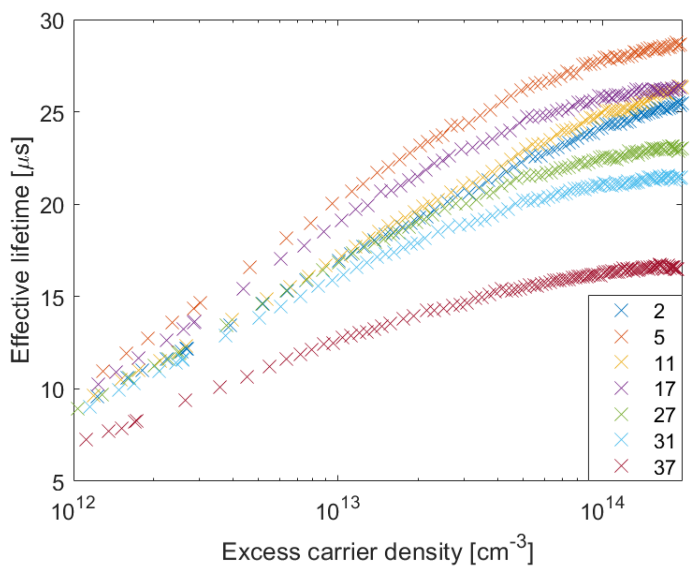

Figure B.3: Effective lifetime as a function of injection level at 25 °C.

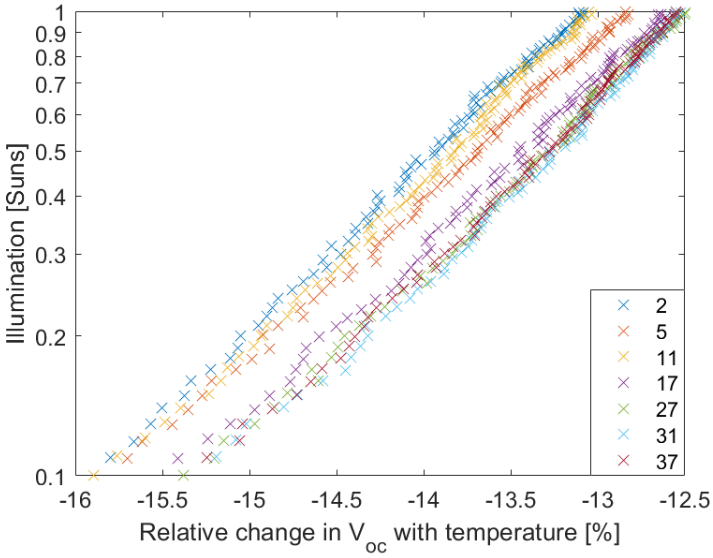

Figure B.4: Relative change in open-circuit voltage for different light intensities when the cell temperature is changed from 25 °C to 65 °C.

B. Temperature Sensitivity of V_{oc} and τ_{eff} with Ingot Position

Fig. B.4 shows the relative change in V_{oc} when the temperature is increased from 25 °C to 65 °C for the intensities 0.1-1 Sun. The data is presented such that a small negative change in V_{oc} corresponds to a cell with a low temperature sensitivity. In Fig. B.4 we see a tendency that the three top cells are less sensitive to a temperature increase, whereas the three cells from the bottom are most sensitive. This is illustrated further in Fig. B.5 which shows the relative change in V_{oc} with temperature as a function of ingot position for the light intensities 0.1, 0.5 and 1 Sun. For all intensities considered, we see a trend that the temperature sensitivity is reduced towards the top of the ingot.

From Fig. B.5, the TCs of the V_{oc} can be calculated for different ingot heights. The relative TCs at 1 Sun are found to vary from −0.330 % to −0.317 % throughout the ingot, corresponding to a relative change of 5 %. This trend is similar to the findings of Ref. [9] where the TCs of the V_{oc} of compensated mc-Si cells were found to vary with ingot height, from −0.325 % for cells from the bottom to −0.313 % for cells from the top, corresponding to a relative change of 4 %. The relative change is found to be 4 % at 0.1 Sun and 5 % at 0.5 Sun. Therefore, the relative variation along the ingot does not seem to change with illumination conditions. This variation in TCs of the V_{oc} throughout the ingot illustrates a potentially non-negligible influence of ingot position for applications at elevated temperatures.

Fig. B.5 shows the relative increase in lifetime with temperature as a function of ingot position for injection levels corresponding to the light intensities 0.1, 0.5 and 1 Sun. The

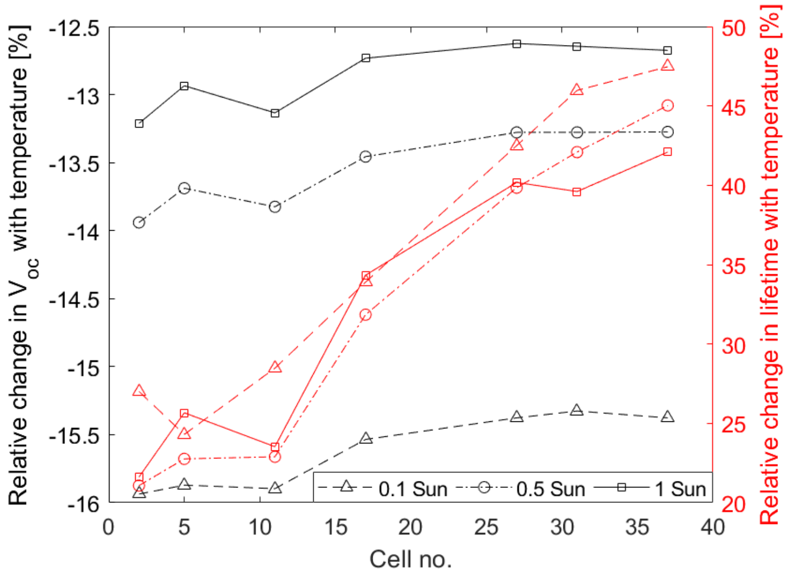

Figure B.5: Relative change in open-circuit voltage and lifetime when the cell temperature is changed from 25 °C to 65 °C for the light intensities 0.1, 0.5, and 1 Sun.

three top cells experience the largest increase in lifetime of 40 − 48 % for the injection levels considered. In contrast, the bottom three cells experience the lowest increase between 20 − 30 %. The relative variation in lifetime seem to be similar for the three injection levels considered.

A Suns-V_{oc} measurement is a global measurement and therefore it does not give information about the temperature sensitivity of the lifetime in different areas of the cell. However, in Ref. [10], mc-Si wafers from the top of an ingot were found to consist of larger areas of cell-limiting lifetimes that improved with increasing temperature. The lifetime of high-quality areas remained unchanged when the temperature was increased. This could explain the beneficial temperature sensitivity of the effective lifetime observed for cells from the top.

The main parameters affecting the performance of a mc-Si PERC cell are the bulk lifetime, the resistivity and the dislocation density [8, 14]. Any performance-limiting factor attributed to the Al-BSF architecture is assumed to have a similar influence on all cells from one ingot. Therefore, the mechanisms affecting the performance of PERC cells are assumed to be good indicators of performance variations for the Al-BSF cells used in this study. Since tri-doped compensated mc-Si was used to fabricate the cells for this study, the resistivity is assumed to be relatively uniform throughout the ingot. The concentration and composition of defects, however, varies significantly because of the directional solidification process that causes most impurities to segregate and accumulate towards the top of the ingot. In addition, back-diffusion from the crucible introduces a high level of impurities at the bottom [6]. The dislocation density also varies throughout a mc-Si ingot and is typically found to increase towards the top [8]. Crystal defects could therefore be responsible for the improved temperature sensitivity observed for cells from the top, however, further studies are needed to explore this hypothesis.

B.IV. Summary

In this study, the combined effect of temperature and ingot position on the V_{oc} of mc-Si cells has been investigated. The V_{oc} was found to decrease with ingot position for a range of light intensities. However, the relative decrease in V_{oc}, when the cell temperature was increased from 25 °C to 65 °C, was found to be lowest for cells from the top. The relative change in temperature sensitivity throughout the ingot was found to be similar for illumination conditions of 0.1, 0.5 and 1 Sun. At 1 Sun, the TCs of the V_{oc} were found to vary with approximately 5 % throughout the ingot.

The lifetime was found to decrease with ingot height for injection levels of around 10^{14} cm^{-3}. The effective lifetime increased for all cells when the temperature was increased from 25 °C to 65 °C. However, the lifetime increase was considerably larger for top cells, ranging from 40 − 48 % for the injection levels considered. For bottom cells, the increase was found to be 20 − 30 %. The observed variation in both V_{oc} and effective lifetime with cell position in the ingot illustrates the influence of cell position for applications at elevated temperatures.

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