



Towards the efficiency limits of multicrystalline silicon solar cells

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ABSTRACT

In this contribution, we present our recent results for high efficiency multicrystalline silicon solar cells. Based on n-type high-performance multicrystalline silicon substrates in combination with the TOPCon solar cell concept featuring a full area passivating back contact and a boron-diffused emitter as well as a plasma-etched black-silicon texture at the front side, a certified conversion efficiency of 22.3% has been achieved, which is currently the world record efficiency for multicrystalline silicon solar cells. A detailed loss analysis of the record solar cell batch discloses the nature of the remaining loss mechanisms, revealing the route for further improvements. We observe an efficiency gap between the multicrystalline and the FZ reference solar cells of $\sim 1\%$. Compared to the FZ reference cells, the mc-Si cells also feature a significantly larger scattering in V_{oc} and J_{sc} as well as a fill factor loss of $\sim 1.5\%$. We show that the scattering in J_{sc} correlates with the area fraction of recombination-active structural crystal defects and the scattering in V_{oc} additionally with lateral emitter-induced inhomogeneities. The fill factor loss is attributed to the general presence of strongly recombination-active grain boundaries. A detailed loss analysis of the record mc-Si solar cell shows that the major electrical losses are due to recombination at grain boundaries (0.7%) and recombination in the emitter (0.6%). By reducing these electrical loss channels, e.g. by an improved crystallization process together with a hydrogenation of the bulk and application of an adapted emitter, we expect to reach efficiencies for mc-Si solar cells in the range of 23%.

1. Introduction

In the past years, research on n-type multicrystalline silicon revealed its large solar cell efficiency potential. The availability of an excellent and robust n-type solar cell process featuring a tunnel-oxide passivating back contact (TOPCon) [1] and the continuously improved material quality of the n-type high-performance multicrystalline silicon (HP mc-Si) are the two key features for highest mc-Si efficiencies. The optimization of the n-type HP mc-Si material with regard to the TOPCon cell concept by improvements of the crystal structure and optimization of the base resistivity together with an improved light trapping by application of a black-silicon plasma process for front side texturing enabled the fabrication of an n-type HP mc-Si solar cell with 21.9% efficiency [2,3]. Recently, this value was exceeded by an HP mc-Si TOPCon solar cell with a certified conversion efficiency of 22.3%, which is the current world record for multicrystalline silicon solar cells. The already high level and the steady and fast improvement of these

efficiencies reflect the large potential of HP mc-Si TOPCon solar cells. But this record efficiency is still $\sim 1\%$ below the efficiency of reference cells on FZ material. Therefore, we perform a thorough loss analysis of the recent solar cell batches in order to explore the remaining limitations and identify options to overcome these. This enables us to further adapt both the crystallization process as well as the solar cell processing to push multicrystalline silicon to its limits, which are by far not reached yet.

2. Material fabrication

The n-type HP mc-Si used in this work has been developed at Fraunhofer ISE. The G2 size research ingots (equivalent to 75 kg of pure polysilicon feedstock) were crystallized by the directional solidification method with seeded growth. High-purity silicon granules from a Fluidized Bed Reactor (FBR) process were used as seed material and were placed in the bottom of a high-purity fused-silica crucible. As

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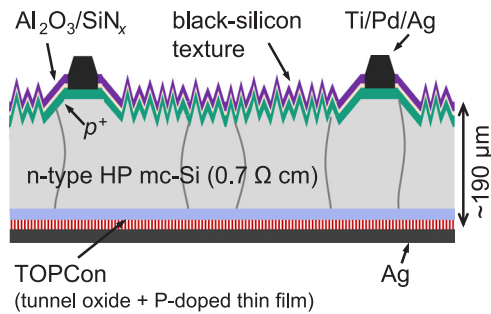


Fig. 1. Schematic of n-type high-performance (HP) multicrystalline (mc) silicon solar cells with black-silicon (B-Si) texture.

dopant material silicon wafers enriched with phosphorus (1085 ppmw) were used. The crystallization resulted in a resistivity profile from $1.5 \Omega \text{ cm}$ above the remaining seed material to $0.5 \Omega \text{ cm}$ at the ingot top. A brick with 156 mm side length was cut from the ingot center. After cropping of 15 mm at bottom and top, the brick was processed into wafers with a thickness of $195 \mu\text{m}$ by multiwire sawing with SiC slurry and structured wire.

3. Solar cell and lifetime sample processing

HP mc-Si solar cell processing included the fabrication of multicrystalline solar cells as well as monocrystalline FZ reference cells. The fabricated mc-Si solar cells are sketched by the cross-section shown in Fig. 1. The details of the standard cell fabrication process applied in the first solar cell batch, which includes a BBr_3 diffusion ($\sim 90 \Omega/\text{sq}$) and a high-temperature TOPCon anneal, can be found in [3]. In the second cell processing batch, we included one group with the standard

fabrication process and additionally investigated the improvement potential of a P-gettering step and an optimization of the emitter diffusion temperature (875°C , $\sim 140 \Omega/\text{sq}$) with and without a “drive-in” oxidation in 5 other groups.

In order to investigate the impact of the boron emitter on solar cell performance in more detail, in a further experiment HP mc-Si wafers were processed to planar solar cell precursors (featuring a TOPCon layer on the rear side and a boron emitter passivated by a stack of Al_2O_3 and SiN_x on the front side, in the following referred to as “emitter lifetime samples”). These emitter lifetime samples were investigated by injection-dependent photoluminescence (PL) lifetime imaging [4]. After characterization, the passivating layers and the emitter were etched back and the silicon bulk was surface passivated by SiN_x on both sides in order to obtain bulk lifetime samples, which were also characterized by injection-dependent PL lifetime imaging.

4. Solar cell results

Fig. 2 shows solar cell parameters of all HP mc-Si solar cells of the first [2,3] and the second cell batch in comparison to the corresponding FZ reference cells. The insets in the efficiency graph show PL images of the record mc-Si solar cells of each batch.

In the second batch, both the maximum efficiencies as well as their scattering are significantly improved for the mc-Si solar cells. The increase in efficiency is mainly attributed to an increase in J_{sc} , while the narrower efficiency distribution is based on less scattering in the fill factor. Note that in Fig. 2, we do not distinguish between the different groups of batch 2, because no clear dependence of the specific high-temperature process sequences on the efficiency was observed. The P-gettering step did not show a significant performance improvement, probably because the bulk quality is already high after the boron diffusion and the grain boundary recombination is not significantly

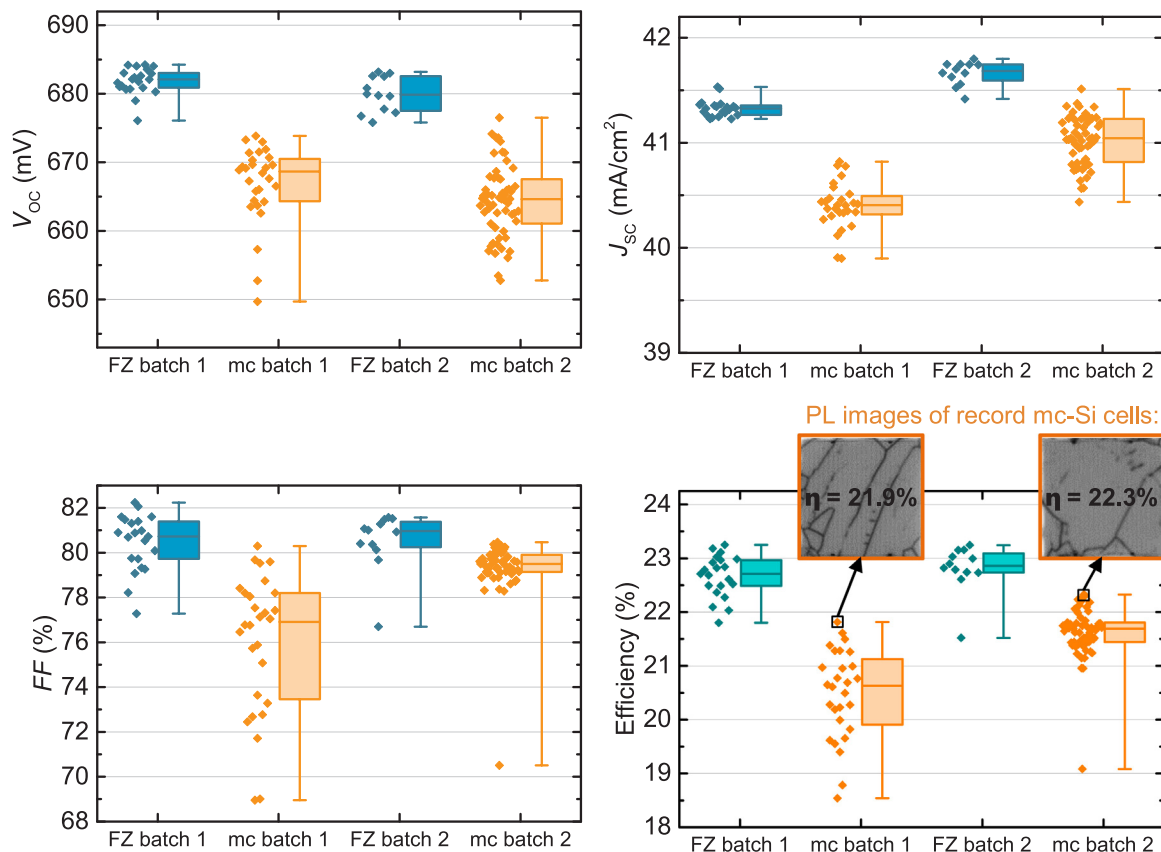


Fig. 2. Overview of the global solar cell parameters from in-house IV measurements under standard testing conditions. The insets in the efficiency graph show PL images of the record mc-Si solar cells of batch 1 and 2.

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