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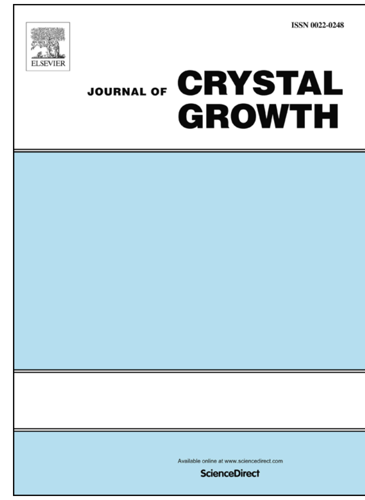

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Patricia Krenckel, Stephan Riepe, Florian Schindler, Theresa Strauch

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Feeding of Liquid Silicon for High Performance Multicrystalline Silicon with Increased Ingot Height and Homogenized Resistivity

Patricia Krenckel, Stephan Riepe, Florian Schindler, Theresa Strauch
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, D-79110 Freiburg
Patricia.Krenckel@ise.fraunhofer.de

Abstract: Feeding of liquid silicon during the directional solidification process is a promising opportunity for cost reduction by increased throughput and improved material homogeneity due to constant resistivity over ingot height. In this work, a liquid feeding apparatus was developed for an industrial type directional solidification furnace. One n-type G2 sized High Performance multicrystalline ingot with liquid feeding of additional 14 kg of undoped silicon feedstock was crystallized. The resistivity was kept within a range of ± 0.1 Ωcm of the target resistivity during the feeding sequence. A smaller mean grain area growth was observed during feeding, whereas the area fraction of recombination active dislocation structures was as low as in a reference ingot. Increased interstitial oxygen and substitutional carbon concentrations were measured for the ingot with liquid feeding. The measured mean bulk lifetime of 190 µs for passivated wafers in the feeding sequence can probably be increased by further pre-melting crucible improvements. For this laboratory experiment, energy reductions of 2 % per wafer and time savings of 16 % per wafer were realized.

Keywords: A1. Directional solidification, A1. Crystal structure, A2. Liquid feeding, B2. Semiconducting silicon

1. Introduction

High performance multicrystalline silicon (HP mc-Si) is the commonly used material for solar cells produced by directional solidification [1]. The homogeneous grain structure, generated by e.g. seeded growth on granular silicon beads, entails low dislocation densities for the majority of the ingot volume [2,3]. Thus, the overall efficiency of solar cells produced from an HP mc-Si ingot is higher than for the previously common standard mc-Si.

Besides this defect engineering improving the material quality, the throughput of the ingot production is an important factor for wafer cost. Due to the irregular geometry of the silicon feedstock, the loading of the crucible is limited and the crystallized ingot measures only about 60 % of the crucible height. Filling the crucible with liquid silicon, as previously described for e.g. the drip-controlled method, increases the yield [4]. Using a conventional directional solidification furnace with a suitable feeding apparatus, feeding of silicon during the crystallization process can be used to grow higher ingots. Previous studies with feeding of solid silicon feedstock showed a possible disturbance of the crystal growth by fed solid silicon touching the solid-liquid phase boundary [5]. The thermal field optimized for a controlled solidification, has to be changed to provide additional energy for the melting of the feedstock. Thus important growth characteristics such as e.g. growth velocity and shape of the solid-liquid interface may be impaired. Feeding of liquid silicon features the advantage of less impact on the melt convection and the crystal growth process itself.

Furthermore, feeding of undoped silicon during the crystallization involves the possibility of influencing the resistivity development over ingot height beyond Scheil's equation [6]. An adaptation of the mass flow to the growth velocity results in a flat resistivity profile over a large fraction of the ingot height. Thus, the resistivity can be adjusted to the optimum value needed for the applied solar cell architecture to increase the overall yield of the produced wafers.

With these advantages in mind, an apparatus for feeding of liquid silicon during the directional solidification of HP mc-Si was constructed and a process sequence developed. For this work, a reference ingot and an ingot with liquid feeding during solidification were produced. The crystallographic and electrical properties of both ingots were analyzed on brick and wafer level.