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# Growth of multicrystalline silicon in a cone-shaped crucible

E. Schmid*, A. Poklad, V. Heinze, D. Meier, O. Pätzold, M. Stelter

Institute of Nonferrous Metallurgy and Purest Materials, TU Bergakademie Freiberg,
Leipziger Str. 34, 09596 Freiberg, Germany

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In this paper, a novel, vertical Bridgman-type technique for growing multicrystalline silicon (mc-Si) ingots in an induction furnace is described. In contrast to conventional growth, a modified setup with a cone-shaped crucible and susceptor is used for the first time. The temperature field and melt flow in the modified setup are calculated numerically and compared with the situation in a cylindrical standard setup. A cone-shaped mc-Si ingot is presented and analysed with focus on the microstructure (inclusions, dislocations, grains) and the minority carrier lifetime, which are compared with the properties of a cylindrical ingot grown under similar conditions. Results of numerical simulations and growth experiments are discussed with respect to the influence of the cone-shaped setup on the temperature and flow fields in the melt, as well as on the microstructure and the minority carrier lifetime in the crystal. They indicate the potential of the novel technology to produce mc-Si ingots with a globular grain structure, low dislocation density, and high carrier lifetime.



## 1 Introduction

Multicrystalline silicon (mc-Si) is one of the most important materials for the production of solar cells [1]. Massive mc-Si ingots are usually grown from the melt by directional solidification in a vertical gradient freeze- or a vertical Bridgman-type furnace, where the temperature field is controlled electronically or by a mechanical movement of the growth setup (e.g., crucible, heaters, insulation), respectively. The advancement of these growth techniques for an efficient production of high-quality ingots is a steady challenge for producers to stay competitive on the global solar market. Thus, the development of advanced setups to improve the solidification process and ingot properties is a main research topic, which has been addressed in numerous recent papers, e.g., [2]-[9].

Transient numerical simulations on the optimization of the heat transfer during growth and post-growth cooling by a modified insulation design were presented in [2],[3] and the effects on the melt flow, melt-crystal interface, and thermal stress were discussed. Kießling et al. [4] investigated the directional solidification of mc-Si ingots under the influence of a heater-magnet module, which simultaneously generates the heating power and a time-dependent magnetic field for tailoring the melt flow during growth. The presented results show the potential of this technique for control of the melt-crystal interface and for the reduction of inclusions in the grown ingots.

Technological developments were also aimed at the control of the initial nucleation conditions to influence the microstructure i.e., grains, dislocations, and inclusions, which is an important issue in growth of high-quality mc-Si ingots. This requires the control of the local thermal conditions near the bottom of the crucible, where the solidification starts. Significant effects on the grain structure were achieved via an external argon flow [5], by a fast cooling of the crucible bottom in an early stage of growth [6] or by an alumina tube below the crucible acting as a cooling spot [7]. Several approaches are based on the modification of the crucible itself. In [8] a crucible with a notched bottom was used to influence the grain competition at the beginning of crystallization. Recently, Ma et al. [9] described a growth setup on the basis of a crucible, whose bottom part is formed by a cone and a central well. The main idea behind is to produce mono-crystalline silicon ingots from a small seed, which is placed in the crucible well. The crucible was proposed to be surrounded by a conformal graphite susceptor and a set of side and top heaters. Numerical results on the temperature and flow field were presented demonstrating the potential of the concept for a control of the heat flux, the melt-crystal interface, and the growth rate, in particular during the early stages of the solidification process, when the interface is located in the cone region of the crucible.

This paper is about a novel growth setup with a cone-shaped crucible and susceptor for the directional solidification of mc-Si ingots. The main objective of this work is to study the influence of the conical setup on the formation of the microstructure and on the minority carrier lifetime. The flow and temperature fields in the melt are calculated numerically and compared with the situation in a standard cylindrical setup. First growth experiments to produce cone-shaped mc-Si ingots are presented. The distribution of inclusions, the dislocation density and grain structure, as well as the carrier lifetime are investigated and the potential of mc-Si growth by solidification in a cone-shaped setup is discussed with respect to growth in a standard cylindrical setup.

*Corresponding author. Tel./FAX: +49 3731 39 2316/2268; e-mail: ekaterina.schmid@inemet.tu-freiberg.de