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Modeling and optimization of the feedstock melting for industrial photovoltaic multi-crystalline silicon ingot

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ABSTRACT

A transient global model of industrial furnace of seed-assisted directional solidification is built and it can reproduce basically the feedstock melting process. Thermal field, velocity field and silicon phase transition are investigated in the numerical furnace with and without a back plate. Simulation result shows that insulation of the plate will lower the possibility of second contamination resulted by circulation flow outside gas hole and flatten surface of seed crystals. Experiment measurements show that deflection of seed crystals in modified furnace with the plate is 2 mm, which is lower about 3 mm than that in original furnace without the plate. The casting experiment also confirms that the ingot quality by adding the plate is improved with 0.13 μs and 2.14% gain on average minority carrier lifetime and effective minority carrier lifetime yield, respectively.

1. Introduction

Directional solidification (DS) technology has been widely used for solar grade multi-crystalline silicon (mc-Si) production (Shur et al., 2011; Zhou et al., 2014) because of satisfactory performance, cost advantage, and simple operation process. During the DS process of mc-Si ingot, many defects and impurities can be generated, which are harmful to the solar cell performance. As a result, conversion efficiency of solar cell (mc-Si) is usually lower than that fabricated by the mono-crystalline silicon. Currently, seed-assisted crystalline silicon including quasi-single crystalline silicon (QS-Si) (Black et al., 2012; Ding et al., 2014; Liu et al., 2015; Zhong et al., 2015) and high-performance multi-crystalline silicon (HP-Si) (Wu et al., 2015; Yang et al., 2015) are developed for photovoltaic market. The seed for growing QS-Si is mono-crystalline silicon, while the seed for casting HP-Si is multi-crystalline silicon. Multi-crystalline silicon seed is paved at the bottom of the crucible to provide numerous fine nucleation points for the controlled grain growth. Through this seed-assisted DS technology, ingot with uniform grain size and low dislocation is obtained (Yang et al., 2015; Zhu et al., 2014). A higher average solar cell conversion efficiency of about 0.5% in absolute value is achieved in seed-assisted grown multi-crystalline silicon in comparison with that in the conventional multi-crystalline silicon under the same cell fabrication process (Ding et al., 2014; Zhu et al., 2014). This technology will be beneficial for competition of silicon solar cells with others such as hetrojunction photovoltaic cell (Pathak et al., 2010, 2015). The mc-Si solar cell fabricated by Trina Solar has reached a solar cell efficiency of 21.25%, and it is also based on HP mc-Si technology (Lan et al., 2016). There still are many challenges for HP silicon, such as the preservation of seed crystals in feedstock melting (Ding et al., 2014; Ma et al., 2012), the improvement of crystalline quality (Khezami et al., 2016; Wei et al., 2015; Zhao et al., 2014) and thermal field optimization of bigger casting ingot.

Due to the development of computer technology, numerical simulation has become a powerful tool for optimization of the DS process. Ma et al. (2011) establish a numerical model and discuss the influence of side insulation, heater position and gas shield on thermal and velocity field. Relationship of oxygen impurity and gas flow in an industrial DS is studied by Teng et al. (2011). Temperature and carbon impurity distribution in a home-made silicon cast furnace is indicated by Liu et al. (2008). Li et al. develop a global industrial furnace model to study the argon flow effect (Li et al., 2012). It's clear that argon flow plays an important role in DS process. Seed crystals preservation is very important for HP-Si ingot growth. In the DS furnace, the partition block is often used to preserve seed crystals of QS-Si ingot (Ding et al., 2014; Ma et al., 2012; Qi et al., 2014), and it is also applied in the preservation of seed crystals for casting HP-Si ingot (Wu et al., 2015). It is very difficult to control melt/seed interface and asbestos felt is used for preservation of seed crystals in the article, however, the interface shape is usually convex and some crystal grains may grow from side wall to hamper the growth of required columnar grains.

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In present study, there are two aspects to further improve the quality of mc-Si ingot: Firstly lowering the possibility of impurities (carbon and oxygen) second contamination, secondly flattening surface of seed crystals. Few paper report about the circulation flow outside the gas hole or take two aspects above together into account. The simulation model of the original furnace without the plate is built and compared with experiment measurement. The simulation can basically reproduce feedstock melting process. Thermal field, velocity field and silicon phase transition in numerical furnace are investigated in different cases (with and without the plate). The ingot grown by the original furnace and modified furnace are evaluated by infrared scans and minority carrier lifetime to analyze the effect of the plate on ingot quality.

2. Mathematical model description

2.1. Seed-assisted DS description

Based on GT solar DSS450 furnace, the global transient model of feedstock melting process is established. The zone including quartz crucible, graphite crucible, heat exchange block, graphite heaters, gas tube, insulations, insulation felt and asbestos felt is so called "hot zone", which is the key to design thermal field. As shown in Fig. 1, the original numerical furnace of seed-assisted solidification for HP-Si ingot is seen in the left side, while the modified numerical furnace with the plate for improving gas shield is presented in the right side. Satisfactory back plate made of scrap cover is installed outside the gas hole without hampering the side heaters. The thickness is about 8 mm with length of 74–84 mm. Thermocouple 1 (TC1) is installed next to the graphite heaters to monitor the temperature, which is used for controlling the heating power, while the thermocouple 2 (TC2) is insulated vertically at the center of the heat exchange block.

The Fig. 2 shows schematic of heat transfer, gas flow and impurities (carbon and oxygen) transportation in the DS growth. The left side of Fig. 2(a) and (b) show hot zone of conventional furnace, the right side of Fig. 2(a) and (b) show heat flow and Ar flow with chemical reactions in the hot zone, respectively. The heat transfer (red arrows) is exhibited in Fig. 2(a). The graphite heaters adjusted by changing power are the heat source. The heat of conduction and radiation is provided for silicon feedstock. DS processes including feedstock melting, solidification and cooling could be achieved by controlling temperature distribution. It is also noted that there are two main heat losses conducted by insulation and cooling block during the heat transfer process. Fig. 2(b) shows the process of gas flow and impurities transportation. As the side insulation

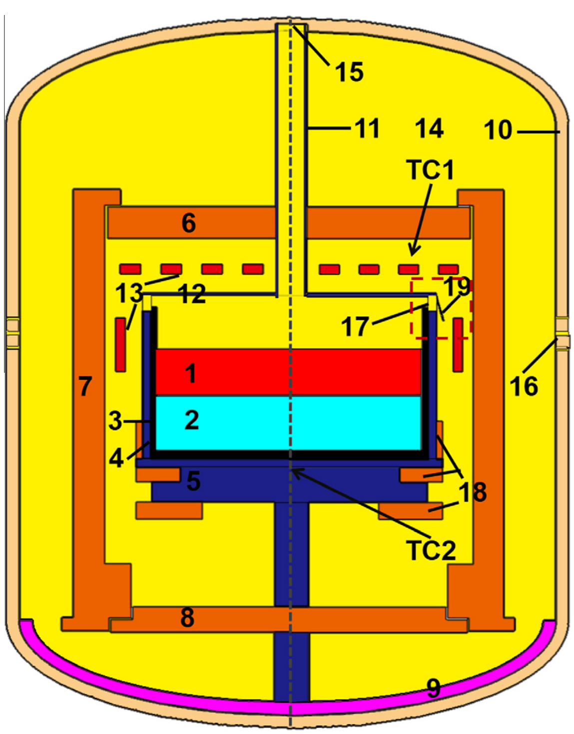

Fig. 1. Configurations of the two seed-assisted DS furnaces: (a) without the back plate (original furnace) and (b) with the back plate (modified furnace).

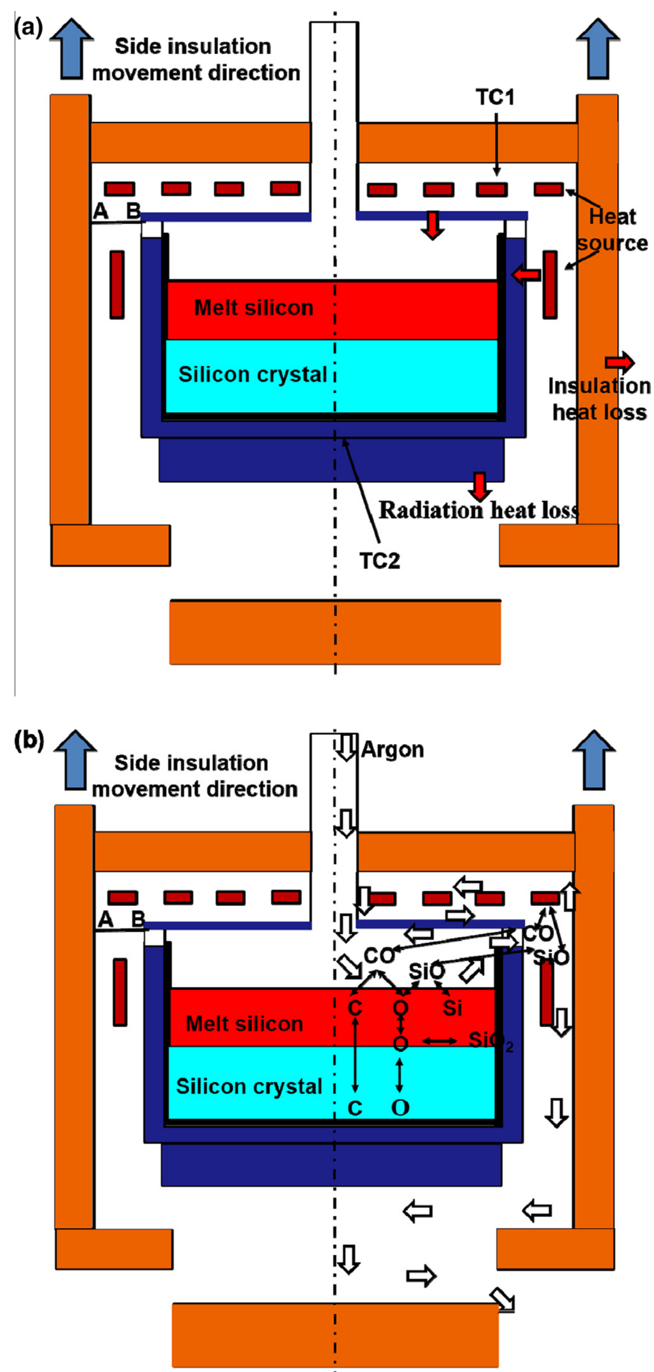

Fig. 2. The schematic of heat transfer (a) and gas flow with impurities (carbon and oxygen) transportation (b) in the DS growth of mc-Si ingot (white arrows represent the gas flow, blue arrows represent the movement direction of side insulation and red arrows represent the heat transfer). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)