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Global simulations of heat transfer in directional solidification of multi-crystalline silicon ingots under a traveling magnetic field

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ABSTRACT

We have performed global simulations of heat transfer during the complete directional solidification (DS) process of multi-crystalline silicon (mc-Si) ingots under a traveling magnetic field (TMF) to investigate the thermal and flow fields in the silicon melt. The melt convection pattern, thermal field, and melt–crystal (m–c) interface shape at different DS stages were compared without a TMF, with an upward TMF, and with a downward TMF. We found that the distribution and the magnitude of the Lorentz force are similar for different melt heights. The melt is mainly occupied by a large vortex, which flows in opposite directions for an upward TMF and a downward TMF. The TMF has a beneficial effect on the melt mixing. The upward TMF makes the m–c interface more concave with respect to the melt, while the downward TMF makes it less concave or convex at the same solidification stage. The interface becomes less concave or convex with increasing solidification fraction under the downward TMF. The amplitude of imposed electric current was adjusted to successfully obtain a slightly convex interface. These results provide important information for optimizing the complete DS process for mc–Si ingots with a TMF.

1. Introduction

Multi-crystalline silicon (mc-Si) ingots grown by the directional solidification (DS) method are the main material for solar cells. Solar cell efficiency is decreased by impurities, precipitates, and structural defects in the mc-Si ingots, and the generation and distribution of these are mainly determined in the DS process. Melt convection is important for heat and mass transfer during the DS process, and can significantly affect the temperature distribution, impurity transport, and the melt-crystal (m–c) interface shape. Therefore, precise control of the melt flow pattern is crucial for optimizing the DS process and improving ingot quality. In the conventional DS system, the melt flow is mainly driven by the buoyancy force resulting from the horizontal temperature gradient. The ability to control the buoyancy force for the melt flow pattern is limited. A more effective way of controlling the melt flow pattern is to use a traveling magnetic field (TMF) [1,2]. A detailed understanding of heat transfer and melt flow in the complete DS process under a TMF is essential in adopting a TMF to optimize the DS process.

Because of the difficulty of experimental measurements in the high temperature melt, model experiments and numerical simulations are often used to investigate melt flow under a TMF. Model experiments for the DS and vertical gradient freeze (VGF) of silicon under a TMF have been conducted in isothermal and non-isothermal small-scale GaInSn melts [3–9]. The flow patterns and mixing effect in a large-scale silicon melt in a DS system under the action of TMFs were also predicted by local simulations with the thermal boundary obtained from global simulations [10–12]. The studies mentioned above did not include the phase change, melt height variation and m–c interface calculation. The m–c interface shape under a downward TMF was simply examined by experimental strain analysis [13], which is inadequate to deeply understand the effect of a TMF on the interface. Although the phase change and interface calculation were considered in some studies devoted to VGF of Ge and semiconductor compound in a TMF [14,15], the thermophysical properties and electromagnetic parameters of Ge and compound are very different from mc-Si, and the hot zone of the VGF system of Ge is also very different from the DS system of mc-Si. Dadzis et al. [16] and Vizman et al. [17] considered the phase change and captured the m–c interface in local unsteady or quasi steady-state simulations for the DS of silicon ingots under a TMF with idealized local thermal boundary conditions. The DS process is a highly coupled nonlinear thermal process with complex thermal interactions between the melt convection and different solid components. It is therefore necessary to employ global modeling, which takes into account all types of heat transfer and phase changes. Because the heating condition and melt height are different at different DS stages, it is essential

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to study the phenomena at different DS stages under a TMF. However, little research has been published regarding heat transfer and melt flow in the complete DS process for mc-Si ingots under a TMF with global simulations.

In this study, we developed a fully coupled global model for the DS process of mc-Si ingots under a TMF, which takes into account all kinds of heat transfer, phase change and m–c interface tracking. Based on this model, we carried out a series of simulations for the complete DS process which was represented by three typical DS stages under different TMFs. The Lorentz force distributions in the melt of different heights were presented in detail. The flow pattern and thermal field in the melt were predicted at different DS stages under different TMFs. The effects of different types of TMF on the melt mixing and the m–c interface shape were analyzed at different DS stages. The effect of imposed electric current amplitude on the interface shape was also examined. The studies can provide important reference for adopting a suitable TMF to maintain a flat or slightly convex m–c interface and good melt mixing throughout the complete DS process of mc-Si ingots.

2. Model description

2.1. Global model of heat transfer

The configuration and computation grids of a DS furnace for the mc-Si ingot have been published in Refs. [18,19]. Both the diameter and the height of the ingot were 10 cm. The major assumptions of the model are: (1) the furnace configuration is axisymmetric; (2) all radiative surfaces are diffuse-gray; (3) the growth system is quasi-steady; and (4) the melt flow is incompressible and laminar. With these assumptions, the governing equations for the melt flow under a TMF can be written as

$$\nabla \cdot \vec{u} = 0, \tag{1}$$

$$\nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \nabla \cdot \left[\mu(\nabla \vec{u} + \nabla \vec{u}^{T})\right] - \rho \vec{g} \beta_T (T - T_0) + \vec{F}_L, \tag{2}$$

$$\nabla \cdot (\rho c_p \vec{u} T) = \nabla \cdot (\lambda \nabla T), \tag{3}$$

where $\vec{u}$, ρ, P, μ, $\vec{g}$, β_T, T, T_0, c_p and λ are the velocity, density, pressure, dynamic viscosity, gravity acceleration, thermal expansion coefficient, temperature, reference temperature, heat capacity, and heat conductivity, respectively. The thermal buoyancy force in the Boussinesq approximation and the Lorentz force $\vec{F}_L$ exerted on the melt by a TMF are taken into account in Eq. (2). The governing equations for other domains and the coupling algorithms for the global modeling of heat transfer in a DS furnace have been published elsewhere [20]. Temperature continuity and heat flux conservation constitute the thermal boundary conditions between any two adjacent domains. The latent heat of solidification is considered in the boundary condition at the m–c interface. The no-slip and non-penetration conditions are applied to the fluid flow at the solid walls.

2.2. Model of TMF

To produce a TMF in the DS furnace mentioned above, an axisymmetric coil system encircling the melt (Fig. 1 (a)) was designed and hypothetically installed in the DS furnace. The coil system consisted of six circular coils with an inner radius of 10 cm. The cross-section of the coils was $2.5 \times 2.5\ \text{cm}^2$ and they were equally spaced at 5-cm intervals. In this study, the coils were fed with a sinusoidal current with amplitude $I_0 = 5$ A and frequency $f = 450$ Hz, and there was a fixed phase shift between adjacent coils of $\phi = 60^\circ$ [7]. The time-averaged Lorentz force $\vec{F}_L$ induced by the TMF coil system in the melt can be obtained by solving the time-harmonic equations for the magnetic vector potential $\vec{A}$ and electric scalar potential φ. The equations are expressed as follows [7]:

$$\nabla \times \nabla \times \vec{A} = \mu_0 \gamma(-i\omega \vec{A} - \nabla \varphi) + \mu_0 \vec{j}_s, \tag{4}$$

$$\nabla \cdot (i\omega\gamma \vec{A} + \gamma \nabla \varphi) = 0, \tag{5}$$

where μ_0 is the magnetic constant (all materials are assumed to be non-magnetic), γ is the electrical conductivity, i is the imaginary unit, ω is the cyclic frequency, and $\vec{j}_s$ is the imposed current density in the coils. $\vec{F}_L$ is calculated using the expression [7,16]

$$\vec{F}_L = \frac{1}{2}(\vec{j}_{re} \times \vec{B}_{re} + \vec{j}_{im} \times \vec{B}_{im}), \tag{6}$$

where the subscripts re and im denote the real and imaginary parts of the magnetic induction $\vec{B} = \nabla \times \vec{A}$ and induced current density $\vec{j} = \gamma(-i\omega \vec{A} - \nabla \varphi)$, respectively.

The magnetic vector potential and electric scalar potential distributions are calculated with the finite volume method. The silica crucible and heat shields are dielectric. The electrical

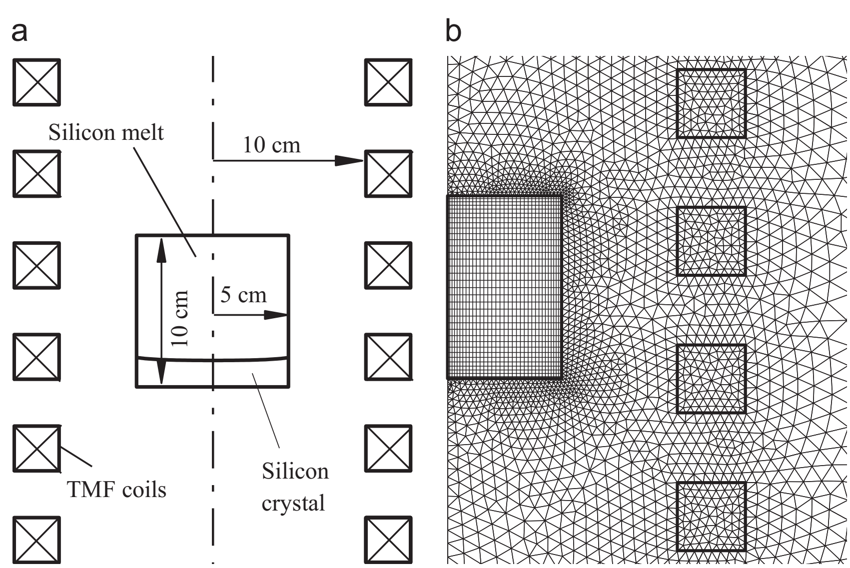

Fig. 1. Axisymmetric TMF coil system: (a) diagram of configuration; and (b) computational grids (left side is symmetric axis).