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ORIGINAL PAPER

Improving Heat Transfer Properties of DS furnace by the Geometrical Modifications for Enhancing the Multi Crystalline Silicon Ingot (mc-Si) Quality Using Transient Simulation

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Abstract

Heat transfer plays a main role on Directional Solidification (DS) process that determines the multi-crystalline silicon (mc-Si) ingot quality. The 2D axi-symmetric model based numerical simulations have been carried out to analyze the heat transfer properties of the DS furnace and to study the thermal effects on mc-Si ingot during the solidification process. For enhancing the heat transfer properties of the DS system and the quality of the mc-Si ingot, the conventional DS furnace was subjected to three types of modifications. The simulation has been made for conventional and modified furnaces and their results were compared and analyzed which confirms that the geometrical modification has influenced the thermal distribution, melt-crystal interface, growth rate, thermal stress and dislocation density of the mc-Si ingot. The following modifications have been taken in conventional DS furnace in sequence: a) For lowering the axial and radial temperature distributions, the bottom insulation was modified (DS-1). b) For melt-crystal interface optimization, the heat exchanger block is grooved in the center part (DS-2). c) Finally, the grooved surface has been subjected to Ar gas flow (DS-3). The evaluations are performed on conventional, DS-1, DS-2 and DS-3 furnaces and their results such as axial-radial temperature distributions, melt-crystal interface, growth rate and thermal stress and dislocation densities are compared and analyzed. The results revealed that the modified furnaces give lower thermal stress and dislocation densities than the conventional furnace. The lower thermal stress with lower dislocation density at the end of the solidification process can prevent the multiplication of dislocations during the cooling process that lead to a good quality mc-Si ingot.

Keywords Computer simulation · Directional solidification · Multi-crystalline silicon · Geometrical modifications · von Mises stress

1 Introduction

Czochralski (Cz) and Directional Solidification (DS) are common methods for producing mono-crystalline silicon and multi-crystalline silicon (mc-Si) ingots. The conversion efficiency of mc-Si based solar cells is slightly less than the mono-crystalline silicon based solar cells. However the DS process has become a leading method for PV applications because of its simpler experimental technique, better feedstock tolerance and higher throughput [1]. The well-known fact is that the DS grown mc-Si contains many defects, such as segregated impurity, randomly oriented grain boundaries, dislocations [2]. We have analyzed the uniform distribution of nonmetallic-impurity atoms in our previous report [3]. C.W. Lan et al. have proposed grain control by introducing cooling spot in the DS furnace that induces the dendrite growth and offers sigma-3 grain boundaries which act as an inactive boundary, hence it does not act as a recombination center [4]. Another important defect is dislocations, especially dislocations can be detrimental to the solar cell performance, and they are classified into primary dislocations and multiplication dislocations. The primary dislocation is formed during the forefront of crystallization process which are caused due to atomic alignment error. Dislocation multiplication is formed by the thermal stress. The thermal stress in the crystal acts as a driving force for the primary dislocations which

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may increase the dislocations multiplicatively about several hundred times of primary dislocations. Therefore, most of the final dislocations in the crystals are multiplication dislocations. The inhomogeneous temperature distribution causes thermal stress in the ingot and it is inevitable in the large-scale growth process [5]. The main aim of this study is lowering the dislocations generation during the solidification process. The lower dislocation density at the end of the solidification process can minimize multiplication of dislocations and enhances the mc-Si ingot quality.

The generation of primary and multiplication dislocations can be controlled by optimal solidification and cooling processes. It is not possible to study the effect of solidification and cooling process separately via experiments, since grown ingot contained both effects at the end of the process. The numerical simulation is a powerful tool for studying the solidification process at any time during the growth process (unsteady simulation). Here, we have studied the solidification process of mc-Si ingot by using appropriate simulation tool and estimated their temperature distribution, melt-crystal interface shape, thermal stress and dislocations density for various geometrical configurations.

During the DS process, the furnace configuration and process operating parameters are the main factors that influence the thermal condition [6]. The thermal stress is induced by the temperature gradient and inhomogeneous temperature distribution in grown ingot [7]. And the generation of dislocations is associated with thermal stress and melt-crystal interface shape of the mc-Si ingot [8]. Hence, reducing the thermal stress is essential. Another main challenge is optimizing the melt-crystal interface shape. Generally, the melt-crystal interface is optimized with the powers of top and lateral heaters. However, the direct parameter for optimizing the melt-crystal interface shape gives more strength to the solidification process. So, we have introduced the modifications in the conventional DS furnace to control the axial, radial temperature gradient along with melt-crystal interface. Here, the three types of modifications have been made in conventional DS furnace configuration for optimizing the axial and radial temperature distribution and melt-crystal interface shape of the mc-Si ingot whose heat transfer properties give an optimal environment to grow the good quality mc-Si ingots. The evaluations performed on conventional and modified furnaces and their results were compared and analyzed with each other and the main objective of this study was to obtain the controlled heat dissipation rate from the DS block, optimizing the melt-crystal interface, bringing down the thermal stress and the dislocation density of the mc-Si during the solidification process by reducing the axial and the radial temperature gradient along with optimizing the melt-crystal interface. The optimal solidification process followed by suitable cooling process can enhance the mc-Si ingot quality.

2 Geometrical Configurations

2.1 Conventional DS Furnace

Figure 1a, shows the 3D schematic view of the conventional DS furnace (G2 size DS furnace, Crystal size: l*b*h= 45cm*45cm*20cm). Initially, the insulation loop is closed for melting the silicon feedstock in the quartz crucible. For solidifying the silicon feedstock and preventing the seed melting, the side insulation is quickly lifted upward at elevated velocity, hence the heat is extracted from hotter to colder zone. Heat is transferred in the form of heat conduction mode through the silicon melt, silicon crystal, crucible bottom and heat exchanger block. Therefore, the crystallization starts from the bottom. Once the crystallization is started the heater power and the lifting velocity of side insulation are carefully controlled for acquiring optimal growth rate. Both top and lateral heaters are used as heat source which are more convenient to control the axial temperature difference and melt-crystal interface in the mc-Si ingot. The convection in the melt is dominated by natural convection, and is not strong enough to develop into turbulent flow due to the top heating [9]. However, the horizontal heat dissipation of the heat exchanger block is difficult to control, because the extruding part of the side insulation redirected the radiation from hot zone to heat exchanger block which offers the radial temperature gradient [10]. During the solidification process, the fast slow movement of side insulation makes different growth rates at different solidification fraction whereas the segregation of impurities may also be affected. Optimizing the melt-crystal interface in the conventional furnace is little complex because it depends on the ratio of side and top heater powers and side insulation velocity [11].

2.2 DS-1 (Circular Bottom Opening DS Furnace)

To get an optimal radiation heat transfer and maintaining uniform growth rate throughout the solidification process in the conventional furnace are little bit complicated due to the broad opening and radiation redirecting behavior of the side insulation [10]. Instead of side insulation, here the modified bottom insulation is used for radiation heat extraction. The bottom insulation is opened in the circular manner and 3D Schematic diagram is shown in Fig. 1b. During the solidification process, the radius of the circular opening is increased to extract the heat from hotter region to colder region. Compared with the side insulation movement, the bottom insulation circular opening is an efficient way

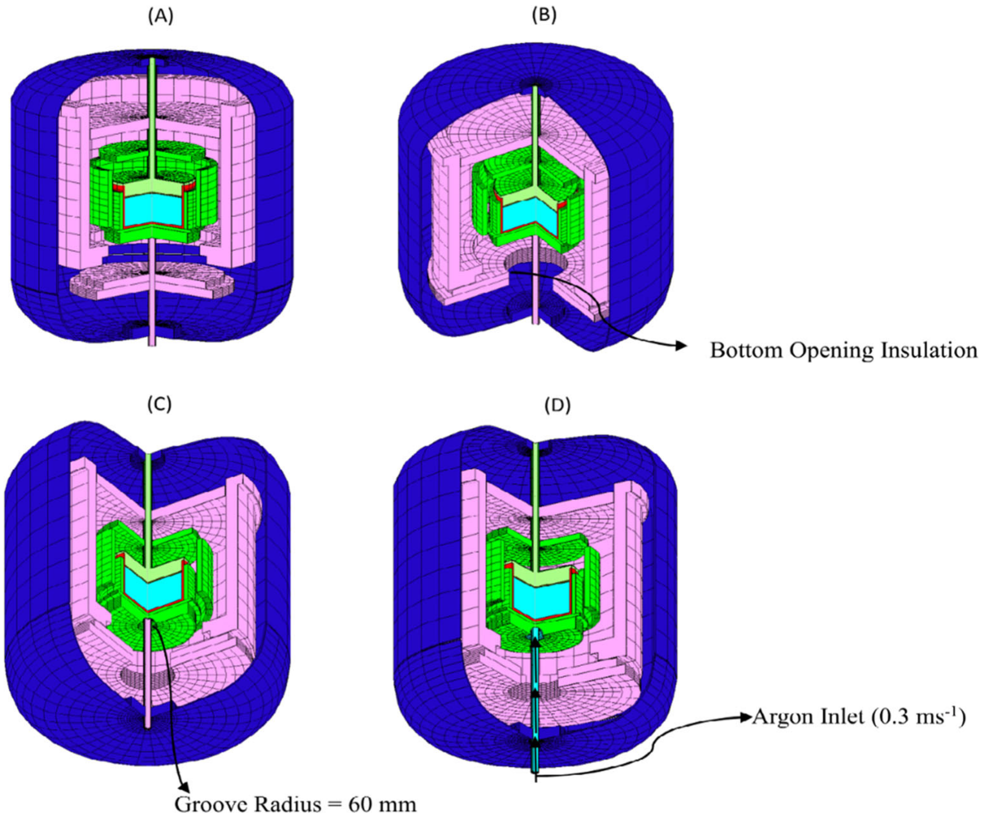


Fig. 1 3D Schematic view of DS furnaces **a** Conventional, **b** DS-1, **c** DS-2, **d** DS-3

to obtaining controlled heat transfer, which lowers the both axial and radial temperature gradient in the mc-Si ingot.

The thermal stress is caused by axial and radial temperature distributions, those are optimized by the DS-1 furnace, even though, on the interface point of view it is not satisfactory. For getting good quality ingots, both thermal distributions and melt-crystal interface are needed to be optimized. Slightly convex melt-crystal interface is preferred for optimal growth and maintaining with slightly convex melt-crystal interface throughout the solidification process is more essential.

2.3 DS-2 (Grooved DS Furnace)

To obtain the slightly convex melt-crystal interface and maintaining it throughout the solidification process, a groove of 60 mm radius is made in the heat exchanger block of the bottom opening furnace (DS-1). The 3D schematic diagram is shown in Fig. 1c. By grooving the heat exchanger block, the heat is dissipated quickly in the center region than the peripheral regions which gives the slightly convex melt-crystal interface during the solidification process. The bottom opening insulation along with grooved heat exchanger can give lower axial and radial temperature gradient along with the convex melt-crystal interface during the solidification process. The convexity of the melt-crystal interface can be changed by changing the groove radius [12].

The nucleation of dislocation clusters at the melt-crystal interface is an additional formation mechanism. These clusters are propagated upwards along the growth direction during the solidification, growing in size until they are blocked by a large angle grain boundary or twin [13]. But in the case of mc-Si these blocking defects are not abundant, and dislocation lines that grow with the melt-crystal interface have been observed to merge together and forming large dislocation clusters [8]. Hence maintaining the same melt-crystal interface shape throughout the solidification may prevent the interface effect on dislocations. The ingot grown with DS-2 furnace maintains slightly convex melt-crystal interface throughout the process that improves the mc-Si ingot quality.

2.4 DS-3 (DS-2 Furnace with Ar gas pipe)

The grain boundaries of the mc-Si ingot is one of the factors that limit the efficiency. The controlled grain growth of mc-Si ingot is obtained by the dendrite growth process. The essential of the dendrite growth is radial temperature difference of the mc-Si ingot. For employing radial temperature gradient, the bottom grooved area of DS-2 furnace is attached to the Ar gas pipe (diameter = 5cm). The argon gas quickly takes the heat away from the grooved surface, which makes the bottom middle region of the crucible colder than the peripheral regions of the crucible. This condition is preferred for the controlled grain growth of mc-Si ingot. But our simulation studies are only based on thermo-elastic model dislocation generation, it does not provide any information about the grains, hence DS-3 grown ingot is evaluated based only on the thermo-elastic model. According to this, the radial temperature distribution offered by this spot cooling effect, causes slightly higher thermal induced thermal stress in the mc-Si ingot than DS-1 and DS-2 grown ingots. Even though, the lower axial temperature distribution due to the bottom opening insulation results in the lower thermal stress in DS-3 grown mc-Si ingot than the conventional grown ingot. The radial temperature distributions and the convexity of the melt-crystal interface shape can be tuned by changing the flow velocity of Ar gas. The proposed condition is well suited for the dendrite growth process of silicon growth, because the optimal radial temperature offers the dendrite growth with favored grain boundaries. The 3D schematic diagram is shown in Fig. 1d.

2.5 Model Descriptions

The simulation tool is designed with 2D computations of global heat transfer that involves conductive, convective and radiative heat transport. A special crystal growth simulation software, CGSim, developed by STR Group, was used for the computations presented in this paper. The software has been verified using a significant number of experiments [14–16]. The following assumptions were made: the inert argon gas was treated as an ideal gas and incompressible, all of the radiative surfaces were assumed to be diffuse gray, the melt was considered as the Newtonian fluid and incompressible, the energy balance equation (1) governs the melt flow pattern, the crystal was assumed to be isotropic for dislocation density calculation and the von Mises stress was used to reflect the thermal stress and the crucible rigid constraint is ignored. Experimentally, the crucible constraint was reduced by using Silicon Nitride coating (Si_2N_3) on the crucible. Most simulation analyzes of thermal stress distribution are based on thermo-elastic stress model [17, 18]. In our simulation we have considered seeded mc-Si ingot growth and analyzed their thermal induced stresses based on thermo-elastic stress model. The thermal induced stress is derived from the inhomogeneous temperature distribution in the mc-Si ingot whose distributions were analyzed for various geometrical configurations by keeping same control parameters. The local dislocation density was carried out from the local stress in excess of the critical resolved shear stress (CRSS), following the HAS model [19]. The thermal stress and the melt-crystal interface determine the mc-Si ingot quality. Here we have considered an optimization of both temperature distribution and melt-crystal interface shape in the mc-Si ingot. The time dependent simulation was solved iteratively by using finite volume method.

$$C_p \rho \,[\frac{\partial T}{\partial t} + (\vec{V}\nabla)T] = k\,\nabla^2 T + \varphi \tag{1}$$

$$\rho C_p \frac{\partial T}{\partial t} - \beta T \frac{\partial p}{\partial t} = k\,\nabla^2 T \tag{2}$$

The conductive and convective heat transfers are governed by the above (1), Eq. 2. The distribution of temperature depends on the thermal conductivities and the volume of the adjacent materials. Here the thermal radiation from the graphite heater introduces the temperature gradients to their near parts according to their thermal conductivities. The thermal conductivities of the adjacent parts of mc-Si ingot such as crucible, susceptors, heat exchanger block are mainly responsible for the temperature distribution in the grown mc-Si ingot. The modifications on the adjacent parts of the mc-Si ingot should affect the thermal distribution in the ingot. In our simulation we have grooved bottom heat exchanger block that influences the thermal distribution in the DS block and gives optimal conditions for mc-Si ingot growth.

3 Results & Discussion

The studies are mainly based on the heat transfer in DS block. In directional solidification method, the thermal distribution in the mc-Si ingot is one of the main factors to determine the mc-Si ingot quality. Due to the heat extraction through the bottom of the DS block, the thermal radiations from the graphite heaters induce the thermal gradient to their adjacent parts such as graphite susceptors, crucible walls, silicon melt, silicon crystal and heat exchanger block. The speed of heat propagation through each part of the DS-block depends upon their thermal diffusivities. The good mechanical property and the good thermal conductivity material such as graphite is used as a heat exchanger block placed at the bottom of the crucible for getting optimal heat extraction. In conventional furnace, the side insulation is lifted during the solidification process. The limitations that we have observed from the side insulation movement are, hot extruding part of the side insulation which offers the inhomogeneous radial temperature differences at the bottom of the ingot by heating the side of the heat exchanger block [20] and the broad opening makes uncontrolled radiation heat extraction. To overcome these limitations, we have designed DS-1 furnace whose bottom insulation is opened in a circular manner during the solidification process. The fixed side insulation and the smaller path of heat extraction through the bottom opening in DS-1 furnace can prevent initial larger growth rate and reduce the radial temperature gradient. Because of these factors, the bottom opening insulation will be an effective parameter for obtaining an optimal growth process. The temperature gradient conditions have been satisfied with the DS-1 furnace and the important factor that determines the mc-Si ingot quality is melt-crystal interface. Earlier reports stated that the preferable shape of melt-crystal interface in DS process is slightly convex which can eject the impurities toward the peripheral region of the ingot [21]. For completing the melt-crystal interface optimization, we have grooved the heat exchanger block of DS-1 furnace. In conventional and DS-1 furnace, the heat from the silicon crystal propagated in conduction mode through the heat exchanger block and emitted in the form of radiation at their planar bottom and side boundaries. In a DS-2 furnace, we have shortened the conduction heat propagation path at the center region of the heat exchanger block by grooving the surface, therefore the heat is transferred sooner in the form of radiation at the grooved area. This can alter the thermal distribution in the mc-Si ingot and makes the center part of the crucible always less hot than the peripheral region. The radius of the grooved surface can result in the convexity of the melt-crystal interface and it can reduce probability of getting concave melt-crystal interface. The optimal axial and radial temperature gradients and the slightly convex melt-crystal interface throughout the solidification can be obtained by using DS-2 furnace. The investigations on the thermal distributions, thermal stress, growth rate, melt-crystal interface shape and the growth rate for those furnaces were carried out with the help of transient global modeling. Further, the grooved area of DS-2 furnace was attached to the Ar gas pipe. By introducing the gas pipe at the grooved surface, the center part of the crucible cooled faster. This spot cooling effect offers the radial temperature gradient in the growing ingot. The dendrite growth of mc-Si ingot requires optimal radial temperature gradient [22]. The radial temperature gradient can be controlled by changing the flow velocity of Ar gas. So DS-3 furnace gives the optimal conditions for dendrite growth of mc-Si ingot. The heat flux diagram in DS block for four furnaces is shown in Fig. 2.

From the heat flux diagram in Fig. 2 we have observed that geometrical modification has influenced the heat flux extraction path. In the bottom opening furnace such as DS-1, DS-2 and DS-3, the smaller bottom hole opening in the bottom insulation gives the heat extraction directly opposite to the growth direction which can give the optimal solidification process than the side insulation opening process.

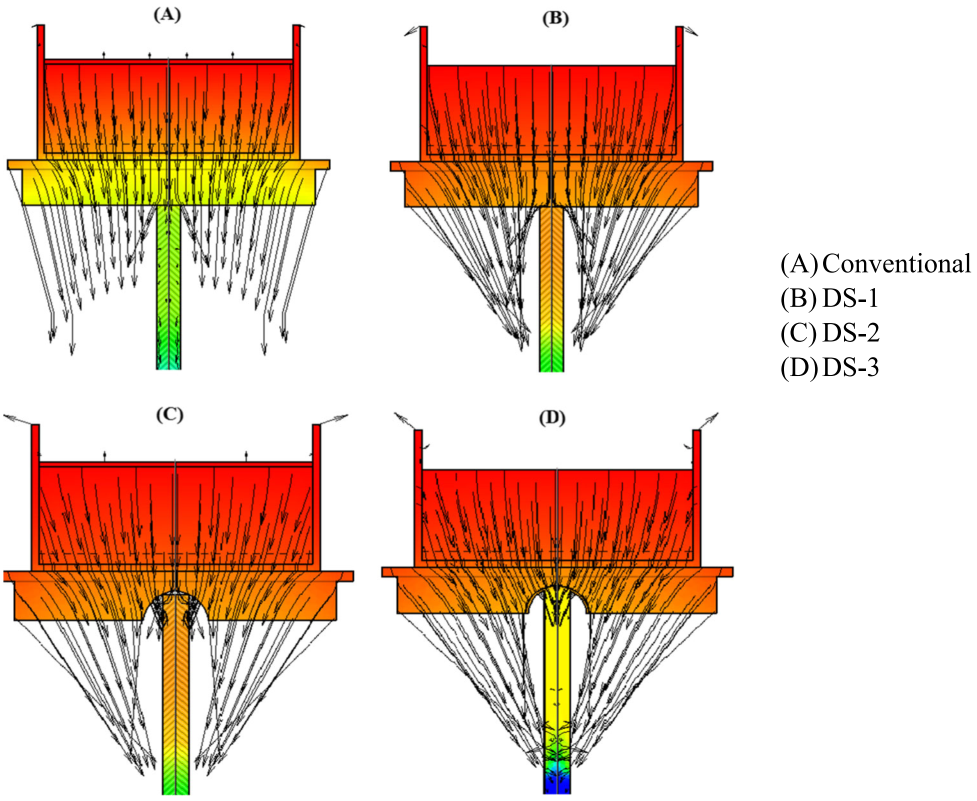


Fig. 2 Heat flux diagram in DS block

3.1 Axial-Radial Temperature Gradient

The main factor that limits the quality of the mc-Si ingot is thermal induced stress, which is caused by the inhomogeneous thermal distribution in the mc-Si ingot during the solidification process. During the phase change of silicon from melt to crystal, it expands about 8% in volume which is compensated by an upward movement of liquid in the solidification process. The inhomogeneous thermal distribution in the mc-Si ingot during the solidification process introduces an uneven thermal expansion to their adjacent parts and also induces stresses by mutual restraints [23]. The axial and radial temperature gradient results in inhomogeneous thermal distribution within the mc-Si ingot and there should be an uneven thermal expansion taking place. Due to this uneven thermal expansion, the continuum silicon particles are constrained from the free expansion and the thermal stress is induced in the mc-Si ingot. The larger radial and axial temperature gradient causes larger thermal stress in the mc-Si ingot.

Figure 3, shows the temperature diagram in the axial direction at center line of the grown mc-Si ingot. All the control parameters and the insulation movement profiles were same for all four cases except the geometrical configurations. In the case of insulation movement profile, the lifting distance of the side insulation is considered as a radial opening distance of the circular opening bottom insulation. From the Fig. 3, it is confirmed that the radial temperature distribution of the mc-Si ingot is greatly affected by the geometrical modifications. The side insulation movement in the conventional furnace offers the higher axial temperature gradient. Even a small distance of lifting of side insulation can offer the larger path to the radiation heat extraction that results in the higher temperature distributions in the mc-Si ingot. When compared with the side insulation movement the bottom opening insulation may act as a more convenient parameter for DS process whose effect on the axial temperature gradient is very optimal. Due to the controlled radiation heat extraction behavior, the circular bottom opening insulation always offers the lesser axial temperature gradient than the side insulation movement. The axial temperature differences ($\Delta T = T_{max} - T_{min}$) at the center of the mc-Si ingot for conventional, DS-1, DS-2 and DS-3 furnaces are 193K, 96K, 92K and 109K. The higher axial temperature gradient is observed in the conventionally grown mc-Si ingot.

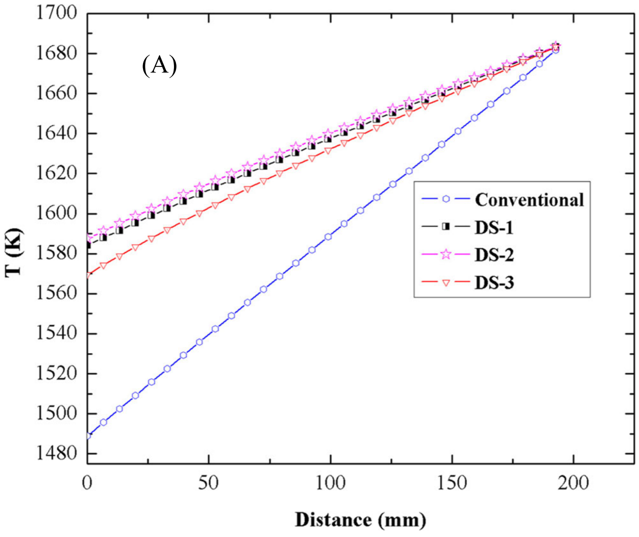


Fig. 3 Axial temperature distribution with height of the mc-Si ingot at the end of solidification process at center line of the mc-Si ingot

The radial temperature distribution was taken from the center of the ingot to the corner region in the bottom of the ingot at the end of solidification and is shown in Fig. 4 (right side y-scale for conventional process and left side y-scale for DS-1, DS-2 and DS-3 processes). The radial heat dissipation is difficult to control in the conventional DS process [23]. The higher radial temperature gradient results in the higher thermal stress in the mc-Si ingot [20]. The extrusion part of the side insulation redirected the heat radiation from the heaters and makes the side of the heat exchanger as hotter than the center region. This results in the higher radial temperature difference in the conventional DS process. The fixed side insulation in DS-1, DS-2 and DS-3 furnaces can overcome this effect. The bottom opening insulation sufficiently decreases the radial temperature differences in the mc-Si ingot. The radial temperature differences between the center and peripheral region of the mc-Si ingot at the end of solidification for conventional, DS-1, DS-2 and DS-3 furnaces are 30K, 17K, 22K and 28K. The larger temperature gradient in the axial and radial direction results in higher thermal stress in the mc-Si ingot. The primary dislocations along with the higher thermal stress in the conventionally grown mc-Si ingot can increase the multiplication of dislocations during the cooling process. The higher dislocation density can limit the minority carrier lifetime of the mc-Si ingot. In DS-1, DS-2 and DS-3 furnaces, the bottom opening insulation offers the lower axial and radial thermal gradient that results in the lower thermal stress in the mc-Si ingot. The lower axial and radial temperature gradients were observed in DS-1 furnace that results in the lower thermal induced stress in DS-1 grown ingot. For interface optimization, we grooved the bottom of the heat exchanger block, DS-2 furnace, which slightly affects the radial temperature gradient. There are several methods found for the dendrite growth process like spot cooling furnace and the crucible with various thermal conductivity material [24]. Here the DS-3 furnace acts as an efficient spot cooling furnace, which can be elevated for the

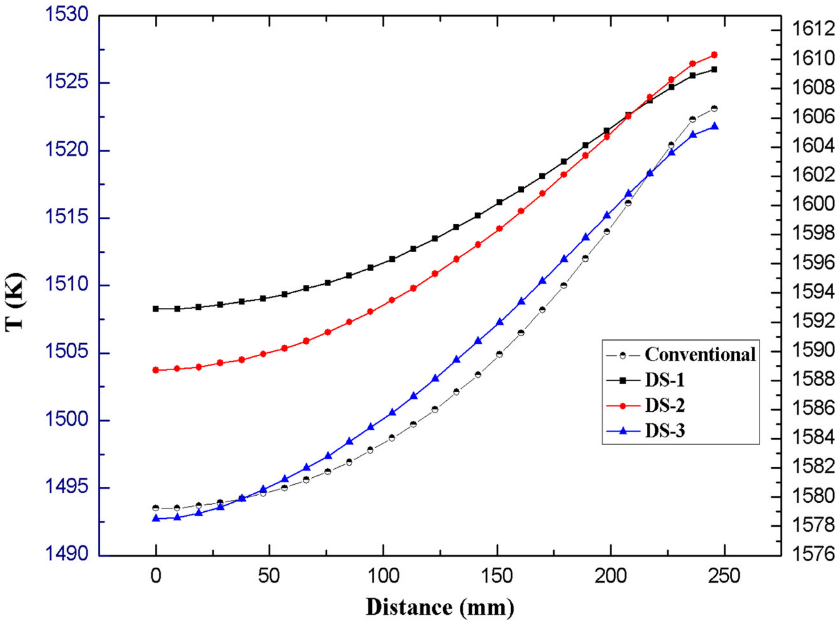


Fig. 4 Temperature distribution from center to peripheral region at the bottom of the mc-Si ingot at the end of solidification process

dendrite growth of mc-Si ingot due to their adjustable radial temperature gradient.

3.2 Melt-Crystal Interface, Growth Rate

The curvature of the melt-crystal interface can affect the crystal morphology and the locations of impurities in the mc-Si ingot during the solidification process [25]. Wenhui Ma et. al. reported that a slightly convex and smaller variation in shape of the interface is favorable for the directional solidification process and a strongly convex shape should be avoided for getting good quality mc-Si ingots [26]. The convex melt-crystal interface has advantage of pushing the impurity atoms outwards from the center region of the mc-Si ingot [21] and it will oppose the nucleation on the crucible side wall. However, the more convexity which results in higher axial temperature gradient should be avoided.

Figure 5, shows the melt-crystal interface shape at the 4th hour of the solidification process. The conventional

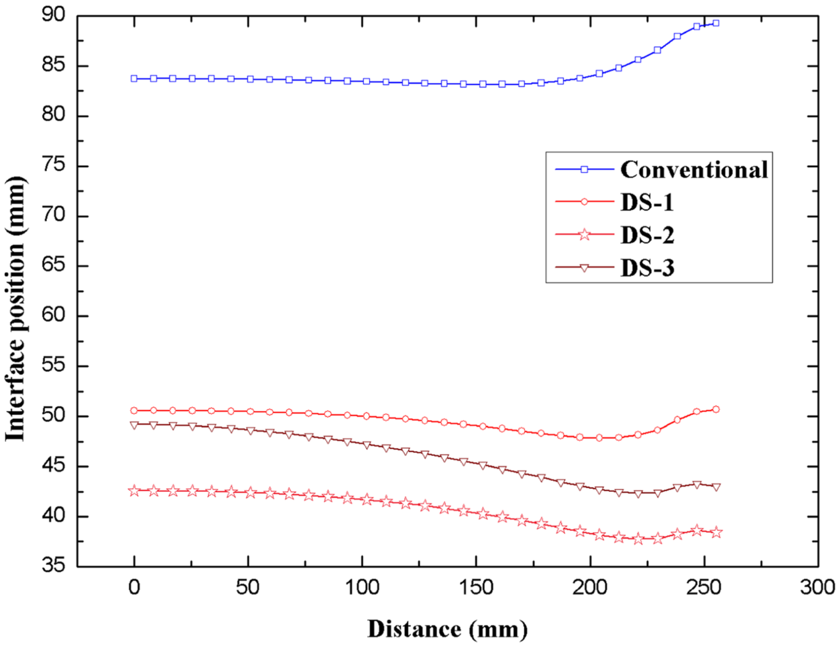


Fig. 5 Melt-crystal interface shape at 4th hr of the solidification process

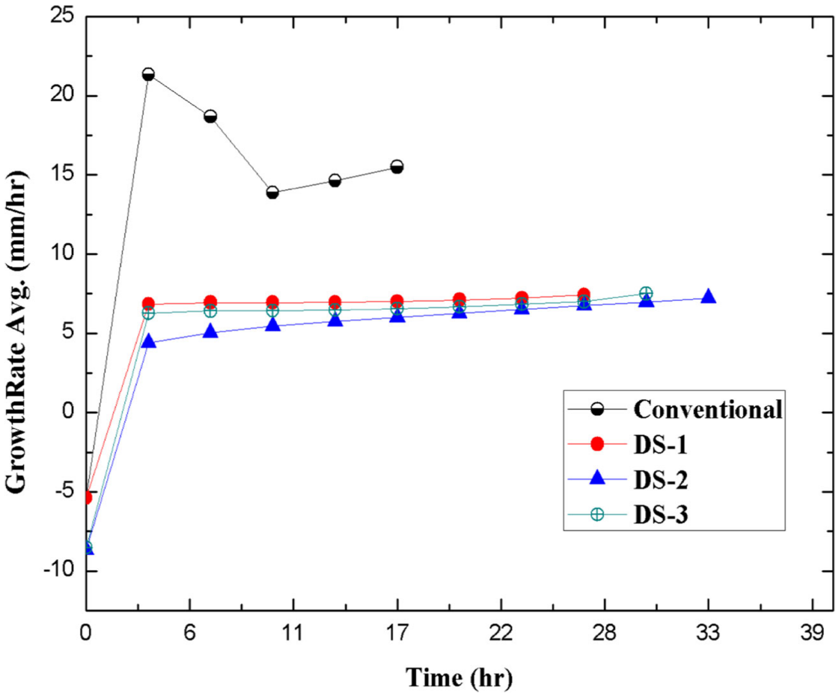
DS furnace has concave melt-crystal interface. The higher heat radiation extraction rate caused by the side insulation lifting process that introduces the larger thermal difference in axial direction and results in the higher initial growth rate. And the melt-crystal interface shape is concave at the initial stage, and then it changes to be convex at the later stage of the solidification process. Due to this double-curved growth interface, some impurities may be trapped in the middle of the ingot [27]. The interface shape near the crucible wall for all ingots is curved upward, which is caused due to the escape of latent heat of solidification through the crucible side walls [28]. In the case of DS-1 furnace, nearly convex melt-crystal interface obtained at the initial stage of solidification process along with the upward curvature interface near the crucible wall, thus may promote the inhomogeneous grain orientation in the mc-Si ingot. This effect can be optimized by introducing grooved furnace (DS-2) which gives nearly convex melt-crystal interface throughout the solidification process. The groove at the bottom of the heat exchanger block swells the center curvature of the mc-Si ingot and it offers the preferred convex melt-crystal interface ever. Even it provides small thermal induced stress in the radial direction, it can be more satisfactory with the slightly convex melt-crystal interface. In the case of DS-3 furnace, the spot cooling effect results in more convexity during the solidification process.

X.J. Chen et al. reported that the stresses in a silicon ingot increase as the solidification time is reduced, suggesting that a long solidification time should be used to reduce stresses in the ingot [29]. The larger initial and uneven growth rate in conventional DS furnace results in larger stress and limits their quality. Whereas the bottom opening insulation furnaces such as DS-1, DS-2 and DS-3 give the smaller initial growth rate than the conventional DS furnace and also give the uniform growth rate in later stages. The Fig. 6, shows the average growth rate as a function of time during the solidification process. The figure shows that the modifications in the DS furnace change the growth rate of the solidification process. The smaller growth rate with increased solidification time was observed in DS-1 and DS-2 furnaces. The bottom opening insulation along with the grooved bottom heat exchanger block in DS-2 furnace can converge the path of dissipated heat radiation, hence the lowered heat dissipation compared to other furnaces gives the smaller growth rate. The experimental validations also suggest that the impurity precipitation free crystals could be produced at a low growth rate [30].

3.3 Thermal Stress – Dislocation Density

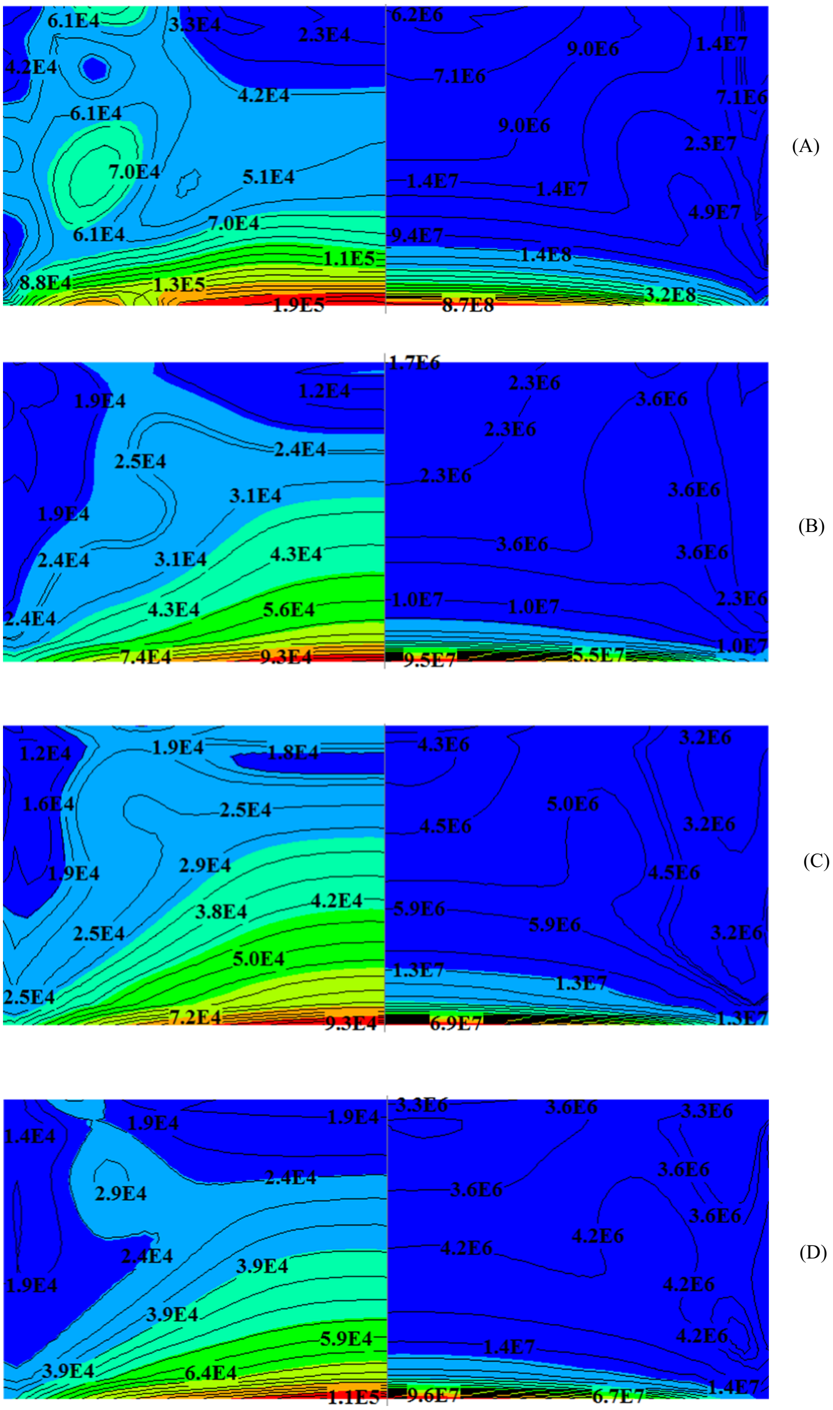
Xinming Huang et al reported that the distribution of thermal stress depends on both the axial and radial temperature gradients and the thermal stress is one of the main factors that affect the propagation of dislocation in the mc-Si ingot [31]. Olga. V. Simirnov et. al. showed that one of the major factors affecting the generation and multiplication of dislocations inside the crystal bulk is thermal stress, which is provided by thermal deformation due to spatial temperature variations during the crystal growth and cooling processes [32]. In unsteady simulation,

Fig. 6 Average growth rate as a function of solidification time



the formation of dislocations due to the stress relaxation is changed according to the thermal distribution in the grown ingot. The controlled heat dissipation rate from the DS block and the suitable heater power decrement rate is essential throughout the solidification process that can establish the optimal temperature distribution in the ingot. By minimizing the inhomogeneous temperature distribution in the ingot the thermal stress can be reduced, which controls the formation of dislocation during the solidification process. The thermal stress (left side) and the dislocation density (right side) at the end of solidification process for conventional, DS-1, DS-2 and DS-3 furnaces are shown in Fig. 7. The higher thermal stress and dislocation density is observed in the bottom center of all the mc-Si ingots due to their higher temperature gradient at the bottom region. The higher axial and radial temperature differences in the conventionally grown mc-Si ingot result in the higher thermal stress and more dislocations within

Fig. 7 Thermal Stress (left) in Pa and Dislocation Density (right) in 1/m2 distributions in mc-Si ingot **a** Conventional, **b** DS-1, **c** DS-2, **d** DS-3



the ingot when compared with modified furnaces. From the thermal analysis, the lowered axial and radial temperature differences is observed in DS-1 furnace that results in the lower thermal induced stress and accordingly dislocation density in the mc-Si ingot. For interface optimization, DS-2 furnace was introduced that results in slightly higher thermal induced stress than DS-1 furnace due to their radial temperature difference. The higher radial temperature gradient due to the spot cooling effect and the lower axial temperature gradient results in slightly higher thermal induced stress in DS-3 furnace than DS-1 and DS-2 furnaces. DS-3 furnace provides optimal conditions for good grain growth.

From the results we conclude that DS-1 and DS-2 furnaces are suitable for optimal seeded mc-Si solidification process because of their lower radial axial and radial temperature difference, uniform growth rate, lower thermal stress and dislocation density. The enhanced slightly convex melt-crystal interface in DS-2 furnace can alter the location of impurities from the center region of the ingot. These factors are essential for getting lower formation of dislocation densities at the end of solidification process. And the DS-3 furnace such as spot cooling furnace may offer the optimal conditions for dendrite growth that elevated radial temperature distribution results optimal grain growth conditions.

4 Conclusion

The transient global simulation was established for conventional, DS-1, DS-2 and DS-3 furnaces and their thermal distributions, melt-crystal interface shape, growth rate, thermal stress and dislocation densities are evaluated. The simulation results showed that the modified furnaces such as DS-1, DS-2 and DS-3, give lower thermal stress and dislocation density in the mc-Si ingot than the conventional furnace. From heat transfer investigations, we found that the circular bottom opening insulation gives the optimal heat transfer situation for seeded mc-Si ingot growth and the bottom opening furnace along with grooved heat exchanger block furnace (DS-2) can also give better melt-crystal interface shape along with lower axial and radial temperature difference, uniform growth rate, lower thermal stress and dislocation density. The controlled grain growth condition was established by the spot cooling (DS-3) furnace which offers the radial temperature that may help to the dendrite growth of mc-Si ingot. We conclude that the modified furnace can give good quality mc-Si ingots with lowered thermal stress and dislocation density. The lower thermal stress and dislocation density at the end of solidification process can prevent the multiplication of dislocation during the cooling process which can improve the mc-Si ingot quality.

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