MODELING OF HEAT TRANSFER DURING SEMICONDUCTOR CRYSTAL GROWTH WITHIN CUSP AND ROTATING MAGNETIC FIELDS

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Introduction. The technologies of semiconductor single crystal growing on ground and in space are a perspective application of magnetic fields. The examples of such application are given in our works: in [1] for the most widespread ground technology of silicon (Si) single crystal growing by the Czochralski (CZ) method and in [2] for the space technology of semiconductor single crystal growing by the floating zone (FZ) method.

In the CZ method, silicon monocrystalline ingots have a cylindrical shape and are grown in a cylindrical high-temperature chamber (hot zone). In Fig. 1 the scheme of a mathematical model of the CZ method is presented, on which a silicon crystal pulled with a rate V_p from a crucible is shown. The melting and heating of the crystalline volume in a crucible is carried out by lateral and bottom heaters. The hot zone is located in a closed water-cooling chamber, whose walls are isolated from the heated up surfaces by thermal shields. The crystal and the crucible rotate in the same or oppisite directions with angular rates Ω_S and Ω_C for symmertrizing of crystal and crucible temperature fields.

The heat transfer processes in the hot zone are rather various and occur in complicated geometry. They include conductive heat transfer in rigid elements

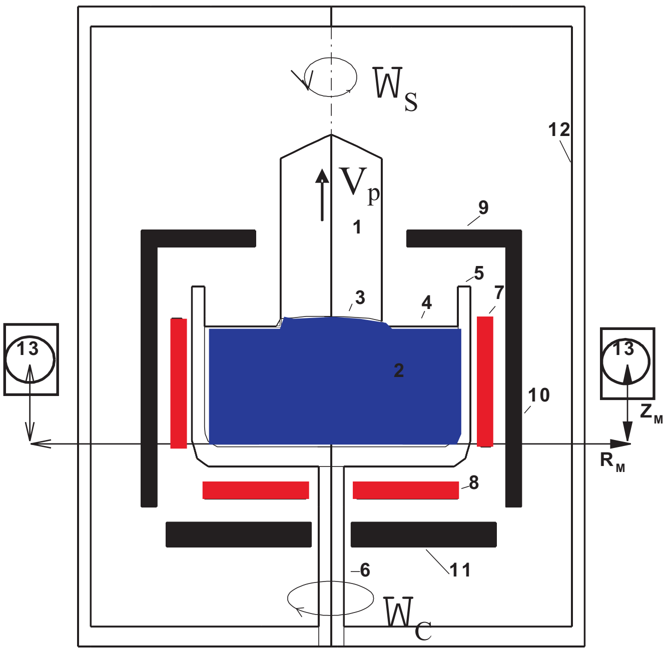

Fig. 1. Scheme of the global thermal model for CZ crystal growth: 1 – crystal, 2 – melt, 3 – liquid-solid interface, 4 – free melt surface, 5 – crucible, 6 – rotating rod, 7 and 8 – heaters, 9,10,11 – thermal shields, 12 – water-cooling camera, 13 – inductor of rotating magnetic fields.

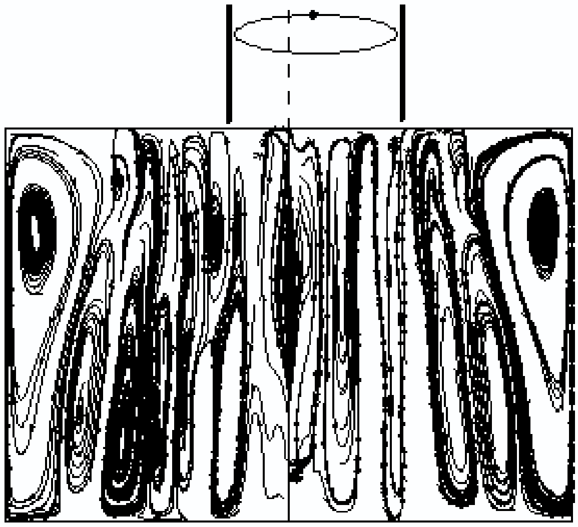

Fig. 2. Non-controlled decay of Si melt flow into a number of vortices caused by axymmetrical rotation of a large-diameter crystal (Re $= 6 \times 10^4$, Gr $= 2 \times 10^9$).

of the furnace, convection in the melt, radiation heat exchange of the heated up surfaces and crystallization process. The numerical research of the heat transfer in such mathematical model is carried out on the basis of global thermal approximation [3], taking into account radiating, conductive and convective (in the melt) heat transfer.

In the present work the features of flow patterns in large melt volumes, appropriate to a large diameter (200 mm) Si crystal growing without a magnetic field application are considered. The influence of crystal asymmetry on melt patterns is discussed. The opportunities of Si melt flow control by means of a rotating magnetic field are shown. In particular, the opportunity of heat transfer symmetrizing and flow patterns formation, ensuring the set shape of the liquid-solid interface is shown.

1. Counter- and iso-rotation of crystal and crucible. Large diameter (200 mm) Si crystals are pulled from large melt volumes in a crucible (more than 60 kgs). The flow and heat transfer under such conditions may become unstable and cause temperature pulsations in a melt. These pulsations result in time–spatial changes of the interface, causing the oscillatory impurity inhomogeneity in a crystal.

Table 1. Physical and dimensionless parameters: ΔT – maximal temperature difference in the melt, Pr – Prandtl number, Ω_S, Ω_C – crystal and crucible rates, Gr – Grashof number, Re – Reynolds number. Here scales for dimensionless parameters are taken: R_S – crystal radius and Ω_S – its rotation rate.

ΔT, K	Ω_S, rpm	Ω_C, rpm	Gr	Pr	Re
162	15	8	1.62×10^9	0.01	6.28×10^4

At present there is a sufficient understanding of laminar axisymmetrical melt flows, which were developed in the 80–90's of the last century. However, non-stationary and three-dimensional patterns are not practically investigated, which in the large melt volumes result in a negative influence on the crystal shape symmetry and its perfection for the standard technological influences: crystal rotation and pulling, crucible rotation and its heating.

The present-day task is the analysis of instability and asymmetry flow reasons, and also search of means for elimination of these undesirable effects.

Some numerical results are illustrated in Fig. 2 for the hydrodynamic and thermal parameters given in Table 1.

In these figures the fluid particles' trajectories are shown. The analysis of these data yields that the melt flow has a complicated multivortical and asymmetric structure causing also an asymmetric thermal field. In addition, to comparison of the roles of the crystal and the crucible, counter- and iso-rotations were calculated. The complicated and multivortical pattern structure similarly arises for a case of crystal and crucible iso-rotations, too. Our analysis shows that it is related to complete prevalence of the azimuthal crucible rotation moment in the melt at $|\mathbf{\Omega}_{\mathrm{C}}/\mathbf{\Omega}_{\mathrm{S}}| > 0.5$. Therefore, the crystal rotation does not play any role in pattern control. It‘s role is necessary and important only for symmertrizing of the crystal thermal field.

2. Symmetrizing control of hydrodynamics and heat transfer in the melt by means of a rotating magnetic field. A mathematical model and application of a rotating magnetic field for 100 mm diameter Si crystal growth are described in [1]. A possible arrangement of a rotating inductor is shown in Fig. 1. More detailed technical information and applications of a rotating inductor are discussed in [4].

The analysis of the rotating magnetic field influence is carried out. In this case, the hydrodynamic parameters (Gr, Re) were added to the MHD parameters given in Table 2: $\mathrm{Ha} = B_Z R_{\mathrm{S}} (\sigma_e/\nu\rho)^{1/2}$ – Hartmann number and $\mathrm{Rm} = 2\pi f R_{\mathrm{S}}^2/\nu$ – magnetic Reynolds number.

In these calculations the crystal and magnetic field rotations in the same directions were supposed and the crucible rotation was not taken into account because its role was carried out by a rotating magnetic field. If compared to our previous [1], we have chosen a more low-frequency rotating field with a smaller induction. The magnetic field results not only in symmetrical melt flow and thermal field, but also in suppression of uncontrolled convective patterns at the crystal that may also promote an increase of ingot diameter stability (see Fig. 3).

3. The features of semiconductor crystal growth in microgravity. The examples of application of a rotating magnetic field for flow and impurity control in the melt on earth and in space for the technologies of semiconductor single crystal growth are considered in [2]. For example, the space experiments on floating-zone melting of germanium aboard of the "Foton" have shown that the use of the rotating magnetic field of 0.2 mT provides adequate mixing in the

Table 2. Physical and dimensionless parameters with magnetic influence: B_Z – induction and f – frequency of the rotating inductor, D_M – diameter and Z_M – axial coordinate of the inductor centre.

B_Z, mT	f, rpm	Ha	$\mathrm{Re_M}$	D_M/R_{S}	Z_M/R_{S}
400	5	1800	1.2×10^4	9.0	1.0

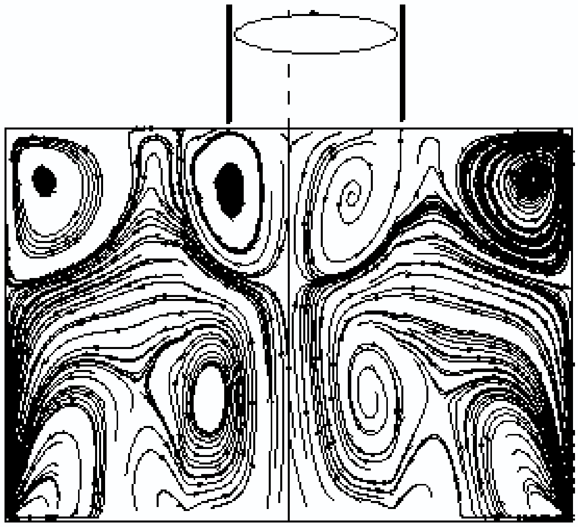

Fig. 3. Controlled symmetrizing of the melt flow, appropriate to Fig. 2, with an imposed rotating magnetic field $\mathrm{Re_M} = 10^6$, $\mathrm{Ha_M} = 1800$.

melting zone and stable growth of highly homogeneous and perfect single crystals under conditions when the liquid-solid interface remains nearly flat throughout the crystal length. To obtain similar quality on earth, magnetic fields approximately 1000 times stronger must be used.

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