INFLUENCE OF HF EM FORCES IN A SKINLAYER AND MARANGONI FORCES ON THE MELT FLOW DURING FZ SILICON CRYSTAL GROWTH

K. Dadzis[1], *A. Muiznieks*[1,2], *G. Ratnieks*[3], *H. Riemann*[4], *A. Lüdge*[4]

[1] *Department of Physics, University of Latvia, 8 Zellu Str., LV-1002 Riga, Latvia*
[2] *Institute for Electrothermal Processes, University of Hanover, 4 Wilhelm-Bush-Str., D-30167 Hanover, Germany*
[3] *Siltronic AG, 24 Johannes-Hess-Str., D-84489 Burghausen, Germany*
[4] *Institute of Crystal Growth, 2 Max-Born Str., D-12489 Berlin, Germany*

Introduction. The floating zone (FZ) process with the needle-eye technique is widely used for the growth of large silicon single crystals for the high-tech electronics industry. The quality of the grown crystals as well as overall stability of the growth process is influenced by the motion of liquid silicon in the molten zone. This paper presents an axis-symmetric numerical study of unsteady laminar hydrodynamics in a specific 2 inch FZ system. The interaction between HF EM forces in a skinlayer at free melt surface and Marangoni forces and their influence on the melt motion is investigated in detail.

1. FZ growth system. During the floating zone (FZ) process, the shape of the molten zone depends in itself on the process parameters, see e.g., [1]. In the present work the shape of the molten zone in the axisymmetric approximation is obtained by solving the thermal-electromagnetic problem numerically with the program package *FZone* as described in [2]. We consider a specific 2 inch silicon crystal FZ growth from *Institute of Crystal Growth* (Berlin, Germany). The system geometry – the calculated shape of the molten zone, process parameters as well as physical properties of silicon used in the calculations are shown in Fig. 1.

Usually, convective heat transfer in the molten zone is neglected in calculations of phase boundaries (e.g., [2]). In the current study an approximate model, which also partially includes the influence of melt motion on heat transfer, was used to obtain a better agreement with the experimentally determined crystallization interface. This explains the curvaceous phase interface shape in Fig. 1.

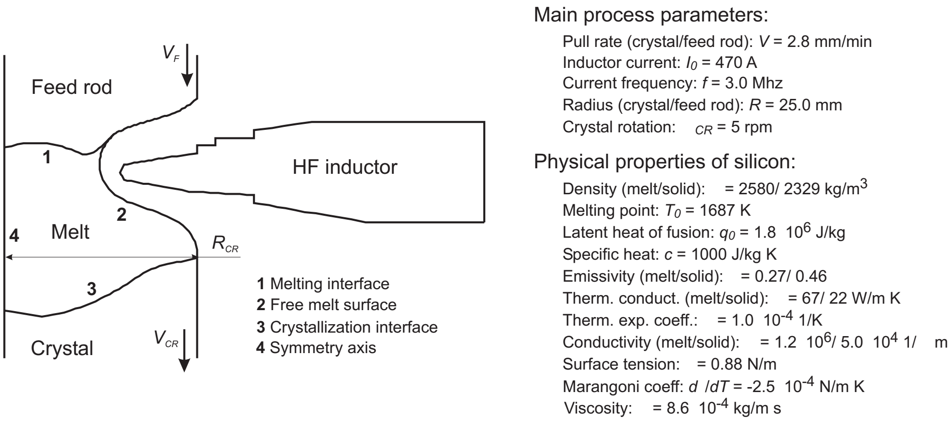

Fig. 1. Geometry – calculated shape of the molten zone, process parameters of the FZ system and physical properties of silicon.

2. Mathematical models of HF EM forces and hydrodynamics. For axisymmetric calculations of the unsteady laminar melt flow a noncommercial program based on the finite element method is used. It solves the coupled system of equations for vorticity ω, stream function ψ, azimuthal velocity u_φ and temperature T in the vertical cross-section. Natural convection along with the Boussinesq approximation, Marangoni forces, EM forces and rotation is considered in calculations. A more detailed description can be found in [1].

The source of EM forces in the molten zone is the HF inductor, whose main aim is to ensure the feed rod melting. The high frequency of the inductor current (about 3 MHz) leads to a distinct skinlayer of thickness of about 0.3 mm in the molten silicon. It is much smaller than the crystal diameter (up to 200 mm). Consequently, EM forces in the melt can be calculated in two following ways (see [4] for a detailed description of EM calculations for the actual FZ system):

1. Force Volume Density Model (FVDM). The inductor EM field in the whole system is calculated by using the finite element method. Extremely fine elements in the melt at the free melt surface are required (for EM and hydrodynamical calculations).

2. Tangential Stress Model (TSM). The boundary element method is used to calculate the HF magnetic field and to obtain the current linear density distribution on the free melt surface. EM forces in the skinlayer are replaced by corresponding tangential stresses (see [3]). Thus EM forces are included in the boundary condition for vorticity ω and there is no need for fine elements at the free melt surface. However, in the current study for a better comparison we used the same finite element mesh with both models.

3. Results of hydrodynamic simulations. Unsteady calculations for the considered system showed that the melt motion always reached an almost steady-state solution with relatively small oscillations. Therefore, the average flow is analyzed in each case. Flow patterns for cases with both models of EM forces are shown in Fig. 2. Qualitatively, the general flow structure is similar in both cases – there are two large vortices in the central part of the molten zone and smaller vortices at corners at the triple points. Small differences are observable only at the free melt surface. However, quantitatively the melt motion was remarkably more intensive in the case with FVDM – extreme values of the stream function (corresponding to the two main vortices) were $-13.76/7.81\,\mathrm{m}^3/\mathrm{s}$ in the case with FVDM and $-8.38/6.40\,\mathrm{m}^3/\mathrm{s}$ in the case with TSM.

The flow pattern in Fig. 2 is obviously determined mainly by the EM forces. The Marangoni forces were found to be several times weaker than the EM forces over the whole free melt surface (see [4] for details of the estimation method).

In order to investigate the melt flow under various conditions, two further series of hydrodynamic calculations were performed. In the first case, the current in the inductor was gradually changed: $I = k \cdot I_0$ with $k = 0.1 \dots 1.0$. This leads to weaker both EM and Marangoni forces because a lower current induces

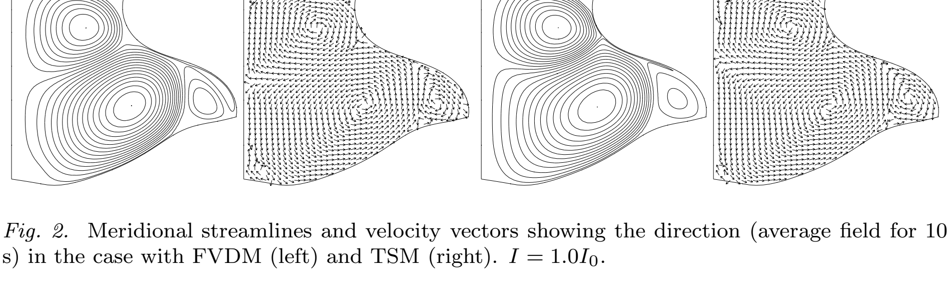

Fig. 2. Meridional streamlines and velocity vectors showing the direction (average field for 10 s) in the case with FVDM (left) and TSM (right). $I = 1.0I_0$.

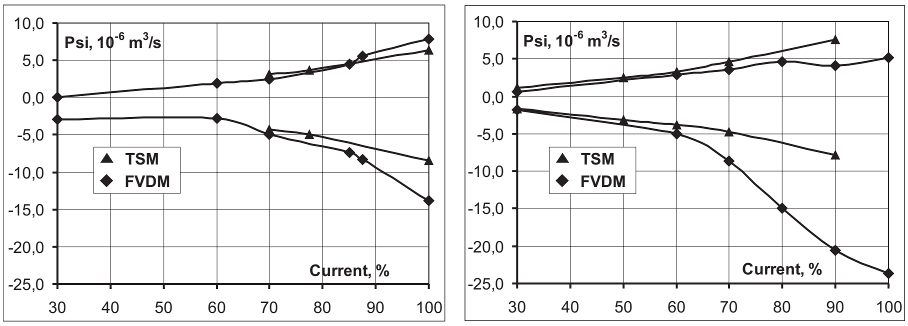

Fig. 3. Extreme values of the stream function vs. the current in the inductor (heat sources changed correspondingly). Left – all forces, right – only EM forces.

lower heat sources on the free melt surface. In the second case, the current in the inductor was decreased but heat sources on the free melt surface were kept constant. Consequently, the melt temperature was higher and the Marangoni forces stronger than in the first case. Physically it can be achieved, for example, by avoiding heat radiation from the free melt surface using additional reflectors or changing the current frequency.

Calculations showed that in the first case (with changing heat sources) the EM forces remained dominant also at small values of the inductor current. The flow pattern changed only a little and was similar to that shown in Fig. 2 (for $I = 1.0 \cdot I_0$). Fig. 3 shows the melt flow intensity in dependence on the inductor current. A comparison is given with calculations, where only the EM forces act in the melt. Calculations were done both for TSM and FVDM. It can be seen that TSM gives a rather lower melt flow intensity if compared to FVDM.

The second case (with constant heat sources) led to the results showing a threshold effect. In calculations with FVDM, the melt flow intensity and the flow pattern changed at about $I = 0.85 \cdot I_0$, as can be seen in Figs. 4 and 5. A similar drop of the melt flow intensity was observed also in the case with a TSM model at about $I = 0.75 \cdot I_0$, however, changes in the flow structure were less distinct, see Figs. 4 and 6. In calculations with FVDM and a reduced Marangoni coefficient ($-1.0 \cdot 10^{-4}$ instead of $-2.5 \cdot 10^{-4}$) the threshold effect became even more complicated – the melt flow intensity fell at $I = 0.80 \cdot I_0$ and $I = 0.60 \cdot I_0$ but the flow pattern changed only at $I = 0.60 \cdot I_0$.

The main reason for the observed threshold effect obviously is the complex interaction between Marangoni, EM and buoyancy forces. In the actual system the EM forces dominate at higher values of the inductor current and lead to a very

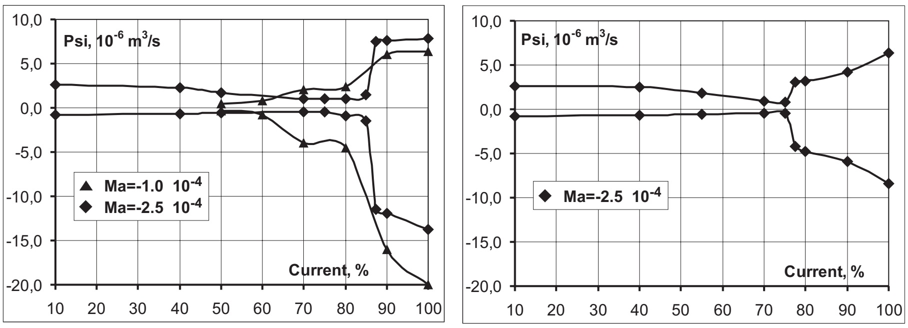

Fig. 4. Extreme values of the stream function vs. the current in the inductor (heat sources are constant). Left – FVDM, right – TSM.

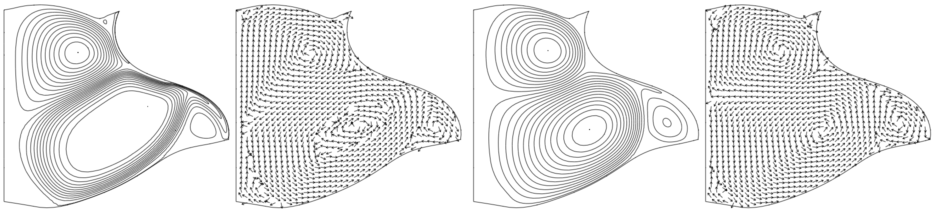

Fig. 5. Meridional streamlines and velocity vectors showing the direction (average field for 10 s) in the case with FVDM. Left – $I = 0.85I_0$, right – $I = 0.875I_0$.

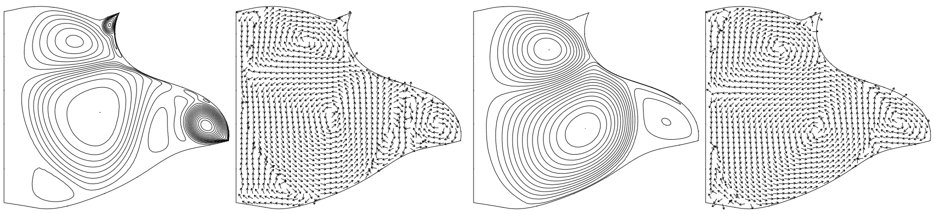

Fig. 6. Meridional streamlines and velocity vectors showing the direction (average field for 10 s) in the case with TSM. Left – $I = 0.75I_0$, right – $I = 0.80I_0$.

strong melt motion. But the EM forces are directed opposite to the Marangoni forces, therefore, the melt flow might change rapidly if they both have similar strengths. Additionally, it must be emphasized that the Marangoni forces depend on the melt temperature at the free surface. An intensive melt motion tends to decrease it and leads to smaller Marangoni forces because a colder melt is transported from the crystallization interface (see the typical flow pattern in Fig. 2). For example, it was found that the highest temperature in the melt fell from 1687.0+50.1 K at $I = 0.80 \cdot I_0$ to 1687.0+21.7 K at $I = 0.90 \cdot I_0$ in the case with FVDM.

4. Conclusions Hydrodynamic calculations show that there are differences in the results with FVDM and TSM approaches regarding details in the flow structure and melt flow intensity. It was found that in the case of TSM the influence of EM forces is underestimated.

It was observed that in the actual system the threshold effect may occur at higher values of the inductor current – the melt flow intensity and the flow pattern may change rapidly at small changes of the inductor current. It is important to avoid such conditions for a stable crystal growth process.

The precise hydrodynamic results obtained in this study can be used further to investigate the influence of convective heat transfer in the melt on the shape of phase boundaries.

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