Comparison Between 2D and 3D Modelling of HF Electromagnetic Field in FZ Silicon Crystal Growth Process

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Abstract

The paper focuses on comparison between high-frequency electromagnetic field calculation with 2D axial symmetric approximation and calculation with full 3D description during the calculation of the shape of molten zone in FZ silicon crystal growth process. Configuration of one in crystal growth experiments used inductor is considered. The used slot parameters of inductor in 2D approximation are given. Induced electric current densities on melt free surface and calculated shape of the molten zone are compared between 2D and 3D case.

Introduction

In modelling of floating zone (FZ) silicon crystal growth process, one important part is to calculate the high frequency (HF) electromagnetic field, the induced surface electric current densities and consequently induced heat power densities on silicon surfaces. These heat power densities define the previously unknown shape of molten zone and are influenced by this shape.

Previously developed 2D axial symmetric model of FZ process [1] used an axis-symmetric 2D approximation of the geometry of HF inductor and of the corresponding electromagnetic field. Nevertheless, in reality the HF inductor used in FZ crystal growth process has only one turn which essentially disturbs the system symmetry and additional 3D geometry elements, e.g. additional slits; therefore the electric current and magnetic field distribution is essentially 3D and can be described with axis-symmetric model only very approximate.

The 3D calculation of HF electromagnetic field in FZ system is known and is described in e.g. in [2]. In the present paper the 3D calculation of HF electromagnetic field from [2] is coupled with the 2D calculation of the temperature fields in silicon parts and with 2D calculation of the shape of molten zone form [1]. This coupling is implemented in the specialized program FZone3D. For one in crystal growth experiments used HF inductor both approaches of inductor modelling: 2D and 3D are carried out and the comparison of the calculation results are made.

1. Description of Selected HF Inductor

Data received from Leibniz-Institute for Crystal Growth (Dr. Riemann) [3] for one special inductor has been used to create 3D system geometry and 3D mesh (number of triangle surface elements for the inductor 4492). In order to better illustrate the real system, inductor itself and its slice in horizontal plane with slots and respective widths are shown in Fig 1.

In 2D axial symmetric approximation [1] two slot configurations were investigated to find better approximation of the 3D configuration of EM field. Configuration one ("SlotConf_1") is as follows: one main slot with width 1.5 *mm* and four secondary slots also with width 1.5 *mm*. Configuration two ("SlotConf_2") is as follows: one main slot with width 1.5 *mm* and three secondary slots with width 3.0 *mm*. Effectively it would describe the slot configuration as schematically is shown in Fig 2.
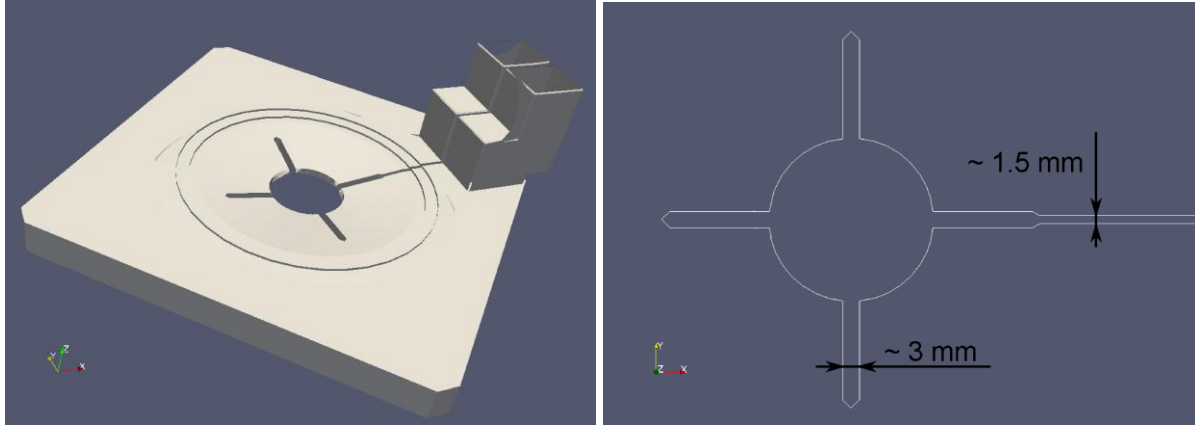

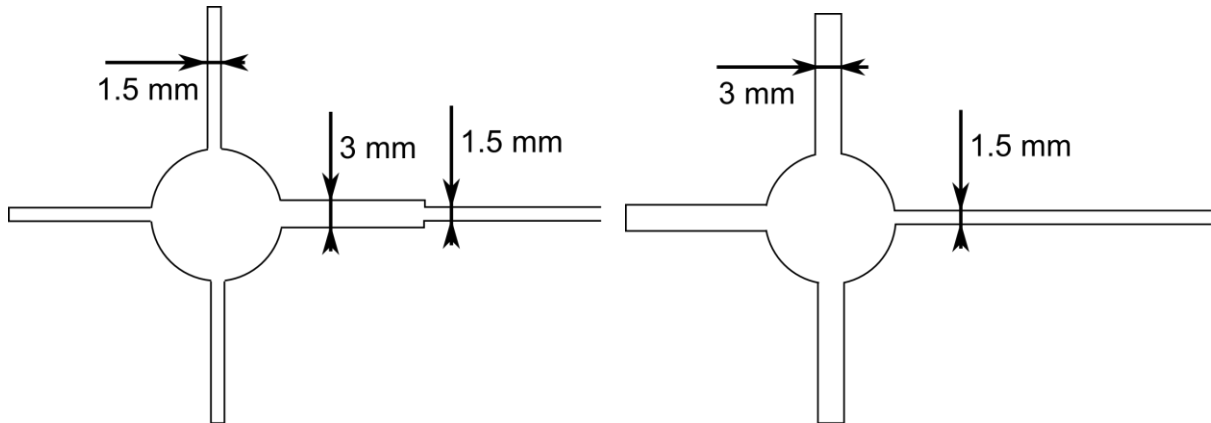Fig. 1. Geometry if HF inductor (left) and geometry of slots widths (right)

Fig. 2. Schematic representation of slot configurations used in 2D axial symmetric inductor approximation, SlotConf_1 (left) and SlotConf_2 (right)

2. Acquired Results and Comparison Between 2D and 3D HF EM Description

2.1. Obtained Results from Calculations With 2D and 3D Inductor Description

In order to illustrate calculation specifics and results obtained, short summary of each calculation case is given.

First calculation:
- Case: 2D EM description (SlotConf_1), 2D radiation and system evolution description;
- Zone height: $H_z = 31.00$ *mm*;
- Crystallization interface deflection: $H_c = 16.90$ *mm*;
- Electric current in inductor: $I = 922.55 \pm 0.15$ *A*;

- Calculation time: $t_{calc} \approx 1\ h$ (converged to stationary solution).

Second calculation:

- Case: 2D EM description (SlotConf_2), 2D radiation and system evolution description;
- Zone height: $H_z = 31.00\ mm$;
- Crystallization interface deflection: $H_c = 15.02\ mm$;
- Electric current in inductor: $I = 881.25 \pm 0.15\ A$;
- Calculation time: $t_{calc} \approx 1\ h$ (converged to stationary solution).

Third calculation:

- Case: 3D EM description, 2D radiation and system evolution description;
- Zone height: $H_z = 31.00\ mm$;
- Crystallization interface deflection: $H_c = 15.75\ mm$;
- Electric current in inductor: $I = 962.65 \pm 0.25\ A$;
- Calculation time: $t_{calc} \approx 2.5\ days$ (converged to stationary solution).

It must be emphasized that all these calculations were done for one system and one crystallization zone height, i.e., the distance between the feed rod edge and the outer triple point of the melt free surface. Comparison of obtained FZ crystal growth geometries and induced electric current density distributions on melt free surface is shown in later sections. Fig 3 shows an example of the 3D calculated HF current distribution on the surface of the inductor; and Fig 4 shows the calculated shape of the molten zone with the corresponding 2D mesh in the feed rod and in the grown crystal for the temperature calculation.
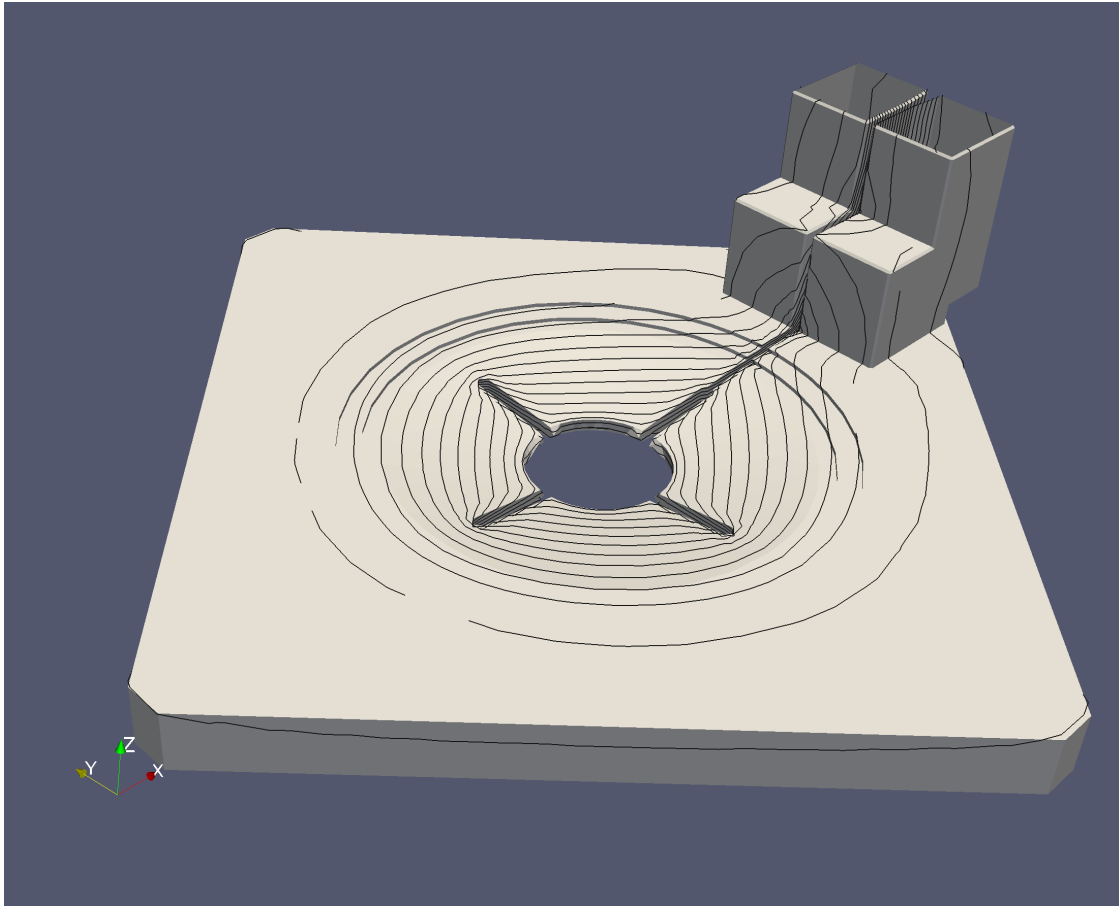

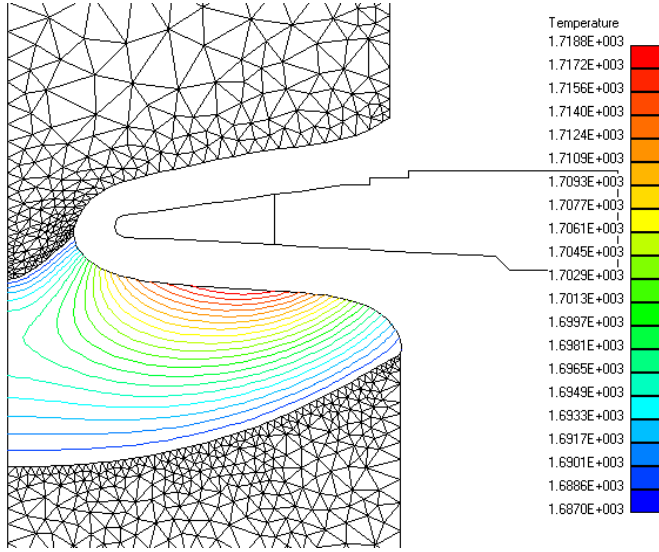Fig. 3. 3D calculated HF current distribution on the surface of the inductor

Fig. 4. 3D calculated HF current distribution on the surface of the inductor and the calculated shape of the molten zone with the corresponding 2D mesh in feed rod and in grown crystal
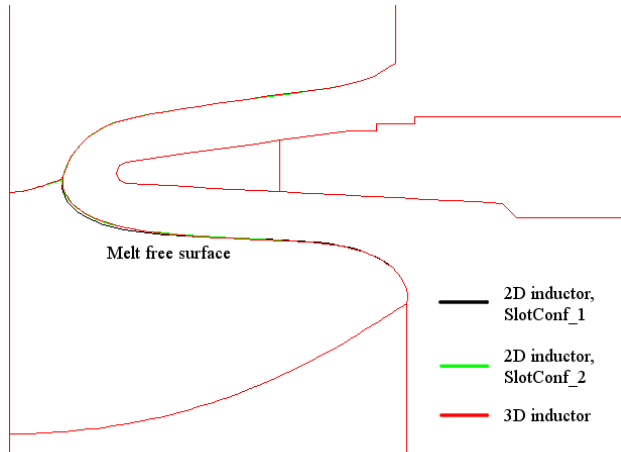

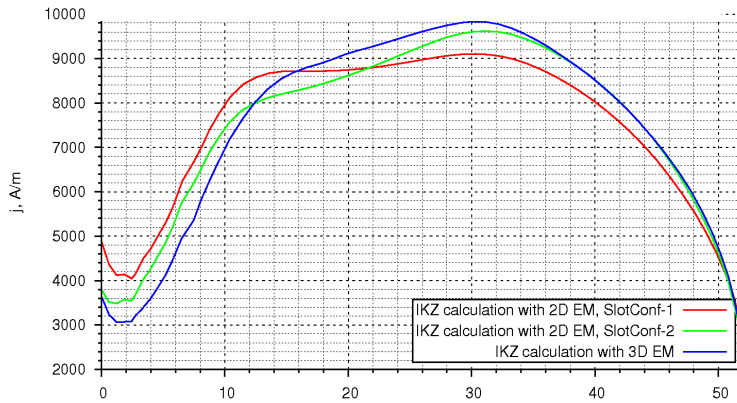Fig. 5. Comparison of "approximately constant" geometries, all cases

Fig. 6. Induced electric current densities on melt free surface, all cases

2.2. Comparison Between Induced Electric Current Density Distributions on Melt Free Surface

In order to evaluate the differences between 2D axial symmetric inductor approximation and full 3D calculation for the EM field, first the calculations for one chosen the same system geometry are carried out. The comparison of geometry for all cases (2D SlotConf_1, 2D SlotConf_2 and 3D) is shown in Fig. 5.

As it can be seen in Fig. 5, although FZ crystal growth system geometry is not exactly constant for all cases (after one calculation iteration, geometry was already modified), shape of melt free surface is very close in all cases. Therefore it can be concluded that direct comparison of induced electric current densities on melt free surface can be done.

Induced electric current densities as a function of melt free surface position (start point is located at thinnest part of FZ system, i.e., the internal triple point) is shown in Fig. 6. In the 3D calculations for this comparison, the induced power surface density on the melt free surface is averaged azimuthally and from this averaged radial distribution the so called 3D current radial distribution is obtained.

2.3. Comparison Between Acquired Stationary FZ System Geometries

In order to better illustrate the consequences of 2D and 3D EM field calculations, stationary results for the shape of the molten zone in FZ crystal growth system are compared in Fig 7. It can be seen that with appropriate 2D inductor description it is possible to obtain the results which correspond to 3D approach quite well.
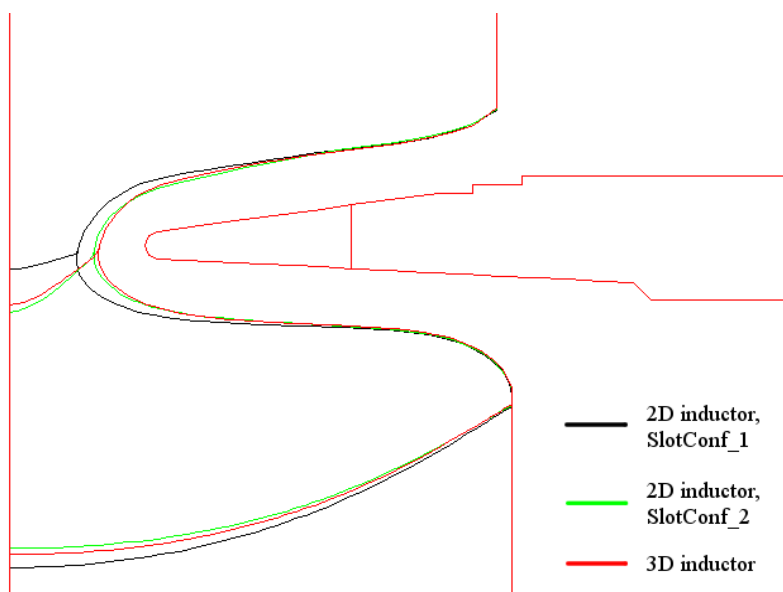
Fig. 7. Comparison of acquired stationary geometries between all cases

Conclusions

For the given silicon geometry, the calculated radial current distributions on the melt free surface are relatively similar to each other. Improvement of 2D axial symmetric slot approximation gives results closer to 3D calculation. Nevertheless the problem remains that this 2D approximation is not well defined.

If the stationary shape of the molten zone are obtained by using 2D and 3D electromagnetic calculations, the results show that with good 2D approximation the shape can be obtained that corresponds well to the 3D approach. Nevertheless the obtained current values for given zone height in 2D and 3D HF inductor calculations are significantly different.

References

[1] Ratnieks, G., Muiznieks, A., Muehlbauer, A.: *Modelling of phase boundaries for large industrial FZ silicon crystal growth with the needle-eye technique*. Journal of Crystal Growth, Vol. 255, 2003, pp. 227-240.
[2] Ratnieks, G., Muiznieks, A., Muehlbauer, A., Raming, G.: *Numerical 3D study of FZ growth: dependence on growth parameters and melt instability*. Journal of Crystal Growth, Vol. 230, 2001, pp. 48-56.
[3] Riemann, H.: *Personal communication*. 2009.

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