International Scientific Colloquium
Modelling for Material Processing
Riga, September 16-17, 2010

3D Electromagnetic and Thermal Modelling of the EFG Process for Silicon Tube Growth

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Abstract

The edge-defined film-fed growth (EFG) process is mainly used to grow silicon ribbons and hollow cylinders as well as hollow polygons of various geometries. The development of the EFG process is primarily focused on technology improvements and cost reduction of wafers for photovoltaic applications. In case of the growth of hollow polygons, three-dimensional (3D) numerical analysis is extensively used because the system of polygonal geometry cannot be adequately described in axisymmetric statement. Electromagnetic simulations of the main and afterheaters predict the heat generation in the system. The calculated 3D temperature fields taking into account complex heat radiation conditions allow the analysis of the temperature profiles along and across the growing silicon tubes. The non-linear model consisting of electromagnetic and thermal simulations has been adjusted and successfully validated by experimental tests with industrial installations.

Introduction

The requirements in manufacturing of solar cells increased dramatically due to the ascended worldwide demand and the consequent shortage of silicon. A continuous increase of efficiency while reducing costs on the other hand are in the spotlight of the development of future production processes.

With this background the so called Edge-defined Film-fed Growth procedure (EFG) (Fig. 1) was developed which allows to pull long and hollow silicon tubes directly from the silicon melt. The wall thickness of such tubes corresponds directly to the thickness of the finished wafer. Thanks to laser cutting the wafers are directly cut from the tube.

The advantages of the EFG-technology compared to other procedures are a high productivity, the low costs of the wafers and a rapid laser-cutting process that guarantees highly mechanical wafer strength with a low rate of material waste. A decisive factor for the quality of wafers is the homogenous temperature distribution in the crystallization front along the silicon tube [2].

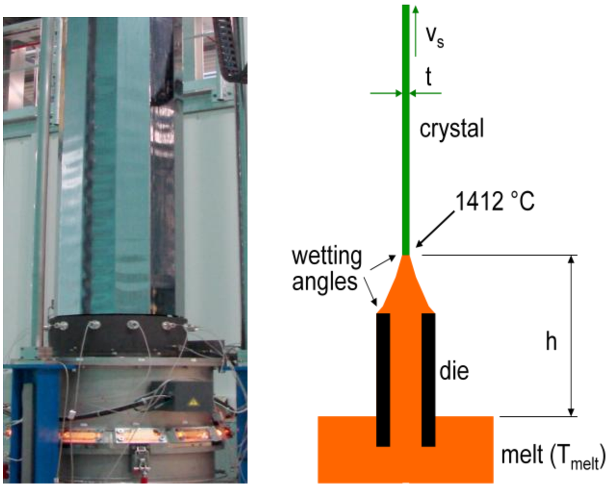

Fig. 1. EFG system and principle of silicon tube growth

Any inhomogeneity temperature disturbs the pull and causes instability. The results are different thickness distributions along the silicon tube.

For further improvement of the production process to gain more reliability and efficiency the Institute of Electrotechnology of the Leibniz University of Hannover developed 3D models of the entire melting furnace. With the help of these numerical models influences on the homogeneity of the temperature at the crystallization front can be investigated.

In opposite to the induction heated furnaces for which already a system of 3D complex numerical models exists [2] new 3D models with even higher complexity had to be developed for the new resistance heated system [1] where 12 sided tubes (dodecagons) instead of 8 sided tubes (octogons) are pulled. The required heating energy for the melting process is provided by an individually adjustable 12-zoned resistance heating element and not by an induction coil.

An immediate benefit is the direct influence on the required process energy in the individual tube sections and thus on the resulting temperature distribution. The possibility of the adjustment setting means a controlled influence of the resulting thickness of the silicon tube in different areas.

With the help of the new numerical simulation models the further development of the system can be accelerated and also cost-effective parameter studies will be performed in less time. Not only the increase of quality of the product is in the front of interest but also to obtain more information about the physical processes during the melting sequence.

1. Development of the Numerical Model

The modelling is currently divided in two steps. The first step is the generation of an electromagnetic 3D model of all heat sources. The second step is to create a thermal model of the actual oven geometry. Both models were developed using the commercial software package ANSYS®.

1. 1. Electromagnetic Model for Main and Afterheater

The heat sources of the EFG system consist of a main heater to melt the silicon and an afterheater positioned above the crystallization front of the tube (Fig. 2).

In accordance with the experiment-tally determined specifications the needed supply voltage is applied at the corresponding points of the heater segment.

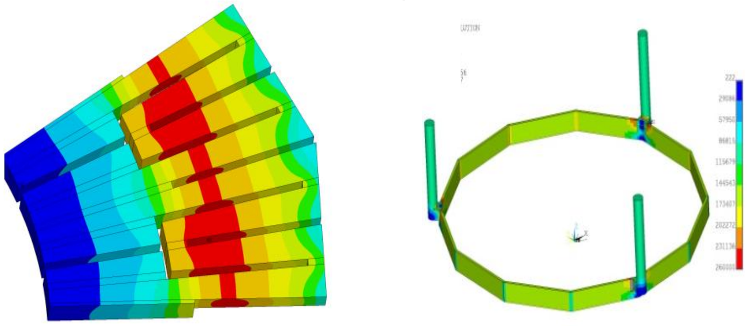

Fig. 2. 30° segment of the main heater (left) and entire afterheater (right)

1. 2. Thermal Model

The main part of the simulation effort concerns the thermal model. This part contains the entire furnace geometry considered as relevant for the crystallization process. For a sufficient optimization of the process two different thermal models have been developed: a fine meshed model of 30° of the whole system for local optimizations and a less fine meshed model of 120° of the whole system for global optimizations. Due to the symmetry conditions the 120° model represents the entire system while the 30° model can only show local effects. Fig. 3 shows the 30° model (left) and the 120° model (right).

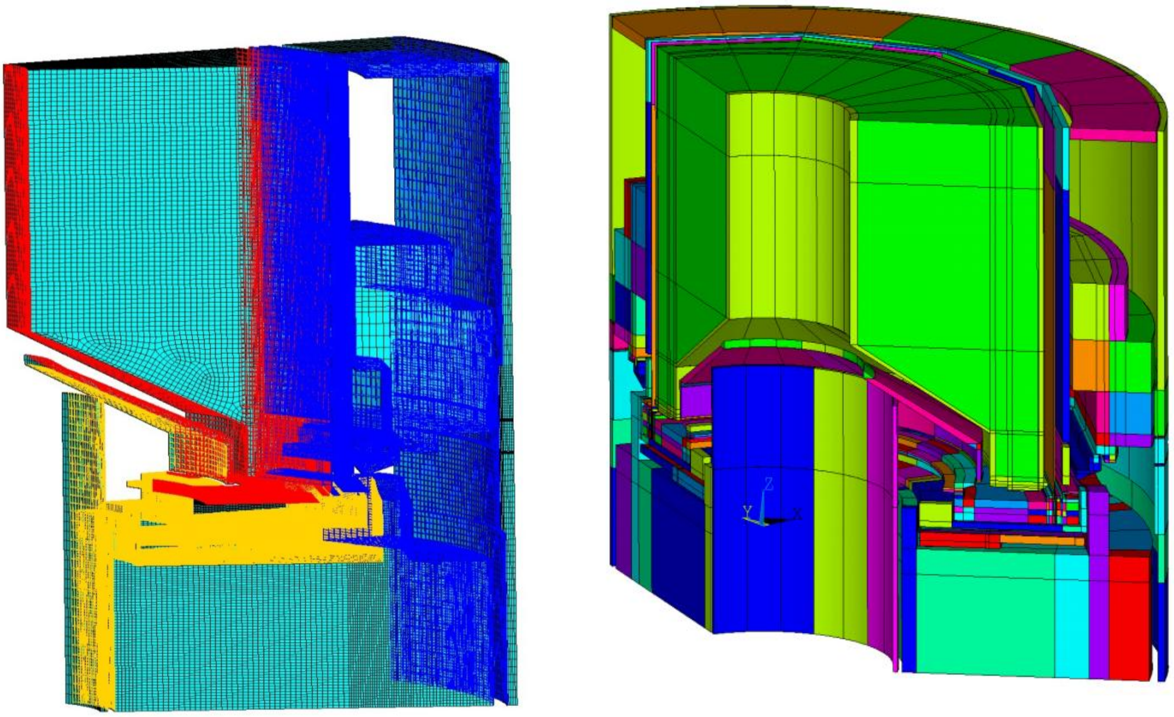

Fig. 3. Thermal models, 30° segment model with mesh (left) and 120° model (right)

Radiation method. Silicon has its melting point at 1410°C. Taking into account the Stefan-Boltzmann law which states that the maximum power density grows with the fourfold power of the absolute temperature of the radiator, one main invention focus is about the development and optimizing use of a suitable radiation model. This focus is with regard to the proportion of radiation throughout the heat transfer process permitted.

In the commercial software package ANSYS® the method of "Radiosity Solver" comes into operation. This latest approach to simulate the radiation exchange offers among others the advantage of easier creation of radiation surfaces, temperature dependent emission levels and the application of symmetry effects. A much more important item is the realization of larger models, as they are possible in direct comparison to the older "aux12" method.

Equation (1) defines radiation between two surfaces:

$$Q_{12} = A_1 F_{12} \epsilon_1 \sigma (T_1^4 - T_2^4), \tag{1}$$

where F_{12} represents the form factor of fraction of total radiant energy going from surface 1 to surface 2.

The Radiosity Solver method calculates the temperature distribution in a segregated, iterative fashion for radiation and heat conduction until convergence is achieved. This method reverts to a defined viewfactor-matrix with the constants F_{ij}. The "aux12" method on the other hand uses an effective heat conduction-matrix. This matrix contains all information about geometric orientations, shapes and emission levels of the numeric model. The calculation of the radiation needs no segregated sub-steps and shares the same routine with the heat conduction. The determination of this effective matrix is very memory and computation intensive.

Radiation model. For the radiation model all surfaces must be covered with the appropriate material emission ratio. Due to the parameterized single volume structure it must be aware that the emission ratio only covers external surfaces. In the case of a selection of a surface area within the general arrangement it is possible that the calculated temperature distribution shows unsymmetrical variations in the affected parts.

Furthermore, a division into so-called enclosures and the establishment of the radiation symmetry conditions has to be carried out. In Fig. 3 (left) an exemplary distribution of the enclosures is shown. By the use of these enclosure-zones a decoupling of different model zones can be obtained. The program takes all single surface elements of the arrangement into account and calculates a solution for the viewfactor-matrix, although a intervisibility through the geometry is not given. This leads to a larger viewfactor-matrix and also to longer computing times. With the division into different enclosure-zones only surface elements with equivalent factor assignment are taken into account.

According to the status of current desktop systems it is impossible to create a finite element system of such complexity that covers the entire scope of the silicon tube. However, it is important not only to examine that part of the model resulting from the repetitive form of the dodecagon, but also the adjacent cuttings. These border parts must also be taken into consideration because a significant proportion of the radiation from the adjacent areas reaches the surfaces of the actual cut.

Using the radiation symmetry option the parts of the generated furnace system can be repeatedly created. The advantage of this method is that only the surface of a part will be mirrored, but not the assigned material values or the resulting matrixes. A recalculation of temperature distribution will not take place. Only with the repeated image of the original calculated thermal distribution the output surface will be formed. This reduces the computing and storage complexity immense and the operability of the numerical model remains.

2. Simulation Results

The coupled electromagnetic and thermal models were used in the first step to recalculate the existing configuration of the EFG system and to compare the simulation results with experimentally available data.

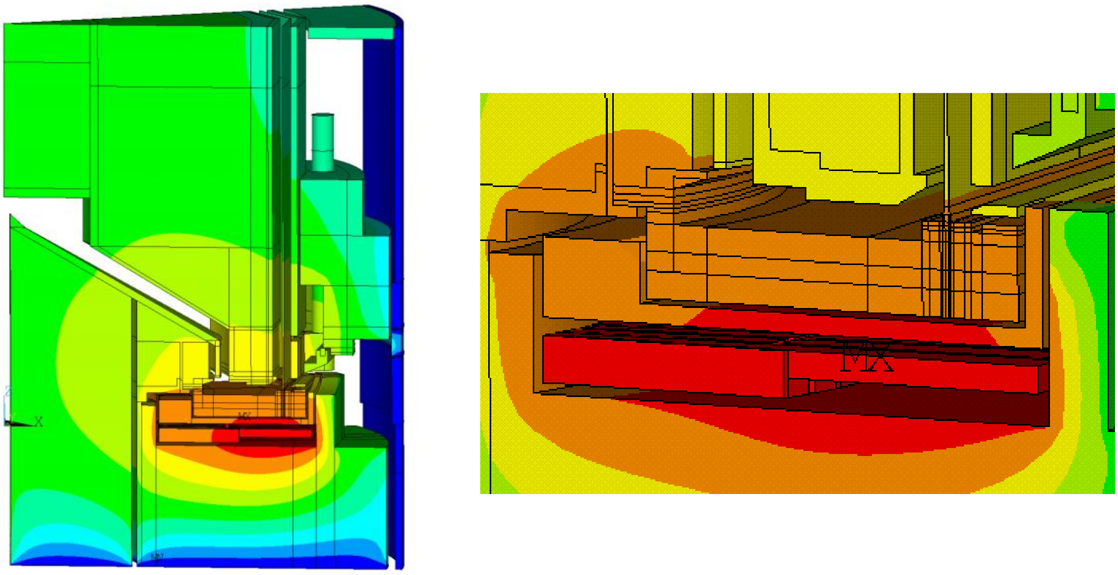

Fig. 4. Temperature distribution in the EFG system using the thermal 30° segment model (left). Zoomed view of the main heater and crucible area (right)

Fig. 4 shows the calculated temperature distribution in the entire EFG system using the thermal 30° segment model for the existing configuration. The zoomed view of the area of the main heater and the crucible show that the highest temperature occurs in this area. The model was adjusted to the real temperature level in the heater zone by experimental data.

The results of the model allow to optimize the design of the main heater in order to get an equal temperature distribution in the 30° segment area.

Because the entire system has a 120° symmetry due to the afterheater configuration (Fig. 5 right) overall temperature distribution can be calculated and optimized only with the 120° model (Fig. 5 left). The calculation of the model takes much more calculation time but it is necessary to optimize the temperature distribution around the entire silicon tube. Due to the symmetry conditions the temperature distribution of the 120° model represents the temperature distribution in the entire EFG system.

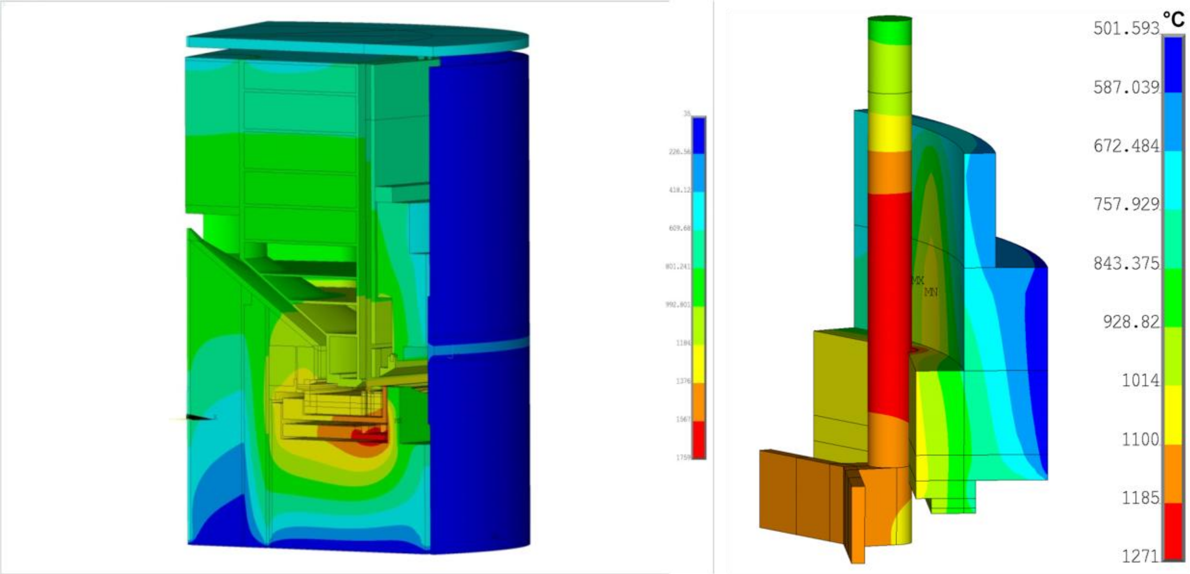

Fig. 5. Temperature distribution in the 120° system area (left) and temperature distribution in the area around the current connections of the afterheater

The 120° model allows to optimize the overall temperature distribution in the EFG system and especially in the grown silicon tube. Due to the concentration of heat in the afterheater area due to the heater current connection, represented by the vertical bar in Fig. 5 left, typically a non-homogeneous temperature distribution occurs close to the heater connections. Therefore additional measures are necessary to avoid these inhomogeneities.

3. First Result of Optimization

First optimizations using the developed models were carried out concerning the configuration of the main heater to avoid local inhomogeneities in the main heater area. The result was an adapted design of the meander structure of the heater segments (Fig. 6).

Fig. 7 shows several steps for the optimization of the temperature distribution in the grown silicon tube just after the meniscus (see Fig. 1 right) using different solutions for the thermal insulation close to the crucible. The results in Fig. 7 show that a symmetrical temperature distribution around the just grown entire silicon tube can be achieved.

More complicated is the optimization of the temperature distribution in the grown silicon tube in the cooling down area taking into account the unsymmetrical configuration of the afterheater. First optimization steps have been already carried out but not shown here.

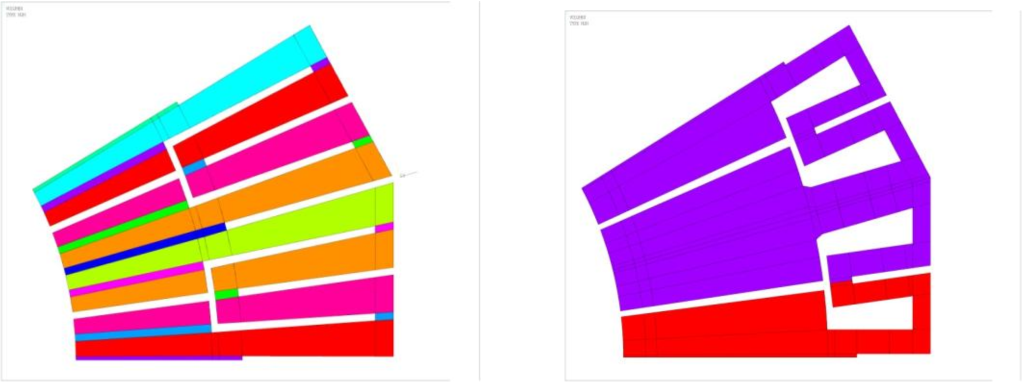

Fig. 6. Original segment (left) and example of an optimized segment (right) of the main heater

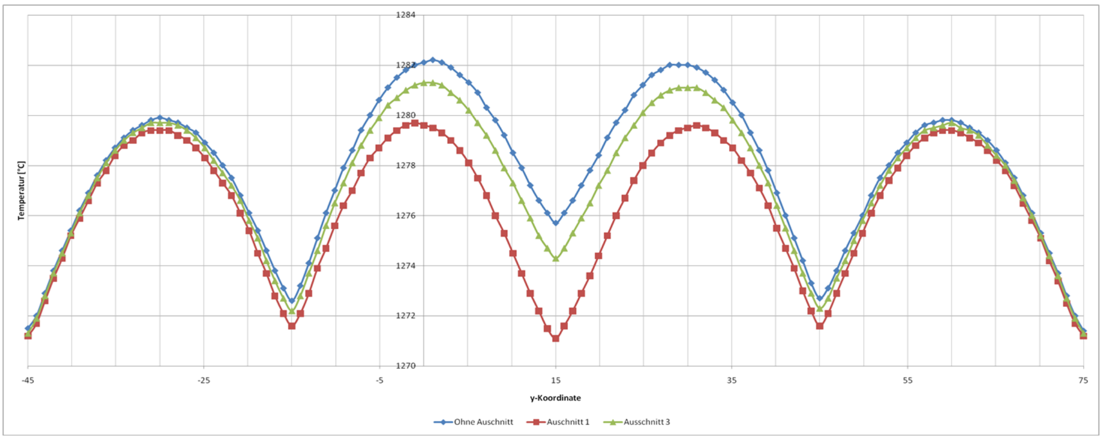

Fig. 7. Temperature distribution in the grown silicon tube for different configurations

Conclusions

Three-dimensional numerical models taking into account the coupled electromagnetic and thermal field including complex radiation conditions have been developed and can be used for further optimization of the EFG system. The models allow either local optimizations using a fine 30° segment model or global optimizations using the 120° model which represents the entire EFG system. First optimizations have been carried out and show the useful application of the complex numerical models.

References

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