Study of the influence of forced and natural convection on impurity segregation and coating stability in the ingot growth of multicristalline Silicon for photovoltaic applications

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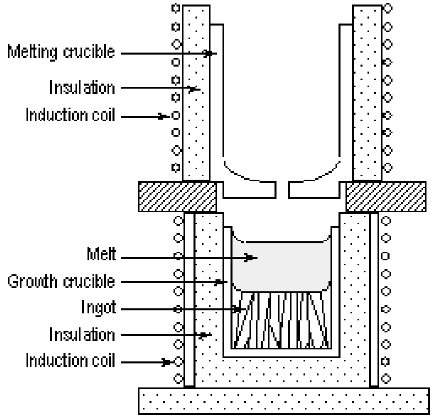
Crystals for solar energy



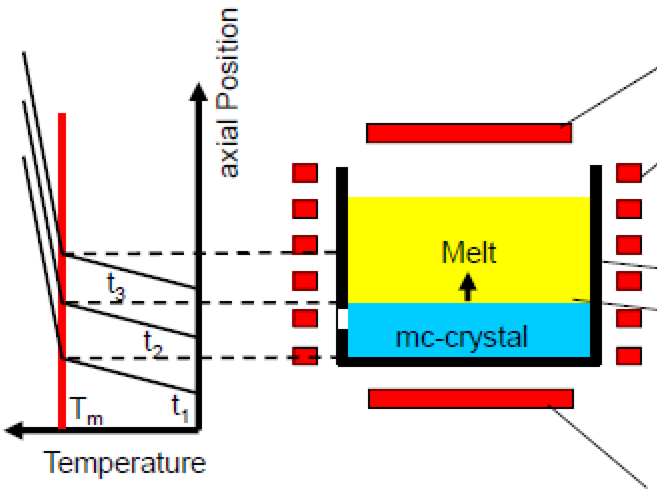
Silicon ingot

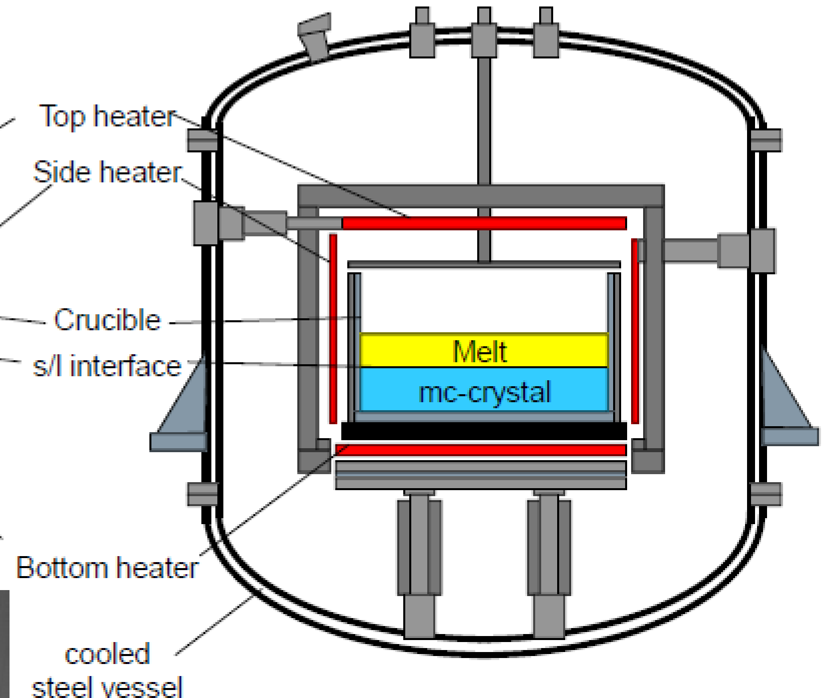
Silicon wafer

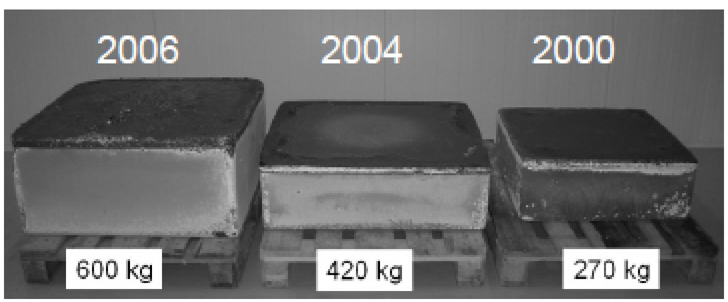
Silicon solar cell

Conversion of sunlight into electric power

Multicristalline Silicon ingot growth by Directional solidification/Casting







typical DS-grown mc-Si ingots
A.Müller 2006

•today's research is on 800 kg ingots, but there is no reason to think that this represents an ultimate limit

•use of silicon feedstock of lesser purity than standard electronic grade material

One major issue : Control of convection

•Increasing crucible size

- •Detrimental curvature of S-L interface
- •Turbulent melt flow ??
- •Cohesion of crucible coatings

•Feedstock of leser purity

- •Optimal segregation of the impurities
- •Achievement of a total mixing regime

Research objectives

- Understanding of melt convection particularities

- Study of the influence of melt convection on interface shape, impurities segregation and coating stability

- Investigation of different methods to tailor the melt convection (like mechanical stirring)

- Numerical simulation is an efficient tool to improve the understanding and the control of the heat and mass transport phenomena occurring during the crystallization process

CONSIL Project

Partners:

•Faculty of Physics, West University of Timisoara, Romania
~Prof.dr. Daniel Vizman

• 2Laboratoire Matériaux et Procédés pour le Solaire, Institut National de l'Energie Solaire CEA/DRT/LITEN/DTS
~Dr. Jean-Paul Garandet

CONSIL Objectives

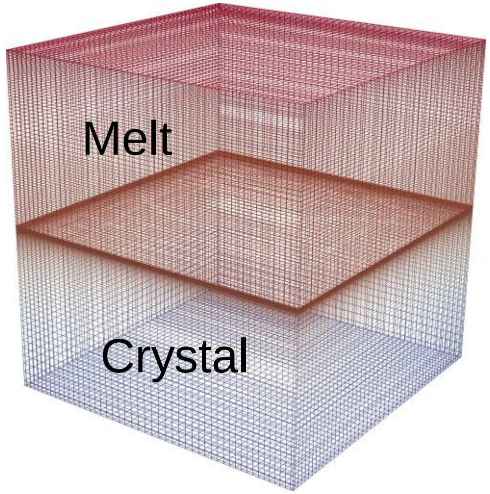
Objectives:

- **O1** Experimental and numerical study of natural convection effect on impurity segregation and coating stability in a Bridgman method for multicristalline Si growth (WUT, INES)

- **O2** Modelling of Si crystal growth process in furnaces with stirring devices (WUT)

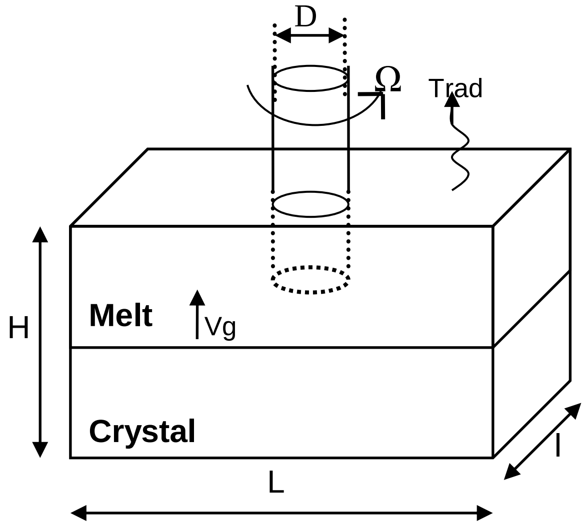
- **O3** Growth of multicristalline silicon in laboratory (2 kg ingots) and pilot scale (60 kg ingots) furnaces with a stirring device (INES)

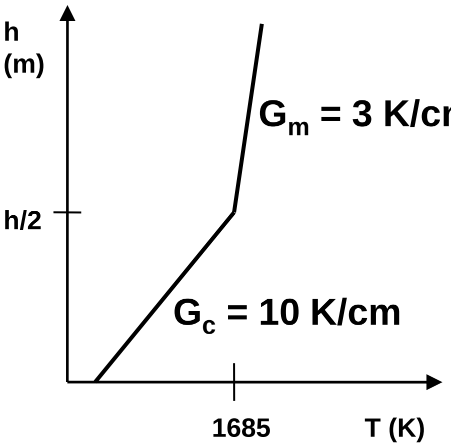
Numerical model



Qasi steady state aproximation:

•the reaction time of the interface shape on changes in the melt flow is smaller than the total solidification time





- L=l=38 cm; h=40 cm (G2)
- D=8cm
- T_{rad} = 1713 K
- v_g = 10 mm/h
- **Ω=0,5,10,20,30,40 rpm**

Navier-Stokes Equations

Conservation of mass

$$\frac{\partial}{\partial y_i}\left(\rho u_i\right) = 0$$

Conservation of Momentum

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial y_j}\left(\rho u_i u_j + \tau_{ij}\right) = -\frac{\partial p}{\partial y_i} + s_i^u \qquad i \in \{1,2,3\}$$

s_i^u: $F_b + F_s + F_L + F_V$

Conservation of energy or mass (Φ – temperature or concentration)

$$\frac{\partial}{\partial t}\left(\rho \Phi\right) + \frac{\partial}{\partial y_j}\left(\rho u_j \Phi - \Gamma_\Phi \frac{\partial \Phi}{\partial y_j}\right) = s_\Phi$$

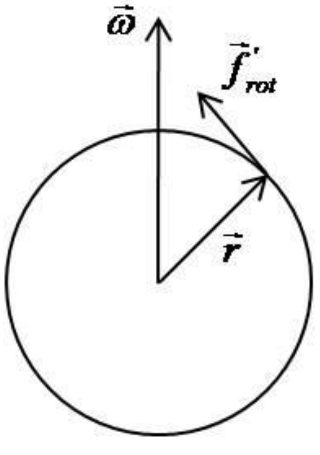
Source terms for Navier-Stokes Equations

Bouyancy forces (gravitation):

$$s_u^i = -\rho\left(T_{ref}\right)g^i \beta_t \left(T - T_{ref}\right)$$

Azimuthal force:

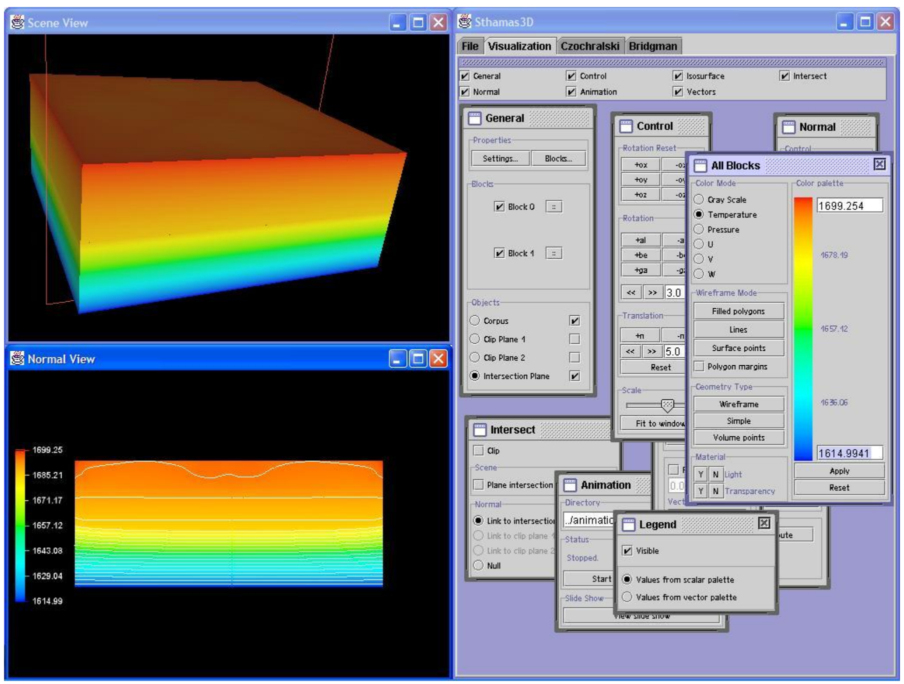
$$s_i^u = (\vec{f}_{rot})_i = \left(\left(\rho\omega \cdot \vec{\omega}\right) \times \vec{r}\right)_i$$

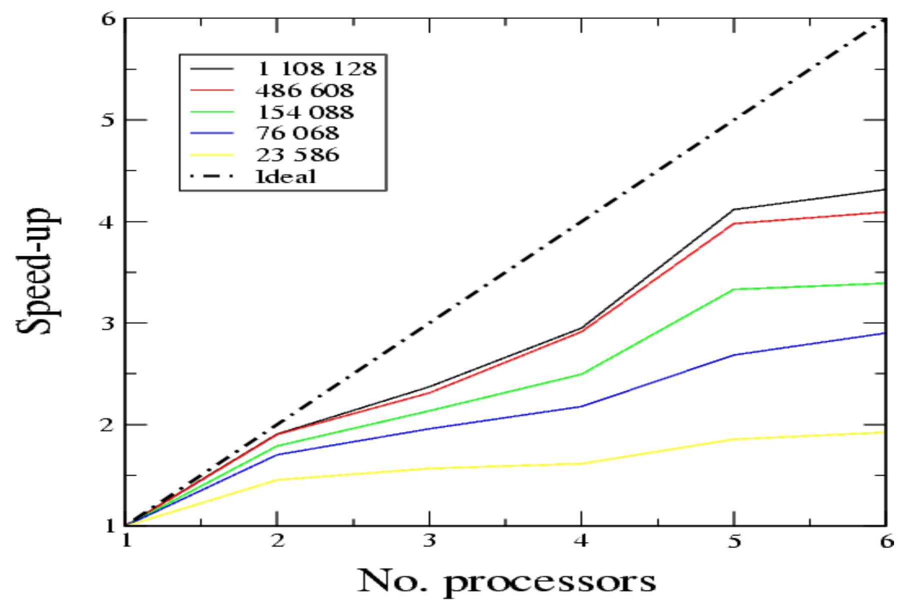


$$\left|\vec{f}_{rot}\right| = \begin{cases} \rho r \omega^2, r \le D/2 \\ 0, r > D/2 \end{cases}$$

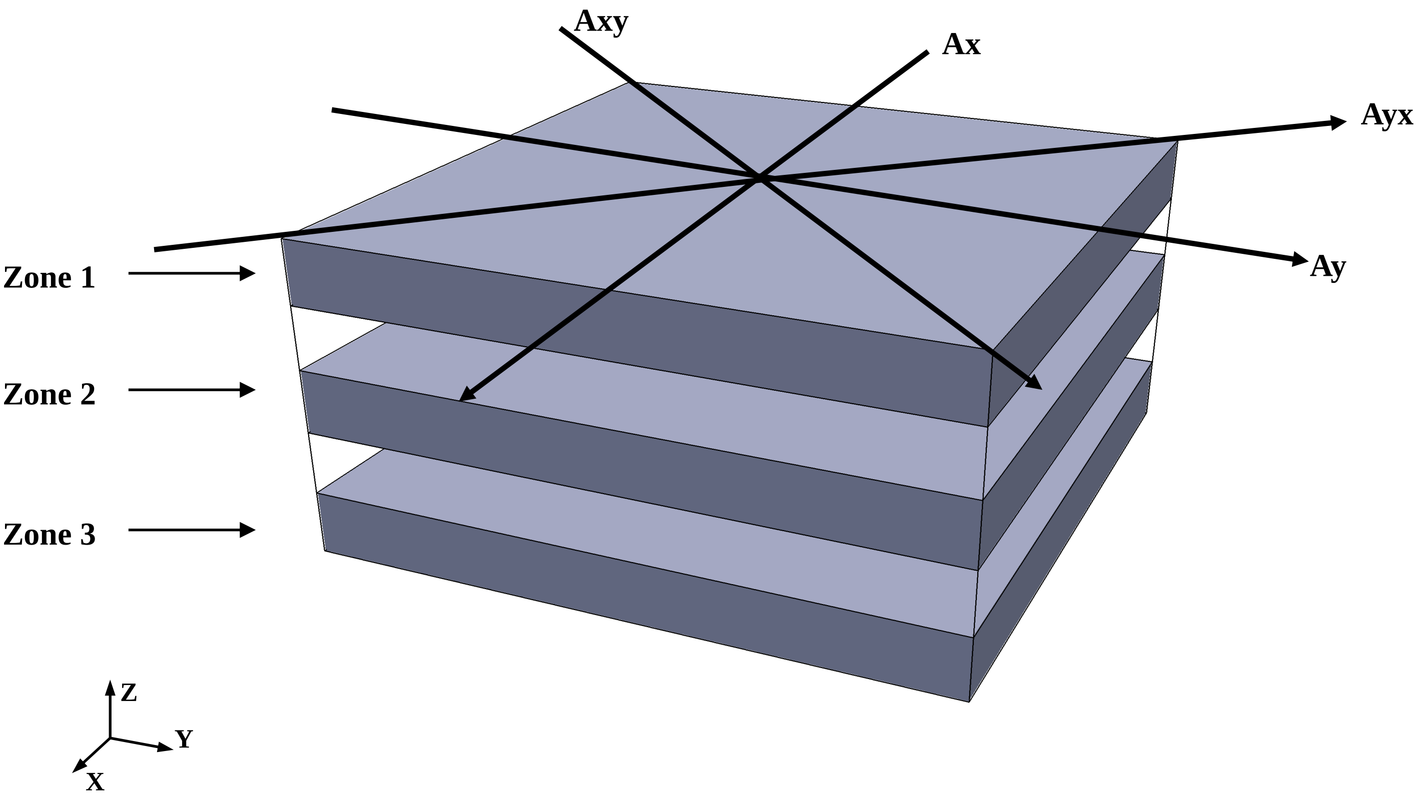
Simulations with STHAMAS3D software

- Direct solution of Navier-Stokes equations; phase boundary tracking; Finite Volume method; parallelization with MPI
- Consideration of Lorentz force by solving additional scalar potential equation
- Higher efficiency for parallel version on a PC cluster



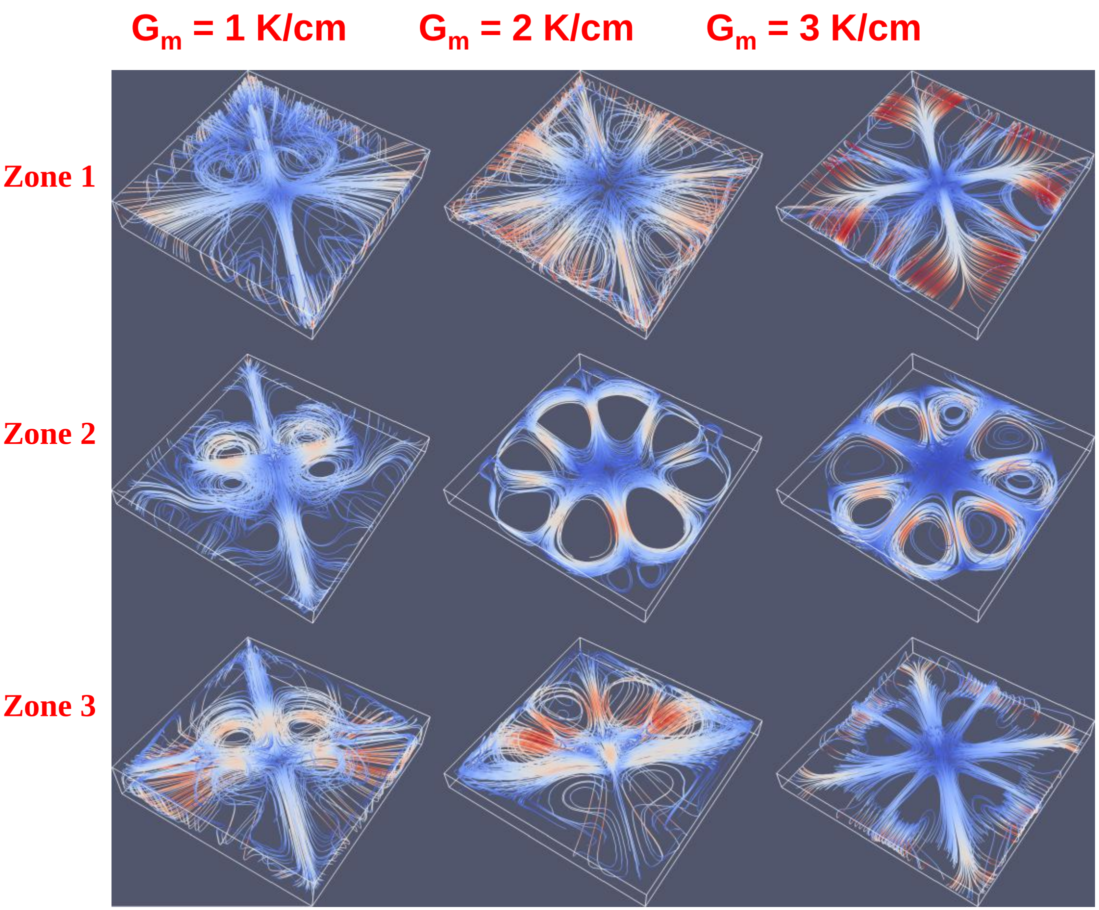


Symmetries in rectangular crucibles



✓ ***Regularity of a flow pattern is defined in relation with the number of symmetry planes.***

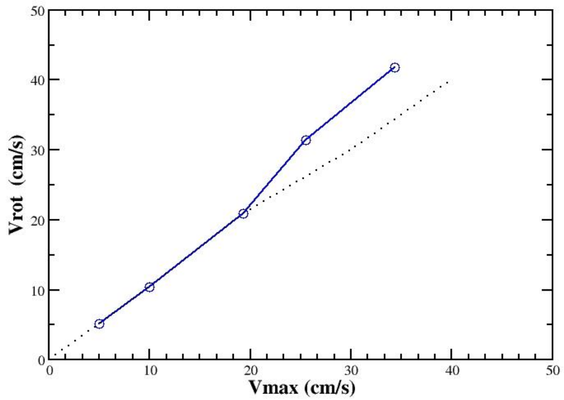
Influence of temperature gradient in the melt on the flow pattern



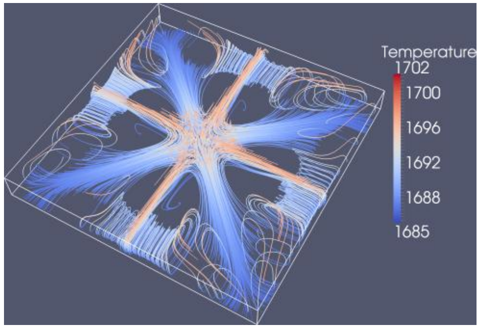
v_g = 10 mm/h

- ✓ Flow pattern regularity increase with the increase of G_m
- ✓ In all zones there is a symmetry along the Axy plane
- ✓ For G_m = 1K/cm common flow structure appear in all 3 zones
- ✓ In zone 3 the flow structure symmetry increases along the Ax, Ay and Ayx planes
- ✓ Convection roles appear near the crucible wall for G_m = 3K/cm
- ✓ În zone 3, regularity increases much more once with the inversion of S-L interface

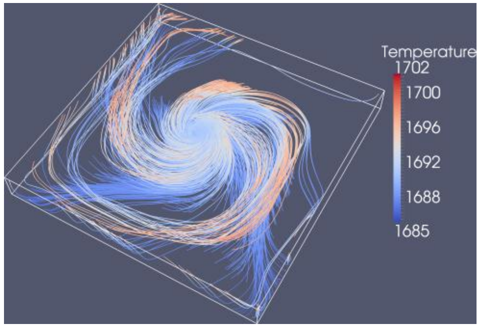
Influence of the stirrer rotation on the melt flow



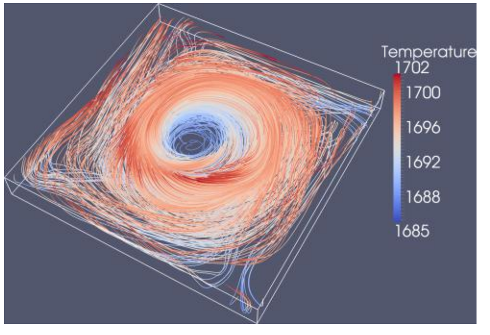
$$\omega^2 D/2 = \rho \left| \left(\vec{V}_{max} \cdot \nabla \right) \vec{V}_{max} \right| \approx \rho \frac{V_{max}^2}{D/2}$$



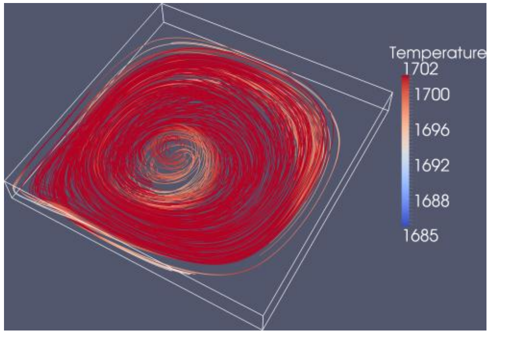
Ω=0rpm



Ω=5rpm



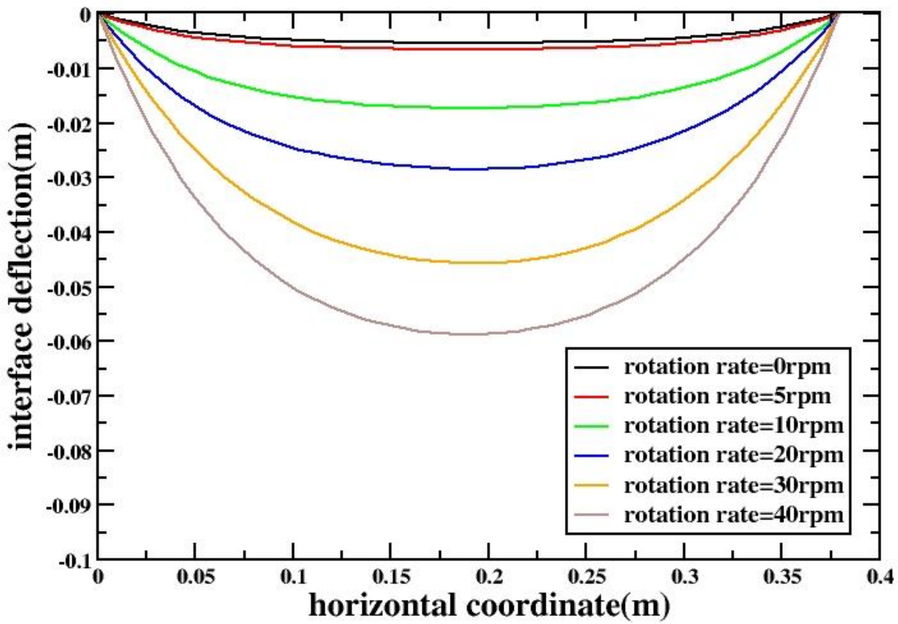
Ω=10rpm



Ω=30rpm

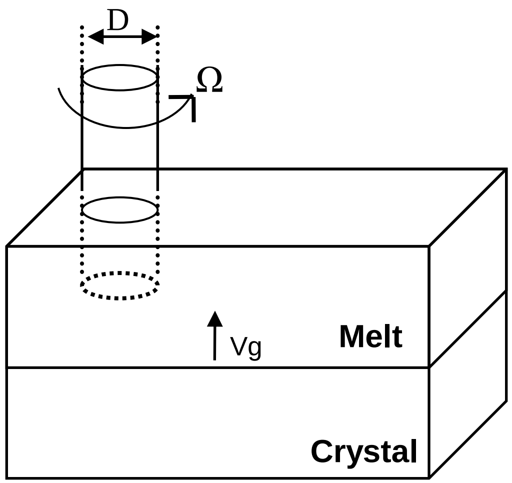
- **Stirrer rotation enhance the melt convection**
- **For small rotation rates (less than 20rpm) a uniform azimuthal rotation is produced and the rotational driving force is balanced by inertia**
- **Stirrer rotation facilitate the transport of hot melt from upper parts to the S-L interface**

Influence of the stirrer rotation on the interface shape

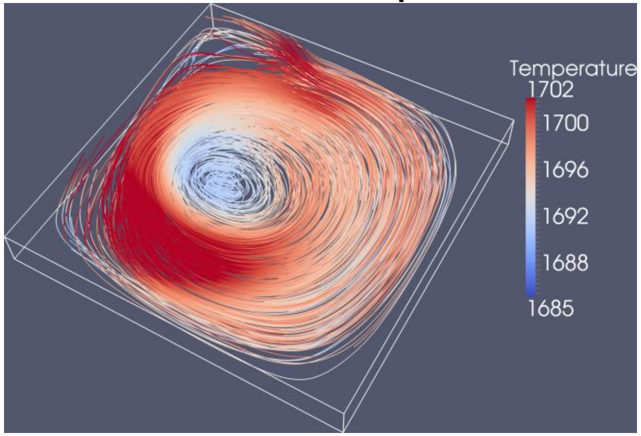


✓With the increase of stirrer rotation the interface deflection increases

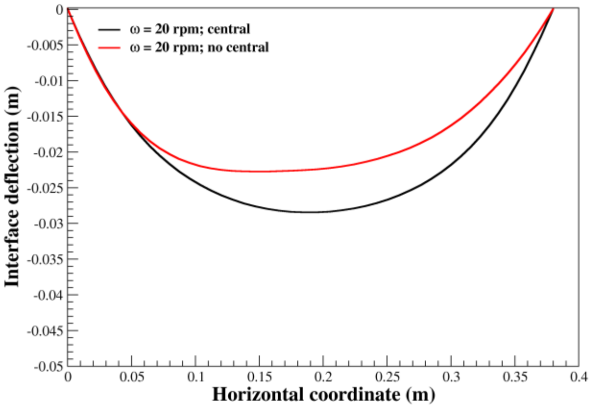
Influence of the stirrer position



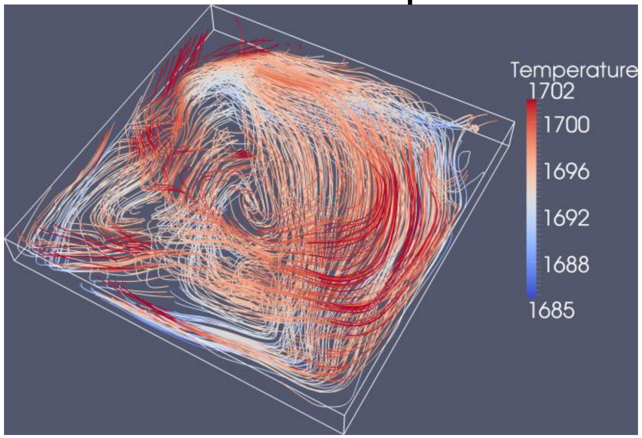
Central stirrer position



Ω=20rpm

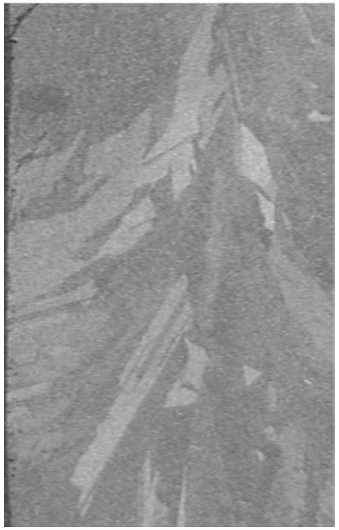


Lateral stirrer position



✓Stirrer position can influence the symmetry of the interface shape.

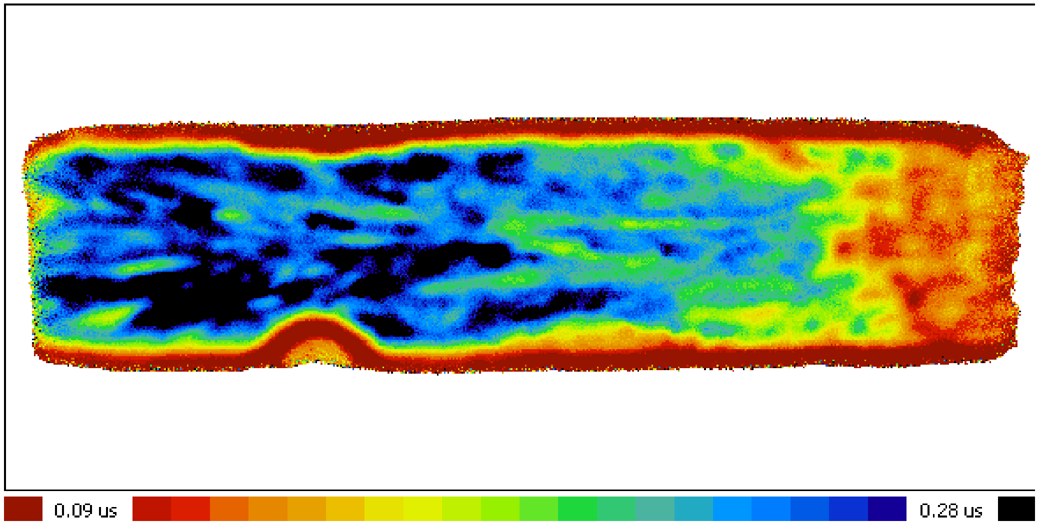
Bridgman Method for growth of mc-silicon



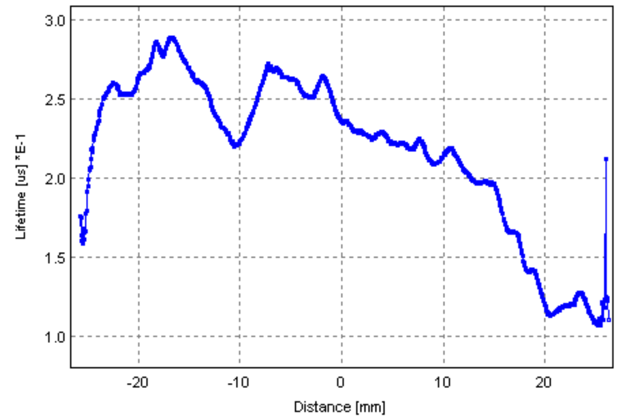
•Multicristalline silicon have been obtained for various growth parameters (growth velocities, temperature gradients, etc)

Lifetime measurements

MW-PCD technique
(,, microwave reflectance photoconductivity decay”)

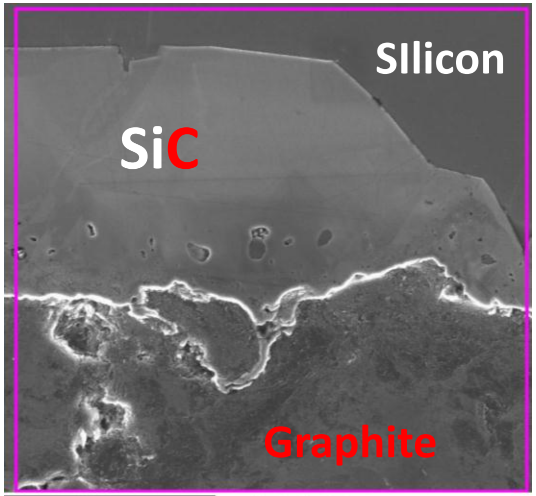


Axial distribution

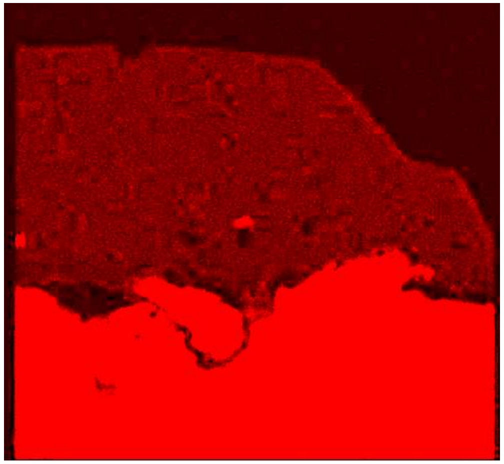


•Lifetime decreases in the upper part of the crystal because of the impurities agglomeration due to segregation

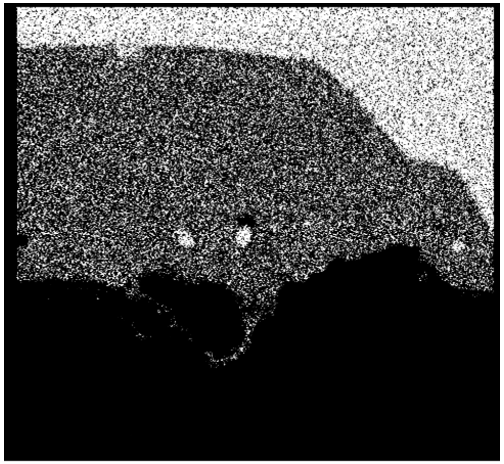
EDX element charts



Electron scanning image



Carbon concentration (red dots)



Silicon concentration (white dots)

•SiC precipitate formed at the crystal crucible edge

Other results

•Master thesis (2011):
Characterization of photovoltaic silicon ingots by measurements of lifetime of minority carriers.
Author: Radu Negrila (6 months at INES)

PHD – thesis (2012):
Study of the directional solidification process by means of numerical methods
Author: Popescu Alexandra

•12 participations at international conferences

•4 participations at national conferences

Other results

ISI-papers

A. Popescu, D. Vizman - Numerical study of the influence of melt convection on the crucible dissolution rate in a silicon directional solidification process, *International Journal of Heat and Mass Transfer 54 (2011), 5540-5544*; **AIS:0.823, IF:2.407**

A. Popescu, D. Vizman - Numerical Study of Melt Convection and Interface Shape in a Pilot Furnace for Unidirectional Solidification of Multicrystalline Silicon, *Crystal Growth & Design 12 (2012), 320-325*; **AIS:0.912, IF:4.720**

S. Dumitrica, D. Vizman, J.-P. Garandet, A. Popescu - Numerical studies on a type of mechanical stirring in directional solidification method of multicrystalline silicon for photovoltaic applications, *Journal of Crystal Growth (2012), doi:10.1016/j.jcrysgro.2012.01.011*; **AIS: 0.490, IF: 1.710**

AIP- conference proceedings

O. Bunoiu, M. Stef, A. Popescu - Interface shape studies in bridgman growth of multicrystalline silicon, *AIP Conference Proceedings 1387 (2011), 226-231*

V. Pupazan, A. Popescu, O. M. Bunoiu, D. Vizman - Influence of growth rate on interface shape and grains structure in multicrystalline silicon growth by bridgman method, *AIP Conference Proceedings 1472 (2012), 210-214*

A. Popescu, D. Vizman - *Crystal Growth & Design 12 (2012), 320-325*; **AIS:0.912, IF:4.720**

Thank you for your attention!