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LIMITATIONS OF THE GROWTH RATE OF SILICON MONO INGOTS GROWN BY THE CZOCHRALSKI TECHNIQUE

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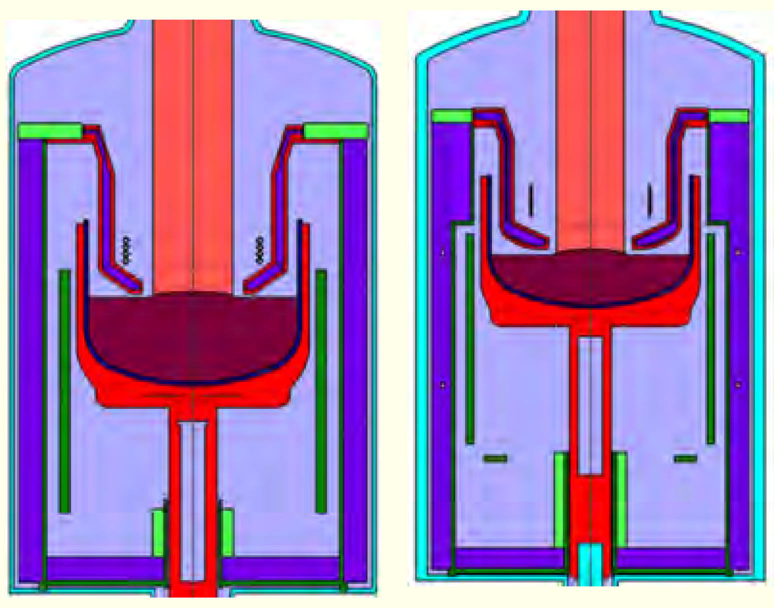
Abstract

In the PV industry, cost pressure subsists in the entire production chain of PV. The improvement of the quality of monocrystalline silicon ingots, grown by the Czochralski technique while increasing productivity and reducing crystallization costs, is a major challenge. The reductions in production costs can be achieved by increasing growth rate and melt volumes. We have investigated the basic limitations of pull rate in the Czochralski process.

Crystal growth



Crystal growth configurations V1 (left), V2 and V3 (right)

growth configuration	crucible dimension [inch]	bottom heater	ACC
Va	22/24	no	no
V1	22	no	yes
V2basic	24	no	no
V2	24	yes	yes
V3	26	yes	yes

Tab.1: *crystal growth configurations*

Limitation of the growth rate in Cz-configuration

(I) Transport of heat through the growing crystal

The physical rate limiting parameter for the growth of ingots in a Czochralski configuration is the dissipation of the latent heat of fusion of silicon at the interface crystal/melt by heat conduction through the growing ingot (I). In (I) λ is the thermal conductivity, A the area of the interface, (dT/dx) is the axial temperature gradient, v_p is the constant growth velocity, ρ is the crystal density, L the latent heat of fusion and s,l are the subscripts for the solid and liquid phase. The heat of crystallization is directly correlated to the growth rate (tab.1).

$$\lambda_s \cdot A \cdot \left(\frac{dT}{dx}\right)_s = \lambda_l \cdot A \cdot \left(\frac{dT}{dx}\right)_l + \rho \cdot A \cdot L \cdot v_p \qquad \text{(I)}$$

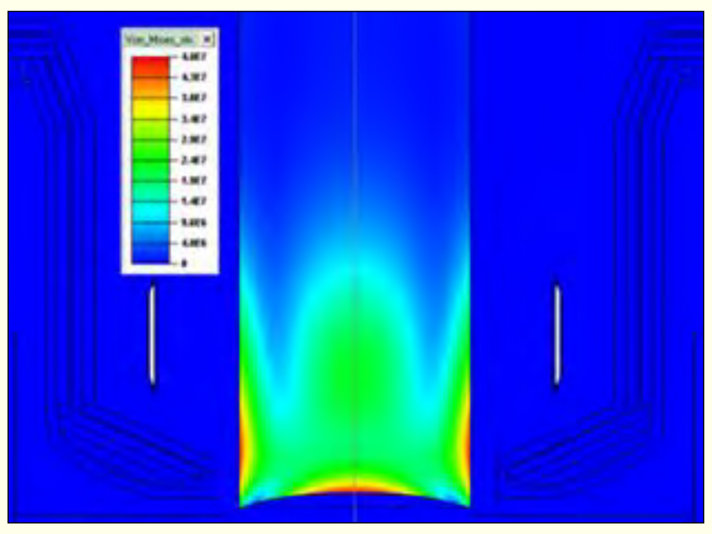
growth rate [mm/min]	latent heat [kW]
0.9	2.3
1.8	4.6

Tab.2: *Released heat of crystallization for 8 inch ingots*

Limitation of the growth rate in Cz-configuration

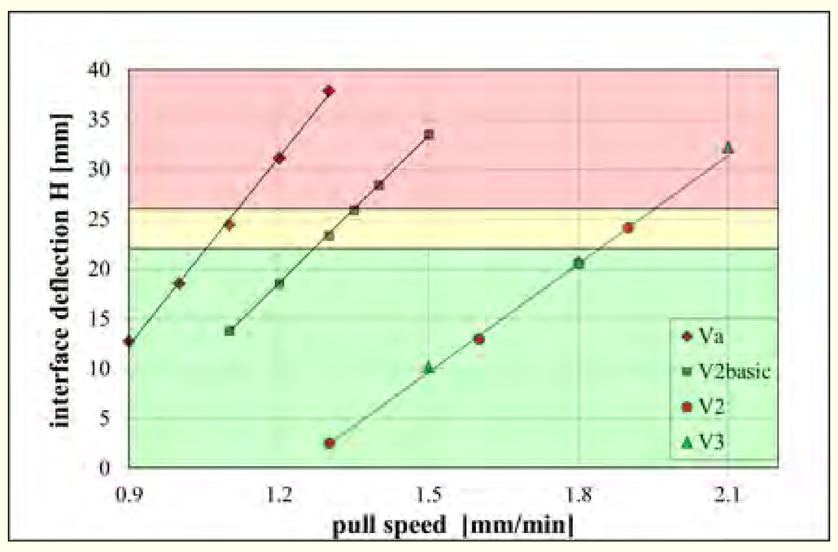
(II) Excessive thermal stresses

growth configuration	mean pull speed in body phase [mm/min]	deflection calc. at 500 mm	twisting	von-Mises stress [Pa]
Va	1.1 - 0.9	24	yes	3.90E+07
V1	1.1 - 0.75	13.5	yes	2.70E+07
V1	1.2	6	no	2.90E+07
Va	1.1 - 0.85	24	yes	3.90E+07
Va	0.9	13	no	3.00E+07
V2basic	1.3	23	no	4.60E+07
V2	1.8	21	no	6.20E+07
V3	1.6	13	no	4.10E+07

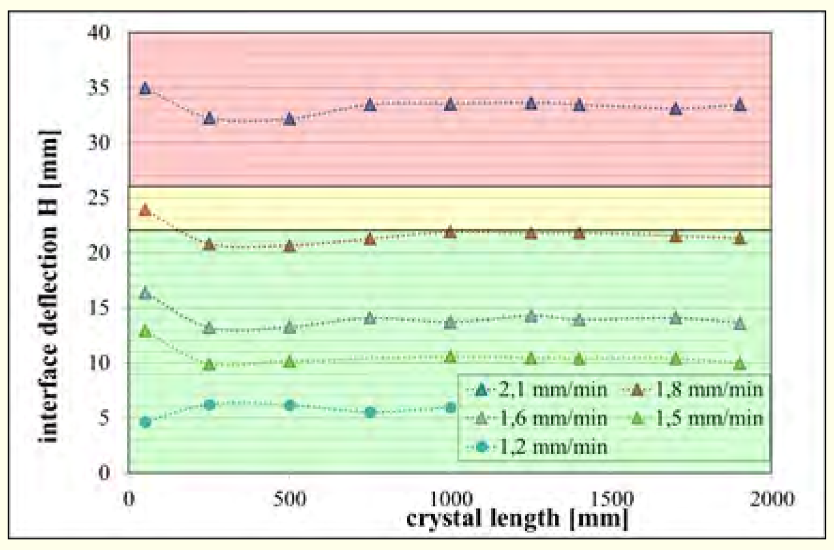


Tab.3: *Von-Mises stresses calculated for the different crystal growth configurations (max. values)*

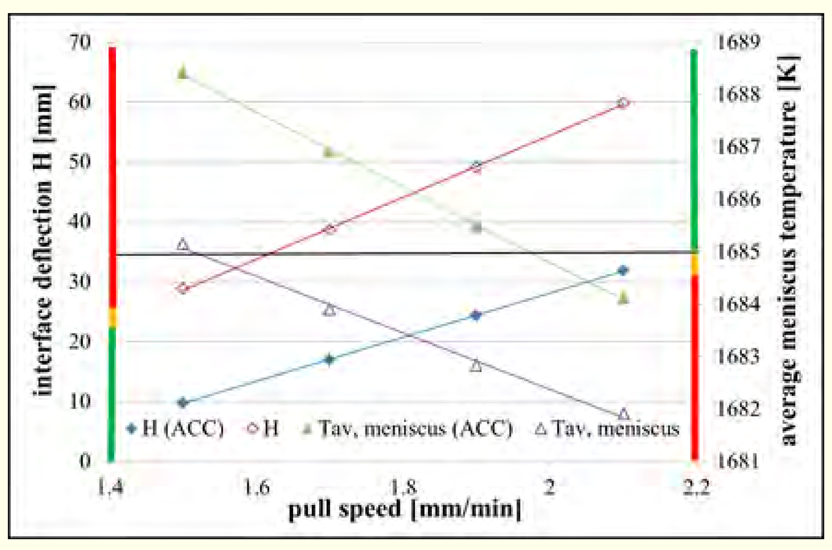
Evaluation of the crystal growth conditions



Stability diagram for different crystal growth configurations



Variation of the interface deflection for different growth rates applied in the body phase in crystal growth configuration V1 for the growth rate of 1.2 mm/min and V2/V3 for the other growth rates

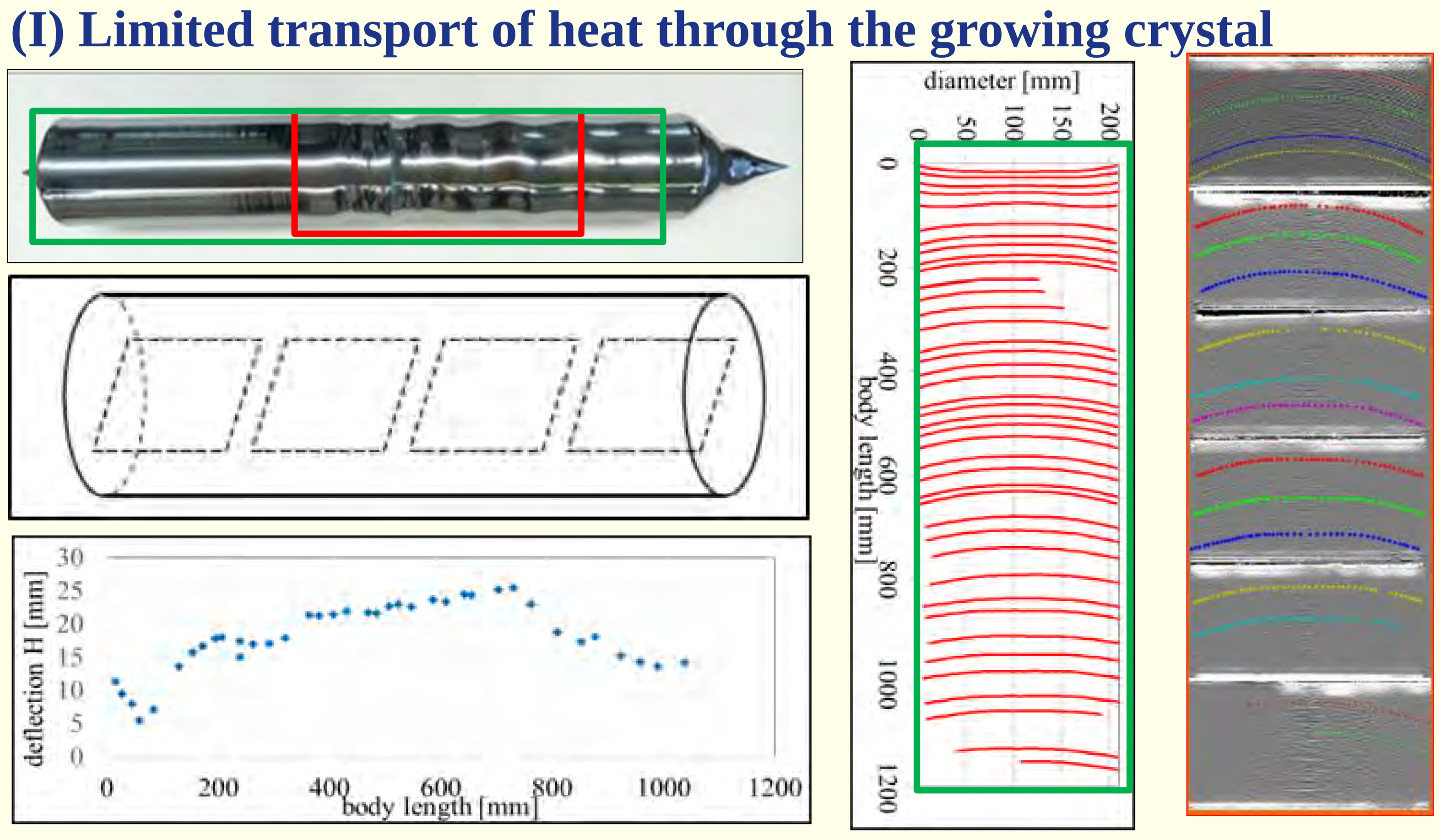


Temperature averaged along the curved meniscus surface and interface deflection versus the average pull speed in crystal growth configuration V2/V3 with (ACC) and without active crystal cooling.

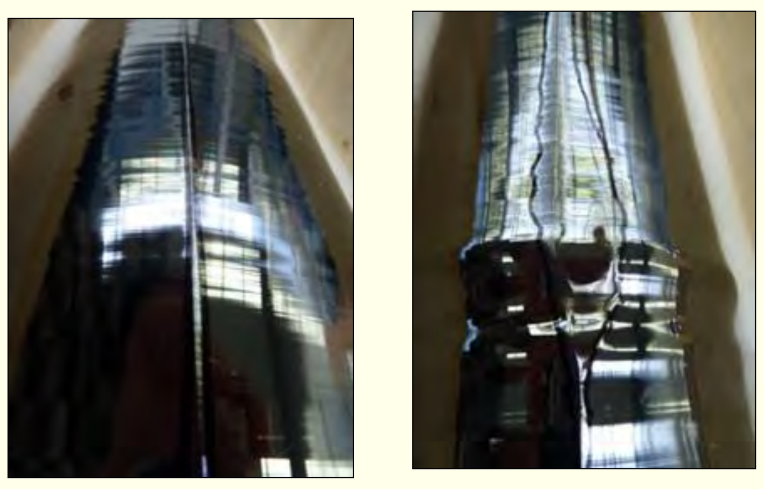
The figures represent stability diagrams in which three areas are marked. In the stable growth region (green) the system is insensitive to changes in the average pull speed. This region is robust and suitable for industrial production. In the metastable growth region (yellow) all growth parameters have to be well tuned. Small changes can lead to unstable growth with loss of the cylindrical shape, i.e. spiral growth. In the unstable growth region (red) no regular crystal growth is possible.

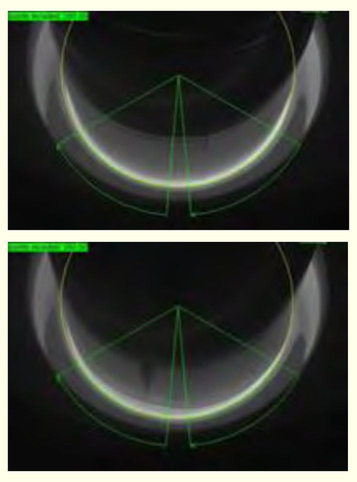
Results: Loss of cylindrical shape (twisting)

(I) Limited transport of heat through the growing crystal



Interface deflection of a twisted crystal characterized by lateral photovoltage scanning (LPS) on vertically cut slices





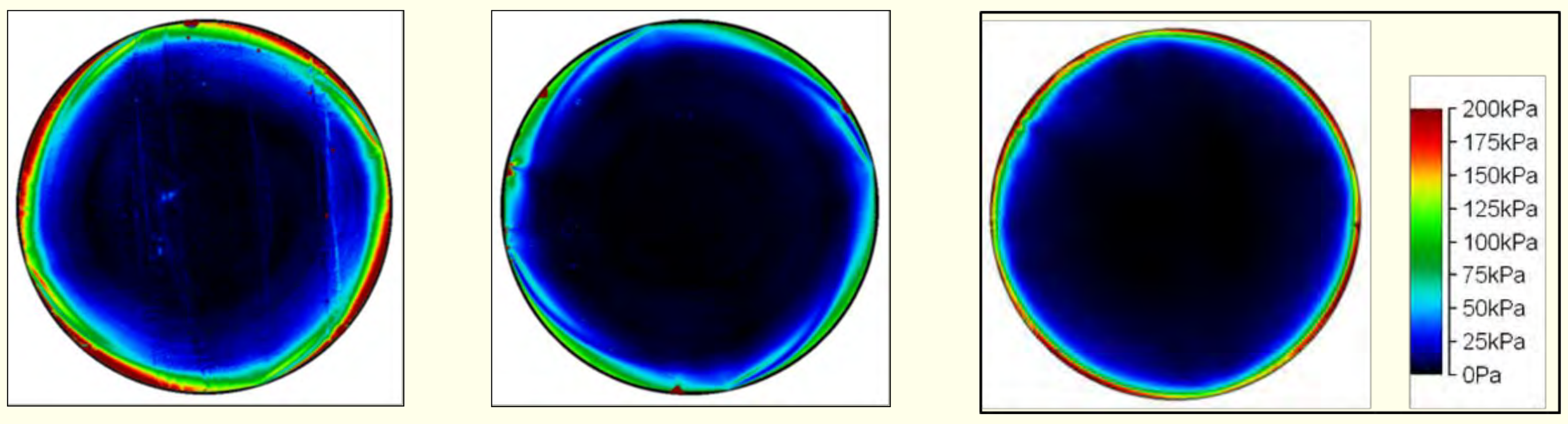
Snapshot of the process camera: stable growth conditions

Snapshot of the process camera: unstable growth conditions

Appearance of the growth ridges (framed in black).

Results: Scanning Infrared Stress Depolarization

(II) Measured shear stress maximum



Shear stress maxima in the samples cut from the middle of the crystals grown in configurations V2 with different pull speeds (0.9 mm/min, 1.3 mm/min, 1.8 mm/min)

The examined samples show practically no differences between each other and are stress-free except for the outer edge area. Along the circumference, the samples show slight tensile stresses and in radial direction slight compressive stresses.

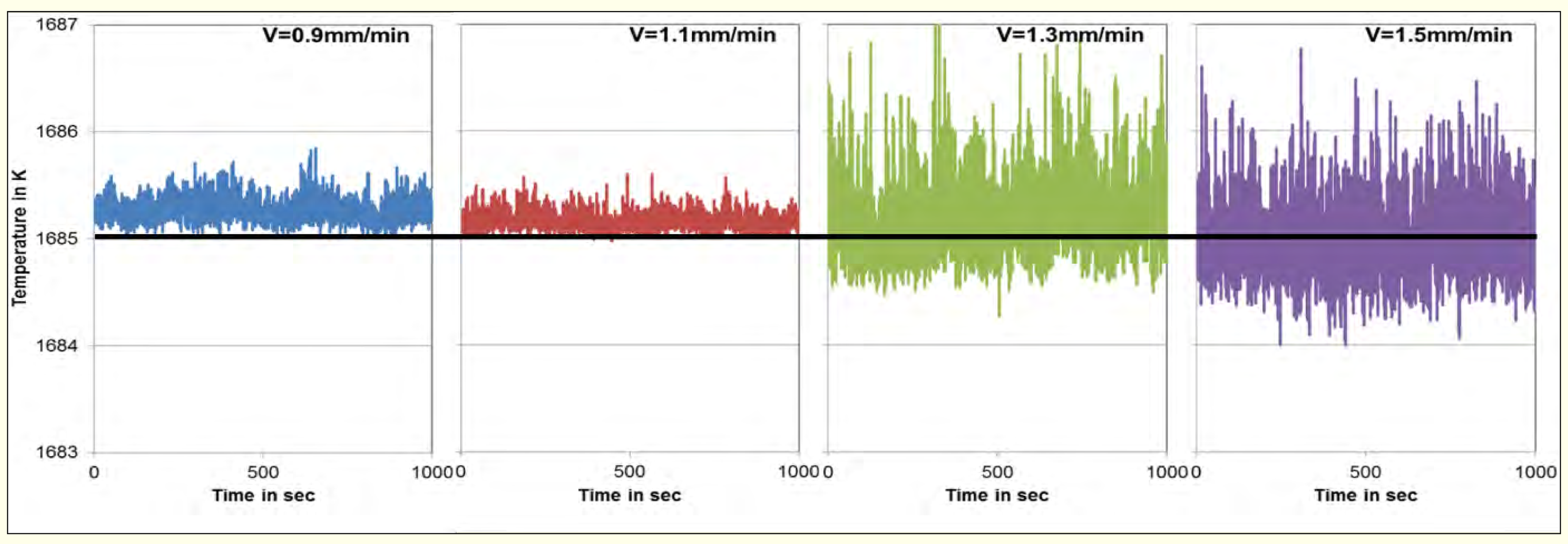
Discussion

Based on the results of tab.3, it is assumed that the interface deflection alone does not correlate with the calculated von-Mises stresses. There is also no correlation with spiral growth. Furthermore we conclude that the interface deflection in combination with the enhanced latent heat due to the pull speed is the cause of the occurrence of spiral growth.

From our point of view, the amplitude and frequency of temperature fluctuations may be crucial for dislocation formation. Friedrich et al. [*] have calculated the temperature fluctuations at the free melt surface for different pull speeds, shown in fig.below (reproduced from [*]). Local and temporal remelting seem to occur at high growth rates resulting in an increasing probability of dislocation formation. These temperature fluctuations should be avoided in any case for a dislocation free crystal growth.

This matter will be a topic for our following research work.

[*] Journal of Crystal Growth **524** *(2019) 125168*



Temperature fluctuations at the free melt surface close to the triple point in a coordinate system rotating with the crystal for different pull rates 0.9mm/min, 1.1mm/min, 1.3mm/min, and 1.5mm/min. The calculations were performed for 26" crucible, 190kg initial charge weight, 100cm crystal length, and no active crystal cooler

Acknowledgements

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