COST EFFECTIVE GROWTH OF SILICON MONO INGOTS BY THE APPLICATION OF INCREASED PULL SPEED IN CZ-Puller

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Increased productivity due to high pull speed

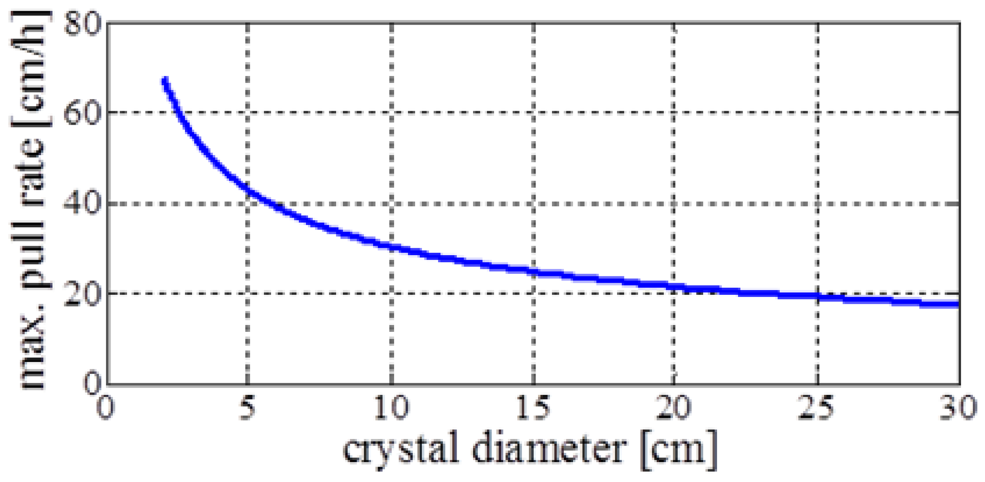
At present, silicon monocrystals are still produced mostly according to the standard Cz-technology. In order to enhance the productivity combined with a reduction of the production costs, the growth configuration was optimized using the commercial program package CGSim [1] for numerical simulation. Two approaches were followed:

I) Optimization of the hotzone without a cooling jacket

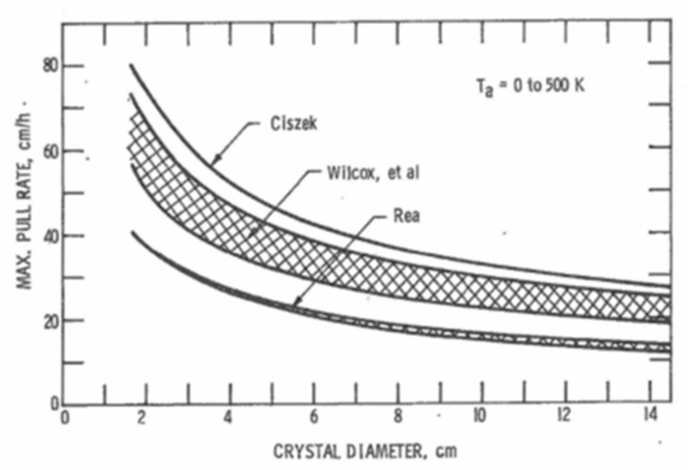
II) Optimization of the hotzone including a cooling jacket

Limitation of pull speed in Cz-configuration

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.
A model first derived by E. Billig [2] assumes the absence of thermal convection and a radiation from the crystal surface to the environment at zero Kelvin. It shows the inverse diameter square root dependency of the pull rate: $v \sim \sqrt{(1/r)}$. Several models have also been published which take into account certain boundary conditions. Especially the model of S. N. Rea seems to be realistic.



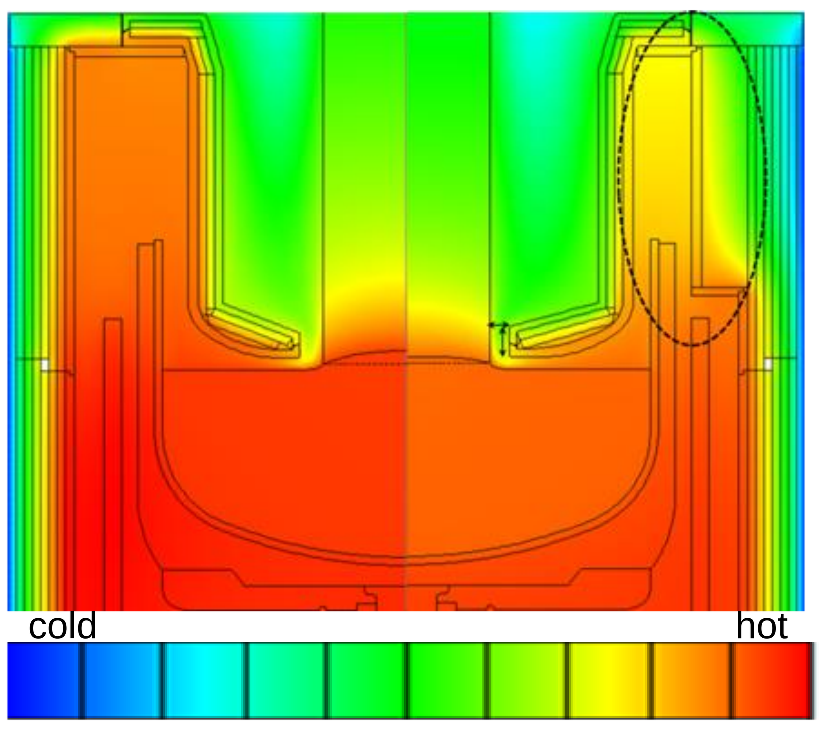
Max. crystal pull speed for silicon versus crystal diameter estimated by the model of E. Billig [2].



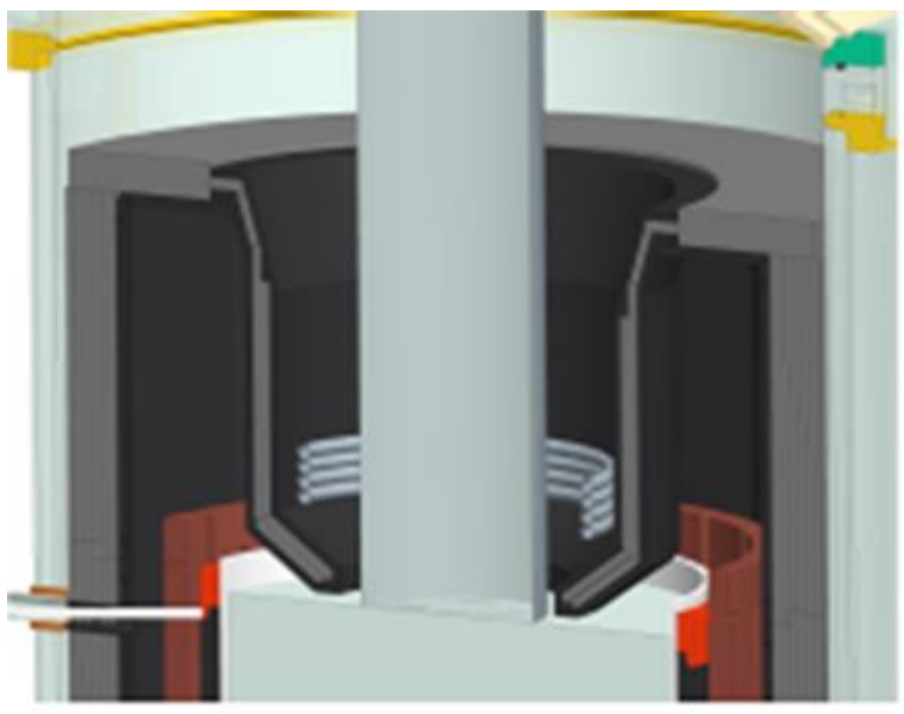
Silicon pull rates predicted by various models. The figure is reproduced from [3].

Numerical simulation

The calculations were performed for 8 inch crystals in a 24 inch hot zone in a SC 24/26 crystal puller of PVA Crystal Growing Systems GmbH. In our development work the CGSim software package from STR [2] was applied.



Geometry and temperature distribution in the standard (left hand side) and optimized (right hand side) hot zone.



Arrangement of the active crystal cooling device in the hot zone.

The standard hot zone was subjected to an extended analysis. The most important evaluation criteria are the deflection of the phase boundary (concavity), the radial temperature distribution on the melt surface and the axial temperature gradients in the center of the crystal and on its surface. The simulation calculations were carried out at a grown crystal length of 500 mm, since from this length no further change of the phase boundary shape is to be expected.

In order to achieve a further increase in the pull speed, an active crystal cooling system has been specifically integrated into the hot zone. This active crystal cooling device is a water-cooled container, often referred to as cooling jacket, placed between the inner heat shield and the growing crystal. The crystal cooling device configuration was first published by S.N. Rea in 1977 [3].

References

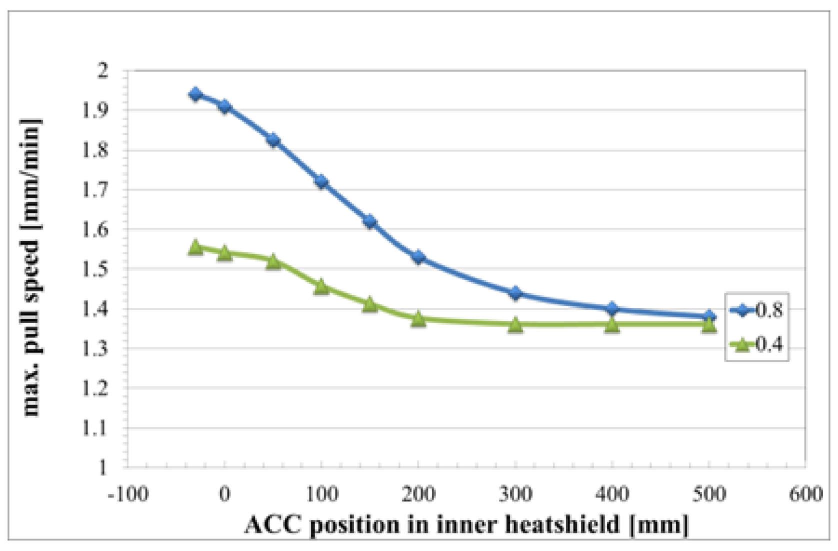
[1] CGSim package, STR Group,Ltd.
[2] E. Billig, Proc. Roy. Soc. (London) 229 (1955) 346-363
[3] S.N. Rea, Final Report, ERDA/JPL 954475 (April 1977)

Acknowledgements

This work was supported by the German Ministry of Economy and Energy under contract number 0325883A.

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

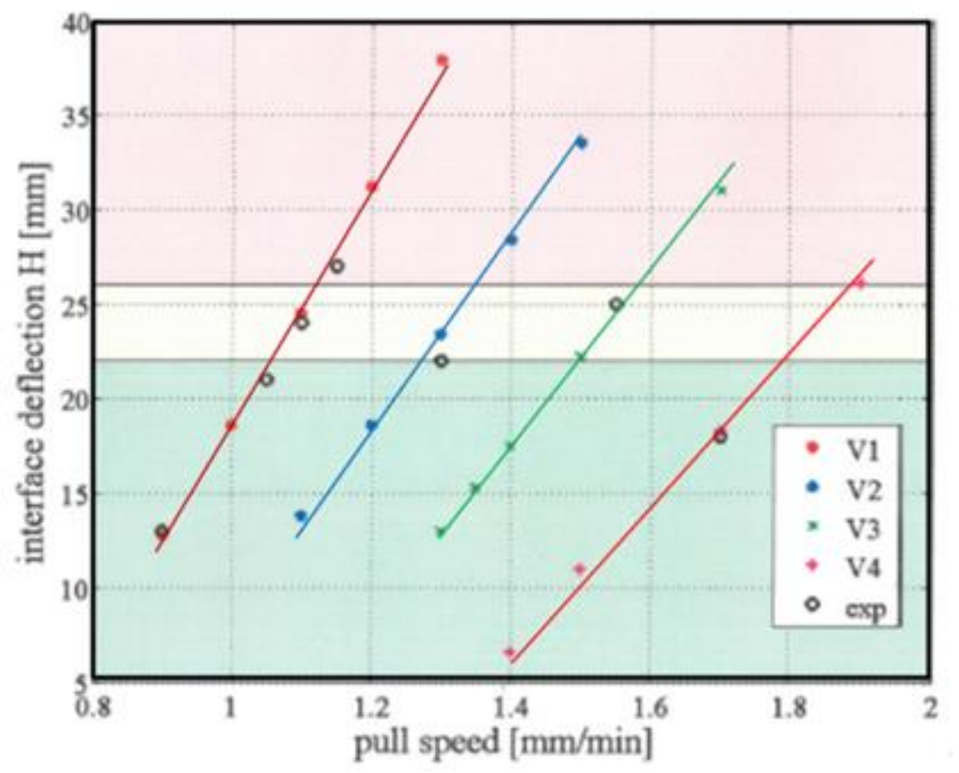
Different geometries with different surface characteristics of the cooling devices have been tested and are still under investigation.



Maximum pull speed versus the distance of the cooling device to the melt surface for the emissivities 0.4 and 0.8. Position 0 represents the applied distance in the growth runs.

Cooling container with a spiral shape and a cylindrical shape with different surface emissivities.

The state diagram below is based on numerical simulations and on real crystal growth experiments. The interface curvature H is plotted versus the average pull speed in the body phase at a crystal length of 500 mm. In the diagram 3 different regions are shown. 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 shape, i.e. spiral growth. In the unstable growth region (red) no regular crystal growth is possible.



V1 – V4, see below:
State diagram of the stable (green), metastable (yellow) and unstable (red) growth conditions. The main parameter deflection H of the interface shape is plotted versus the pull speed.

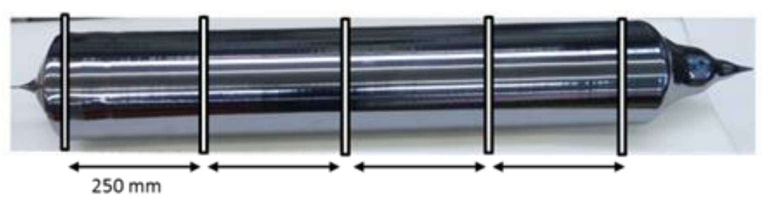
The figure does not represent an analytical model but rather an empirically determined state diagram. In our crystal growth configuration the limit of the pull rate seems to lie in the range of 1.3 mm/min without active cooling and 1.8 mm/min with active crystal cooling.

Crystal growth

Several crystals have been grown in 4 different growth configurations V1 – V4. In growth configuration V1 and V2 no active cooling devices were applied, whereas in the growth configurations V3 and V4 two different cooling devices were tested. All growth configurations and their potential regarding the maximum pull speed are shown in the state diagram.

growth configuration	hotzone	cooling device	emissivty	position of cooling device
V1	standard	no	-	-
V2	optimized	no	-	-
V3	optimized	cylinder	0.4	0
V4	optimized	spiral	0.6	0

Growth configurations with main parameters



Position of the samples for characterization

V1	sample 1	sample 2	sample 3	sample 4	sample 5	
center	10.8	9.1	8.2	7.5	6.5	$x\ 10^{17}\ cm^{-3}$
half radius	10.4	8.9	8.1	7.7	6.4	$x\ 10^{17}\ cm^{-3}$
edge	6.3	5.7	4.6	5.6	5.8	$x\ 10^{17}\ cm^{-3}$

V2	sample 1	sample 2	sample 3	sample 4	sample 5	
center	9.5	6.6	5.8	4.6	4.7	$x\ 10^{17}\ cm^{-3}$
half radius	9.2	6.6	5.6	4	4.3	$x\ 10^{17}\ cm^{-3}$
edge	3.6	3.2	2.3	1.6	3.6	$x\ 10^{17}\ cm^{-3}$

V4	sample 1	sample 2	sample 3	sample 4	sample 5	
center	10.8	6.1	6.1	8.6	9.7	$x\ 10^{17}\ cm^{-3}$
half radius	10.2	6	5.9	8.7	9.3	$x\ 10^{17}\ cm^{-3}$
edge	4.1	3.9	3.5	5.9	6.1	$x\ 10^{17}\ cm^{-3}$

O_I-concentration in the crystals V1, V2, V4. The C_S-concentration in 95% of all samples were below detection limit (<$10^{16}\ cm^{-3}$)

Economic analysis of the high pull speed

growth config.	mean pull speed. [mm/min]	time body phase [h]	Δtime body phase [%]
V1	0.9	20.5	0
V2	1.3	14.6	29
V3	1.6	12.05	41
V4	1.7	11.5	44

growth config.	Δ energy [%]	Δ argon [%]	Δ cooling water [%]
V1	0	0	0
V2	32	29	29
V3	41	41	39
V4	43	44	37

Measures of the productivity of the examined crystal growth configurations in the body phase. The Δ-data represent savings potentials referred to V1.