Behavior of particle depots in molten silicon during float-zone growth in strong static magnetic fields

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Introduction:

Solar cells made from directionally solidified silicon cover 57% of the photovoltaic industry's market [1]. One major issue during directional solidification of silicon is the precipitation of foreign phase particles. These particles, mainly SiC and Si_3N_4, are precipitated from the dissolved crucible coating, which is made of silicon nitride, and the dissolution of carbon monoxide from the furnace atmosphere. Due to their hardness and size of several hundred micrometers, those particles can lead to severe problems during the wire sawing process for wafering the ingots. Additionally, SiC particles can act as a shunt, short circuiting the solar cell. Even if the particles are too small to disturb the wafering process, they can lead to a grit structure of silicon micro grains and serve as sources for dislocations. All of this lowers the yield of solar cells and reduces the performance of cells and modules. We studied the behaviour of SiC particle depots during float-zone growth under an oxide skin, and strong static magnetic fields. For high field strengths of 3T and above and an oxide layer on the sample surface, convection is sufficiently suppressed to create a diffusive like regime, with strongly dampened convection [2, 3]. To investigate the difference between atomically rough phase boundaries and facetted growth, samples with [100] and [111] orientation were processed.

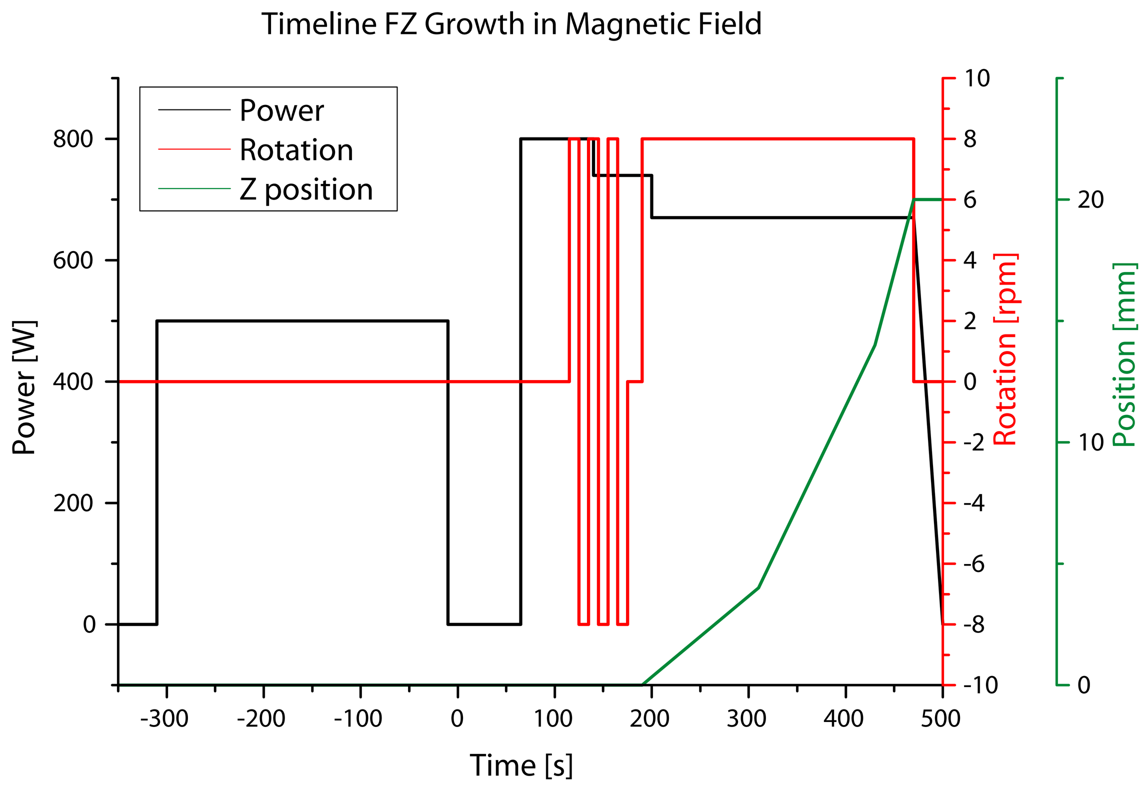
Experimental:

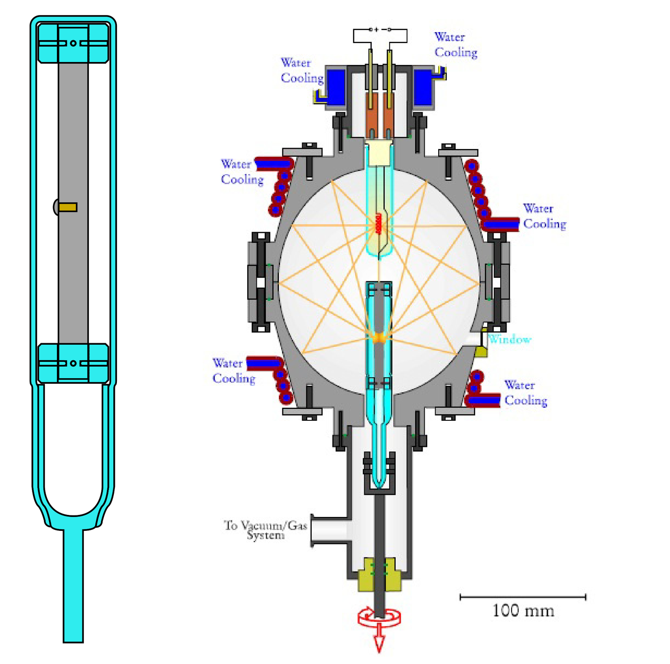
Mirror furnace in superconducting magnet:

- Translation: - 2mm/min (120s)
  - 5mm/min (120s)
  - 10mm/min (40s)
- Rotation rate 8rpm
- mixing by Accelerated Crucible Rotation Technic for 60s

Samples:

- 3 Silicon rods [100] @ 0T, 3T, and 5T
- 3 Silicon rods [111] @ 0T, 3T, and 5T
- Rods with oxide layer to suppress Marangoni convection
- SiC particle depot mix of: - 4mg 7µm dia.
  - 2mg 60µm dia.



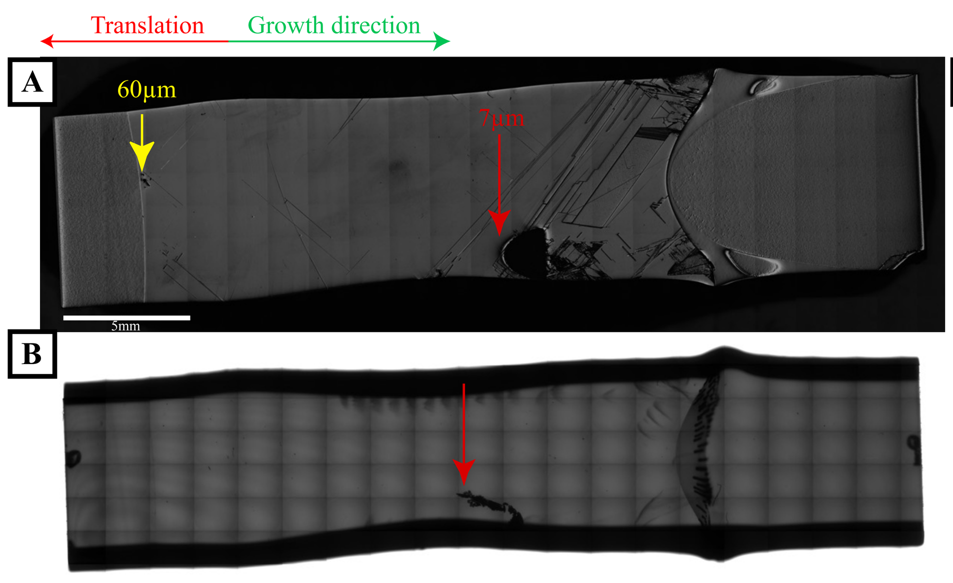


Schematic drawing of the sample in a fused silica ampoule and monoellipsoidal mirror furnace "ELLI"

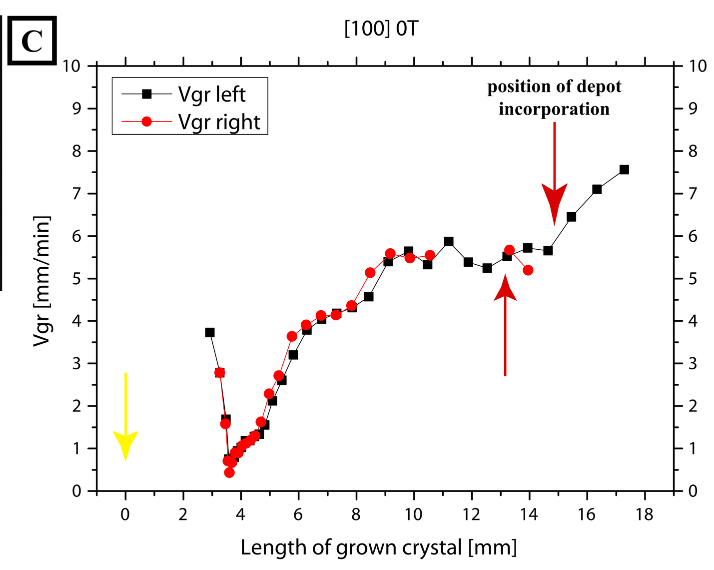
Results:

[100] Orientation

0 T

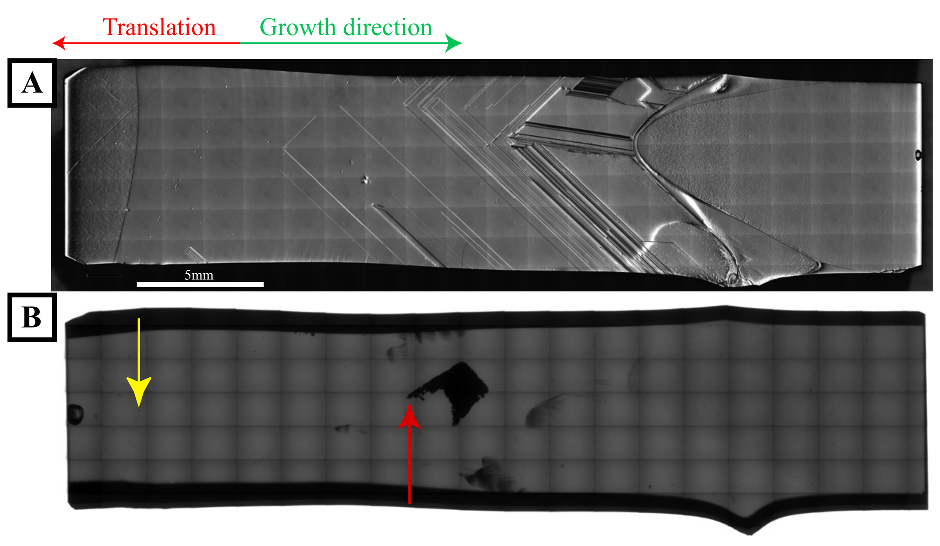


A: DIC micrograph of Si sample grown at 0T field strength
B: IR transmission micrograph
C: Growth velocity from striation evaluation

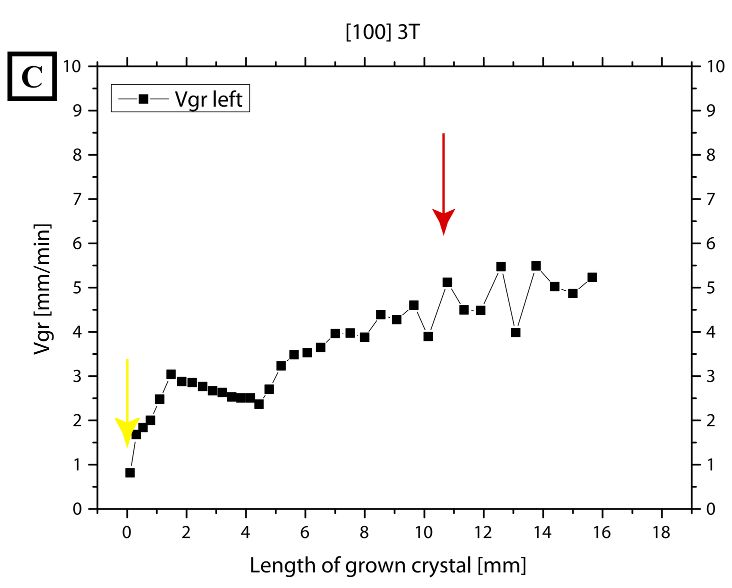


Vgr left: growth velocity from striations on the left edge of the crystal.
Vgr right: growth velocity from striations on the right edge of the crystal

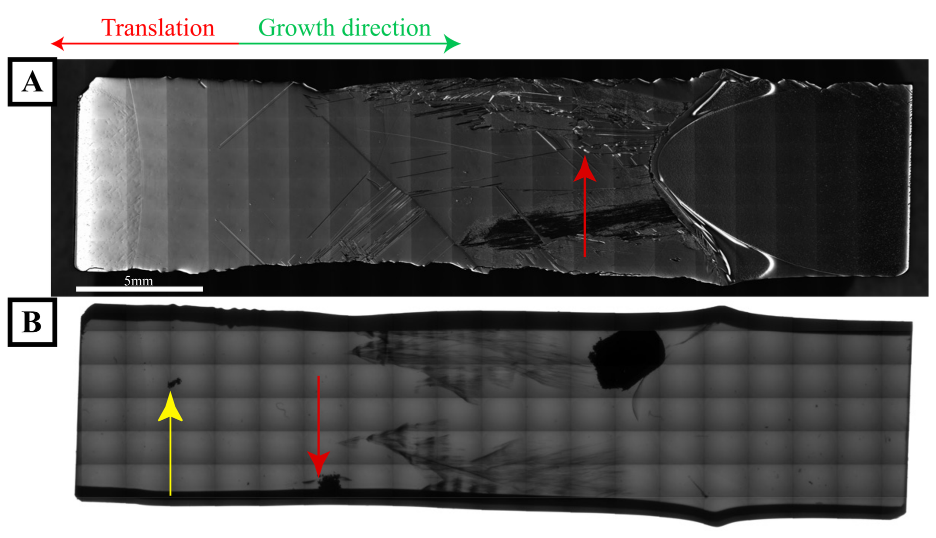
3 T



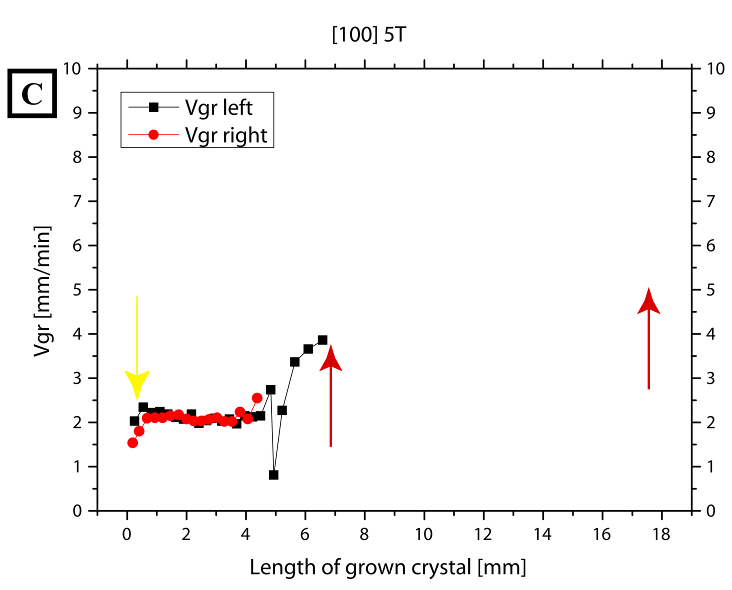
A: DIC micrograph of Si sample grown at 3T field strength
B: IR transmission micrograph
C: Growth velocity from striation evaluation



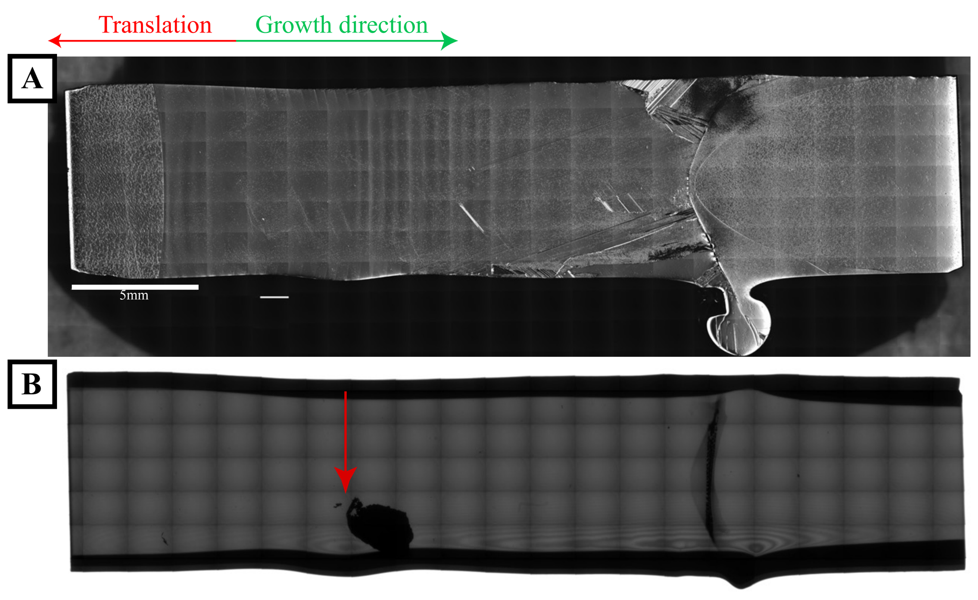
5 T



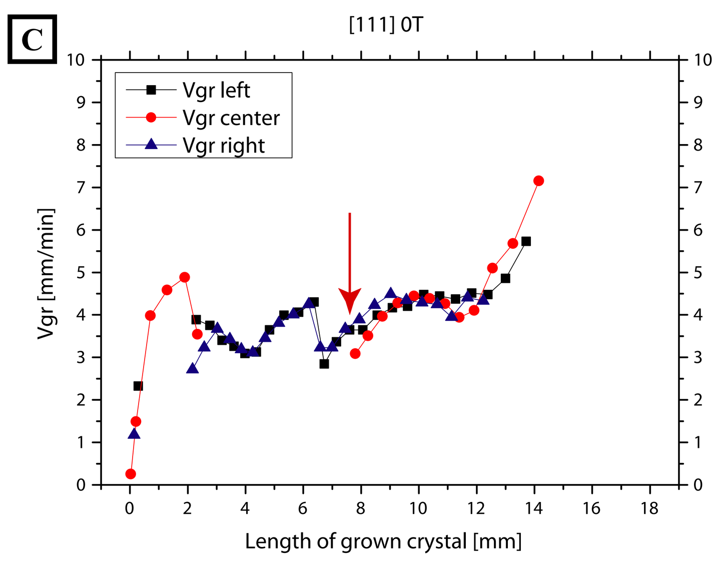
A: DIC micrograph of Si sample grown at 5T field strength
B: IR transmission micrograph
C: Growth velocity from striation evaluation



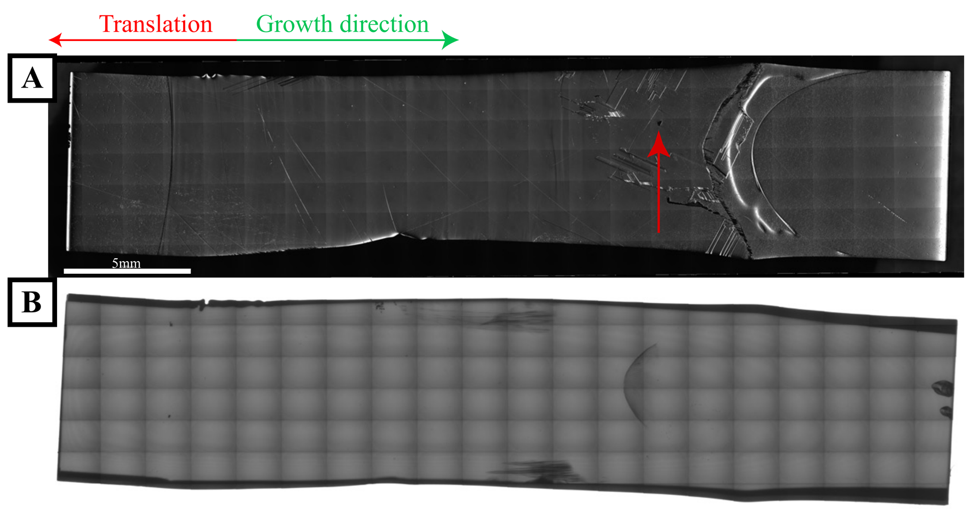
[111] Orientation



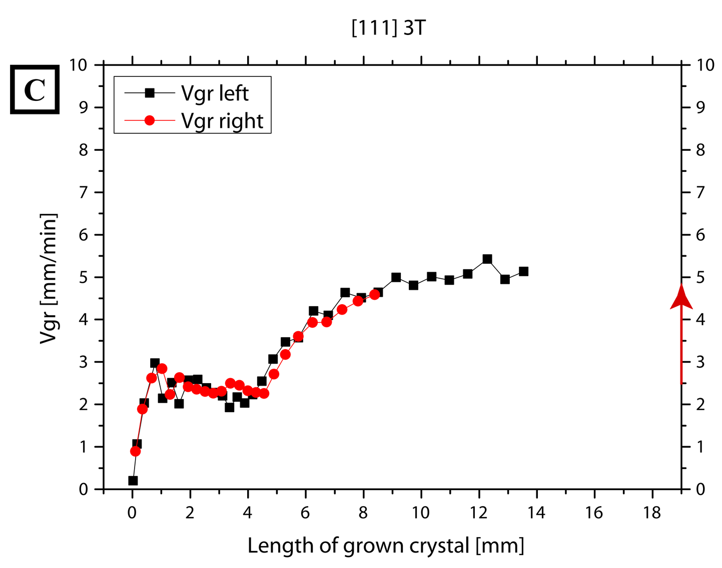
A: DIC micrograph of Si sample grown at 0T field strength
B: IR transmission micrograph
C: Growth velocity from striation evaluation

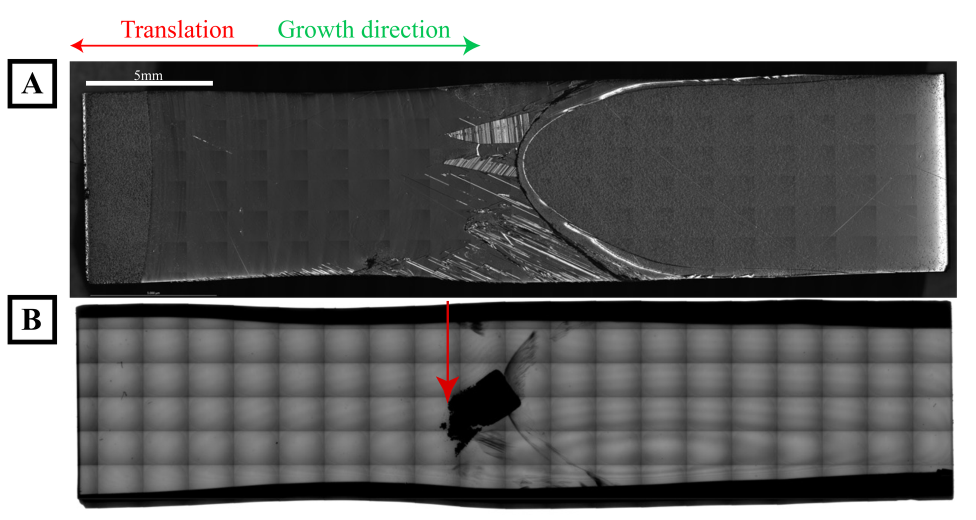


Vgr center: growth velocity from striations in the center of the crystal

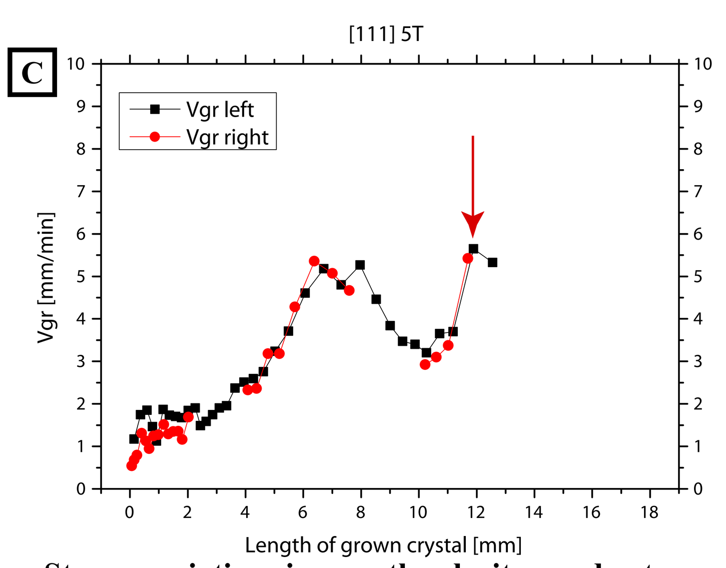


A: DIC micrograph of Si sample grown at 3T field strength
B: IR transmission micrograph
C: Growth velocity from striation evaluation





A: DIC micrograph of Si sample grown at 5T field strength
B: IR transmission micrograph
C: Growth velocity from striation evaluation



Strong variations in growth velocity are due to heating power variations. Intervention was necessary since fogging of the ampoule influenced the zone height.

Conclusions:

- **Buoyancy convection seems to have no significant effect on depot incorporation**
- **Crystal orientation seem to have no significant effect on depot incorporation**
- **Depots of 7µm particles get incorporated with growth rates higher than 5 mm/min**
- **Depots/parts of depots of 60µm particles get incorporated at first lower phase boundary**

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References:

[1] Photon Magazine, 4, 2012
[2] A. Cröll et al. Journal of Crystal Growth 83, p.555-563, 1998
[3] A. Cröll et al. Journal of Crystal Growth 79, p.65-70, 1986