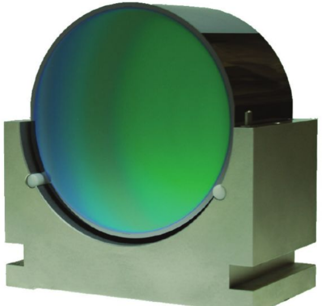
Summary of Silicon Workshop

24th & 25th of April in Maastricht



Why silicon and why this workshop ?

- Low thermal noise
- Low thermal expansion at ≈20K and ≈120K
- High thermal conductivity (low thermal lensing)

BUT

Many questions to solve in order to realise:

cSi test masses and cSi suspensions

We wanted to bring those questions on one table:

who work on realizing ET

&

who grow high-quality silicon:
Leibniz Institute for Crystal Growth (Berlin)

Current questions for ET (short version)

- How to produce 50 cm diameter, 50 cm thick mirror substrates with
  - low optical absorption, i.e. high purity
  - low mechanical loss
  - few defects/structural discontinuities etc. (causing e.g. birefringence, beam distortions etc.)

- How to produce monolithic suspensions which
  - are strong enough to carry ~200 kg of silicon
  - ideally have monolithic contact points for bonding to test masses
  - meet the (not-yet fully specified) geometrical specifications

Mirror Substrates

different production processes

→ different size limitations

→ different types of impurities

→ different material properties

- **Float Zone**
- **Czochralski**
- **Directional Solidification**

Float Zone (FZ) Silicon

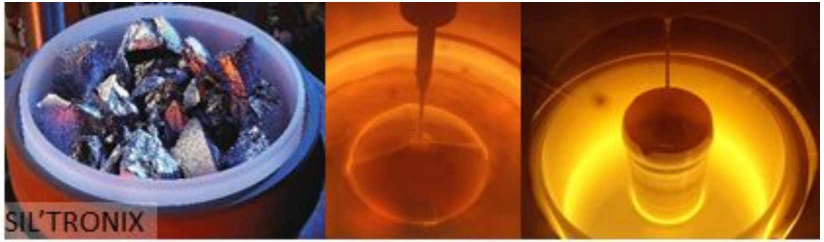
Status:

- Grown by re-melting polycrystalline seed rods in crucible-free inductive heating process
- Purest available material (> 10k Ωcm commonly available → absorption ≲ 3 ppm/cm)
  (hard to measure accurately very high resistivity → not reliable)
- Size limited to 20 cm
  - Technology to grow 20 cm diameter crystals only known by some producers
  - Larger diameters are very interesting for industry, but physics of melt flow and inductive heating prevent much larger sizes (realistic diameter increase: mm rather than cm)

Possible experiments/next steps:

- Composite test masses to increase mirror size/mass (planned by Glasgow)
- Different beam sizes on ITM and ETM
  - Only ITM needs low absorption → different types of silicon for ITMs and ETMs possible
  - Use small FZ mirror for ITM, possibly combined with composite test masses for mass increase
- More explorative: radial size increase of FZ crystal?

*Magnetic** Czochralski (*m*Cz) Silicon



Status:

- Purity up to ≈ 1 - 2 kΩcm possible, higher purity unlikely achievable → major development
  - Starting material for FZ and Cz is the same (very unlikely)
  - Impurities from growth apparatus material (mainly oxygen from crucible and carbon from hot zone)
  - inhomogeneous impurity distribution (trend: lower in the center and at the top of (cylindrical) crystal)

- Lower purity mainly problematic for absorption; thermal noise very similar to FZ

- Diameter up to 45cm possible
  - More commonly available: 30 cm; **45cm currently not produced anywhere**, but possible at high costs
  - Size limited by magnet

****We usually talk about 'magnetic Czochralski' (mCz) silicon when we mean magnetically purified Cz silicon with fewer impurities near the center.***
For large Cz crystals, magnetic fields are always used, to avoid strong melt flows. This results in an impurity reduction, depending on the direction of the magnetic field.

*Magnetic** Czochralski (*m*Cz) Silicon

Questions:

- Measurements have shown similarly (low) absorption for mCz as for high-purity Fz - why?
  - Wrong resistivity specifications ?
  - Are there impurities which affect the resistivity but not the absorption (at relevant wavelengths)?
  - Are other properties affected by impurities, which ‘distort’ thermally-based results and are potentially relevant for GWD mirrors, i.e. thermal conductivity, thermal expansion coefficient etc.

Possible experiments/next steps:

- Systematic change of impurity concentration
  - IKZ will try to grow a FZ (because of more stable material properties) ingot with impurity gradient
    → investigate effect of impurities of various material properties
    → check correlation of impurities and absorption for very low impurity levels

- Different furnace materials (Currently silica -> induces mainly oxygen impurities)
  - Do other furnace materials induce fewer impurities/other impurities with smaller effect on absorption?

Directional Solidification

Mainly used for solar cell industry: Large, cubic crystals are grown in a furnace using 'seed plates' at the bottom.

Status:

- Crystals of up to 1200kg can be grown
- Rather high number of impurities, induced by furnace (despite SiN coating)
  - Impurities not relevant for common applications of this type of material
- Dislocations clusters due to junctions of seed plates
- Mechanical loss of small test sample found to be similar to FZ silicon (PhysRevResearch.4.043043)

Possible experiments/next steps:

- Test mechanical loss of a sample from above 'seed-junctions'
- Investigate better ways to arrange seed plates
- Reduce impurities
  - Similar to Cz plans, i.e. investigate other crucible materials, test effect of impurities etc.

Suspension Fibres

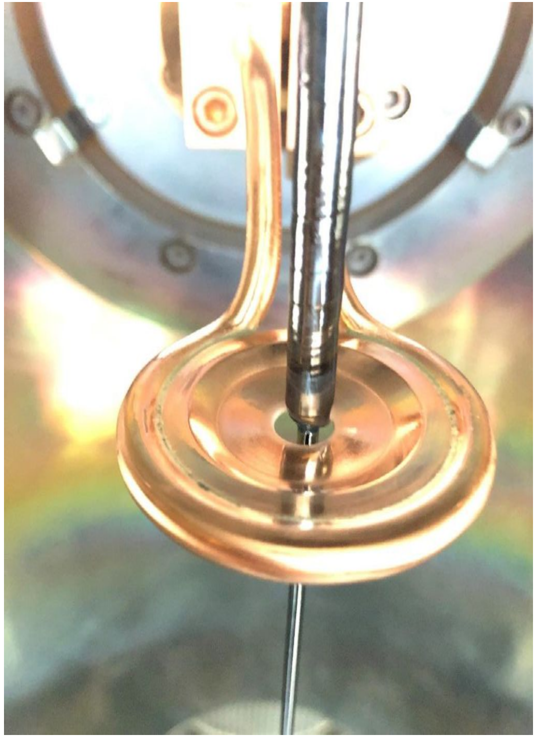
- **Float Zone**
- **Pedestal**

Suspension Fibres

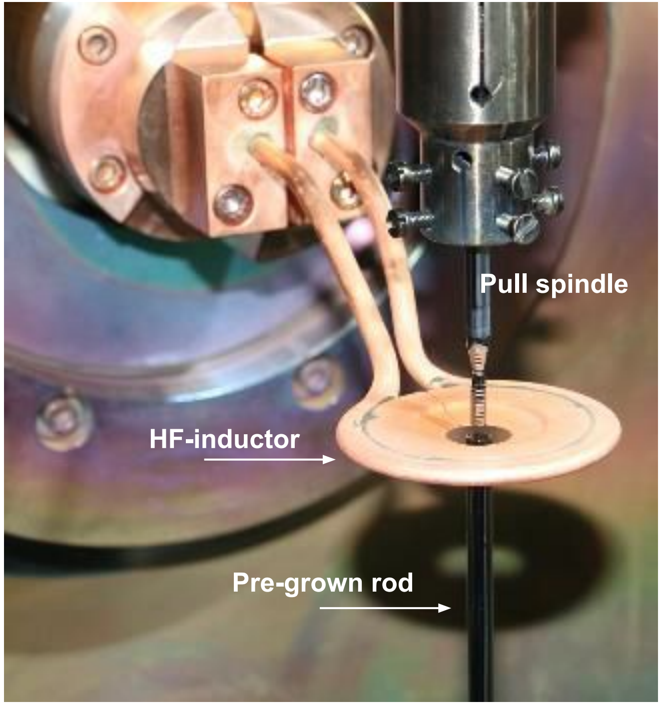
Growth methods

Float Zone

Pulling down



Pedestal



Pulling up

Suspension Fibres

Short for better heat extraction but long for lower thermal noise (longer → lower resonance frequency)

Status:

- Exact dimensions required for ET are not yet specified
  - Depend on heat extraction and breaking strength
- IKZ has grown FZ fibers
  - ≈ 3 mm diameter and ≈ 1m long (≈ good for ET)
  - ≈ 1 mm diameter and ≈ 0.4 m long (≈ good for ETpathfinder)

Main Question:

Can fibre extremities be shaped during growth to achieve monolithic joints for bonding?

→ In principle yes, but maximum diameter change within one ‘process’ is 1:3

Possible experiments/next steps:

- Test breaking strength of existing fibres
- Add 8-10 mm head to 3 mm fibres, test breaking strength again
- Investigate welding of small fibre heads to larger heads inside furnace

Workshop Participants

Leibniz Institute for Crystal Growth:
Robert Menzel, Iryna Buchovska, Frank-Michael Kiessling

Maastricht Univeristy:
Alex Amato, Stefan Danilishin, Diksha, Stefan Hild, Guido Alex Iandolo, Luise Kranzhoff, Zeb van Ranst, Viola Spagnuolo, Jessica Steinlechner, Sebastian Steinlechner, Janis Woehler

Perugia-Camerino:
Flavio Travasso

Nikhef:
Alessandro Bertolini

Glasgow University:
Simon Tait, Andrew Spencer

more workshops to come,
if you are interested in participating,
please contact us!