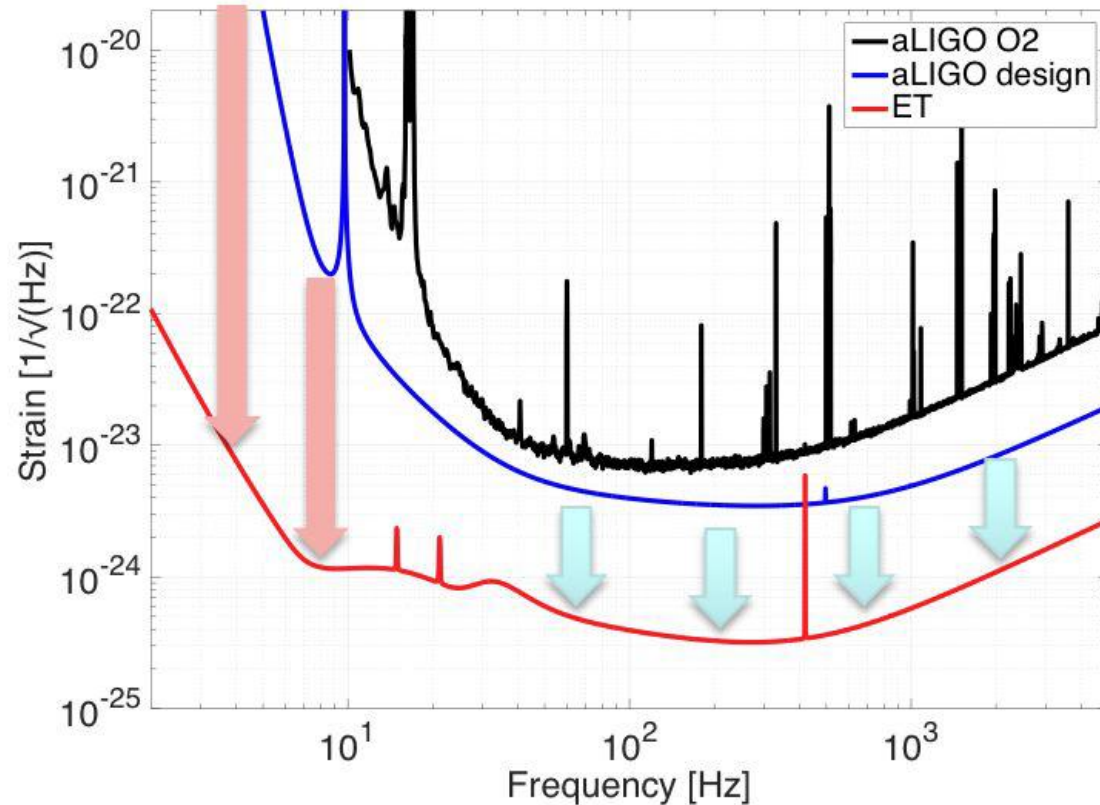


Summary of MAD substrate discussion

Laura Silenzi

Introduction



$$CTN = \sqrt{\frac{4k_B T}{\pi^2 f w^2 Y_s} d\phi \left[\frac{Y_c}{Y_s} + \frac{Y_s}{Y_c} \right]}$$

- Go to cryogenic temperature to reduce thermal noise and get a factor 10 improvement at mid frequency range
- Current silica good at room T, but not at low temperatures

New materials to work at cryogenic T are needed

Substrate requirements

ET mirrors require low optical absorption as

- Some of the mirrors have to be transmissive
- Absorption would heat the cryogenic mirrors
- Tolerable absorption: order of a few 10 ppm/cm

Mirror diameter has to be approximately 45 cm (or larger) with a mass of ~200kg

- To reduce coating thermal noise
- To reduce radiation pressure noise

Substrates: candidate materials

Silicon

- requires to move from 1064 nm to 1550 nm (or 2 μ m for some coating materials)
- low optical absorption requires very pure material, i.e. float zone (FZ) silicon or Czochalski silicon

High-purity material not available in such large sizes. Challenges:

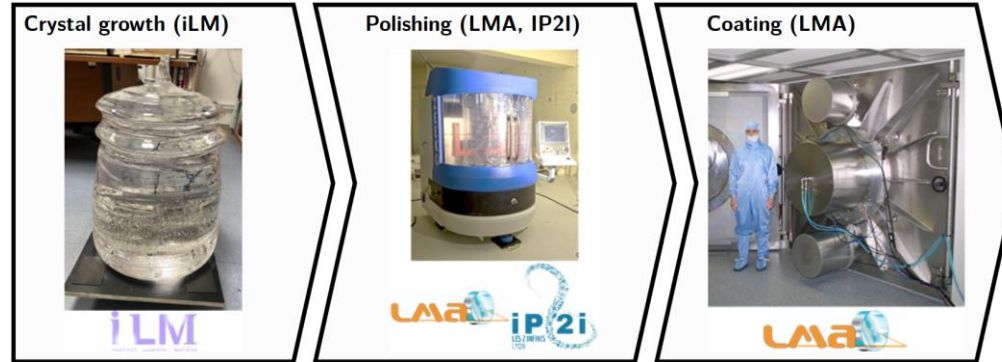
- **make large material purer**, optimizing the process
- **make pure material larger**, optimizing the process or with composite test masses

Sapphire

- Used at 1064 nm
- Already used in KAGRA, with some limitations (inhomogeneities, birefringence, bubbles, smaller mirrors with respect to the ones required for ET)

Progress with sapphire (iLM, LMA, IP2I)

- Growth, polishing and characterization facilities in Lyon (substrates and fibers)



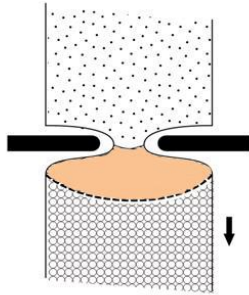
- Challenge to grow sapphire with low absorption and controlled birefringence
 - Progress at Lyon has grown 30 mm diameter sapphire with 15 ppm/cm
 - Progress at KAGRA has found low birefringence sapphire (x10 more homogeneous birefringence <https://dcc.ligo.org/LIGO-G2502021>)
- Flatness $PV = \lambda/60$ demonstrated after polishing of 10 cm diameter sapphire substrate
- Commissioning ongoing to improve the roughness tools and machine accessories (slurry recycling system and substrate positioning)

Polishing and characterization of sapphire substrates for third-generation gravitational wave detectors in Lyon (S.Nadji)

Silicon growth methods

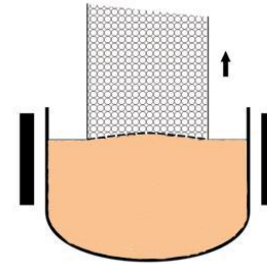
Float Zone (FZ)

- highest purity
- limited diameter (< 200 mm)



Czochralski (Cz):

- larger sizes
- impurity from crucible



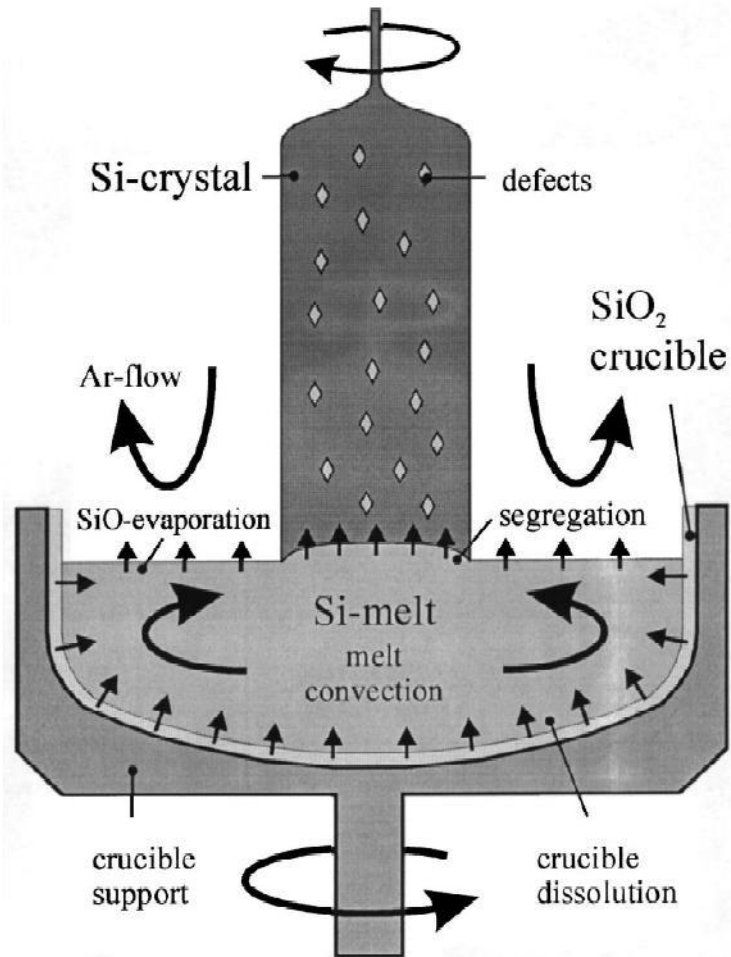
Challenge: combine purity of FZ with scale of Cz
Multiple groups presented novel solutions

Credits pictures: Growth method dependent purity of silicon crystals for ET (F. M. Kießling)

Large diameter FZ silicon (Topsil)

- 200 mm FZ-Si currently produced (semiconductor market)
- 300 mm FZ-Si project underway (plan for project finish for 2028)
- Scaling limited by thermal stress, arcing, RF power
- 450 mm FZ possible, with about €15 M over 5 years

Improving Czochralski purity



- Cz growth introduces oxygen and metallic impurities (crucible erosion)
- Use magnetic fields to damp convection and lower oxygen uptake
- Crucible coatings minimize erosion (and metallic contamination as a consequence)
- Optimisation of rotation, speed, and furnace atmosphere to improve purity

Growth method dependent purity of silicon crystals for ET (F. M. Kießling)

NeoGrowth Silicon

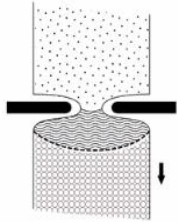
- Continuous growth method (similar to FZ), crucible-free
 - a resistive heater melts feed material that forms a small puddle on a large seed crystal, from which the ingot is grown
- Demonstrated 450 mm ingots, 15 cm height
- Low stress (< 5 MPa) to maintain low dislocations
 - Possibility to remove dislocations with a custom design and development of the melter and the seeding process



Low oxygen, high purity, proven crystal growth method for 450mm + silicon optics (N. Stoddard)

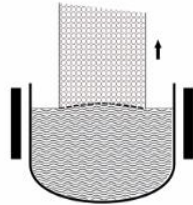
Self-Crucible Growth (IKZ)

Float-Zone (FZ)



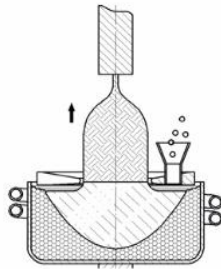
- Ultrahigh purity achievable (limited only feedstock purity)
- Diameter limitations beyond 200 mm

Czochralski (Cz)



- More Scalable diameter (up to 450 mm demonstrated)
- Contamination during growth (O, C from quartz crucible & graphite heaters)

Self-Crucible growth method



- No diameter limitations as in FZ
- No contamination due to a crucible or graphite heaters

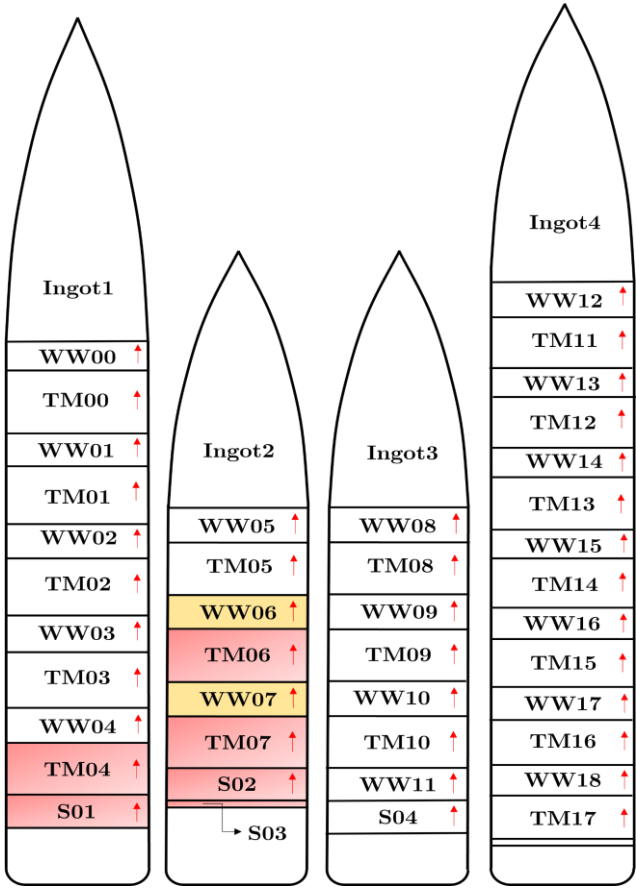
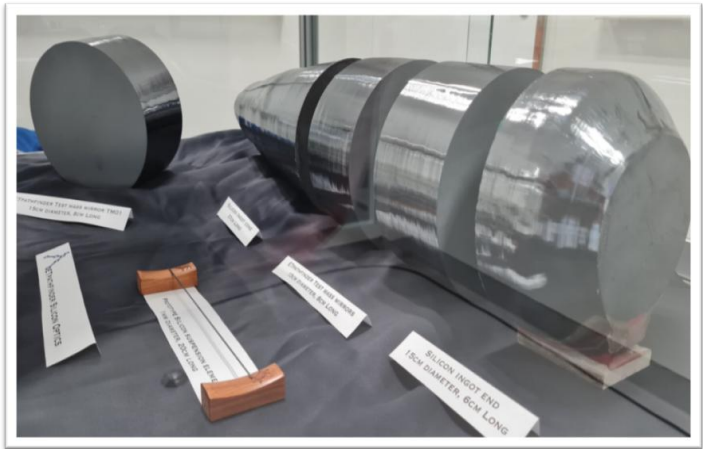
➡ Concept with potential to combine the advantages

- Melt sits in granular seed bed — avoids crucible contact
- Demonstrated 2" mono, 4" partly crystalline
- Oxygen at FZ level, carbon $\approx$ Cz level
- Potential for large-diameter growth with low stress

Towards high-purity, large-diameter silicon mirror substrates: A self-crucible growth concept (R. Menzel)

Mechanical properties FZ Si (ETPathfinder)

- ETpathfinder is a 10 m prototype for cryogenic interferometer
- IKZ produced 6” FZ silicon wafer from which the test masses for ETpathfinder mirrors (see next talk of S. Steinlechner) and a number of ‘witness wafers’ were cut
- In radial distribution study there is no significant difference in measured mechanical loss



<https://journals.aps.org/prd/abstract/10.1103/xzbl-3snb>

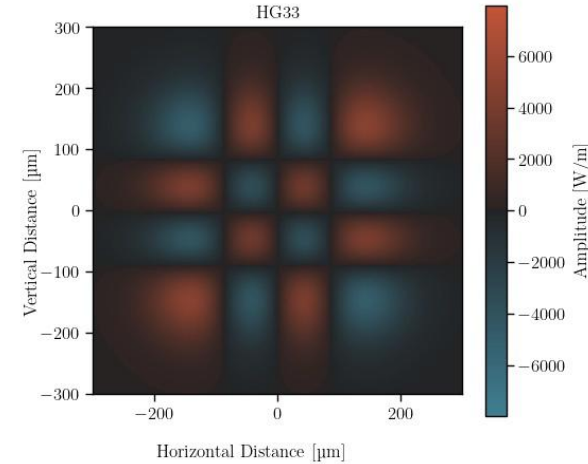
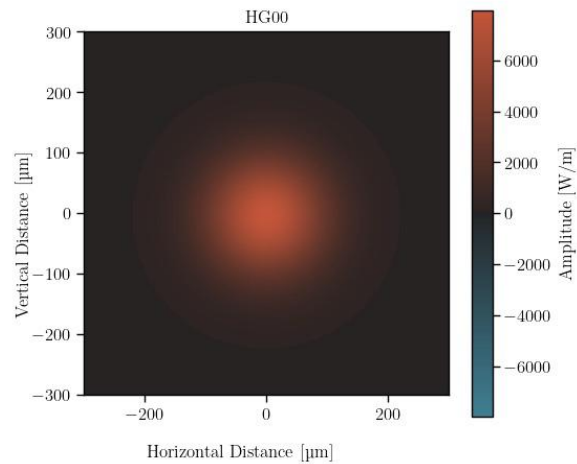
Mechanical characterization of silicon for the ETpathfinder test masses (G. A. Iandolo)

Composite Si optics (IKZ, DZA, Glasgow University)

- Bond multiple high-purity FZ pieces (20 cm or 30 cm) to have full-size mirror of around 210 kg mass
- FE models of stress, optical scatter, and thermal noise
- Bonding methods: hydroxide catalysis and direct bonding

Composite Si optics (Leuven)

- Bond lines → optical absorption and scattering
- Hermite–Gaussian HG_{33} mode avoids seams (intensity zeros)
 - Align the bonds exactly with the intensity pattern dark lines. This way, the laser light never illuminates the seams



- ET-OPT project (high power prototype dedicated to ET-HF research) building 10 m HG_{33} test interferometer

Surface absorption

- Surface absorption identified in polishing procedure
 - Not attributable to a native SiO or SiO₂ layer
 - Not within the first 100 nm of silicon
- Develop an etching procedure to systematically investigate at which depth surface absorption occurs
- Develop a polishing procedure which meets ET's strict surface quality requirements, while investigating possible surface absorption at every polishing step

Summary



- Multiple groups are working on these topics and involved in the development of new strategies and fabrication process
- More and more production facilities seem to get interested
- Several options to follow up