Crystalline silicon mirrors

Substrate and Coating Requirements

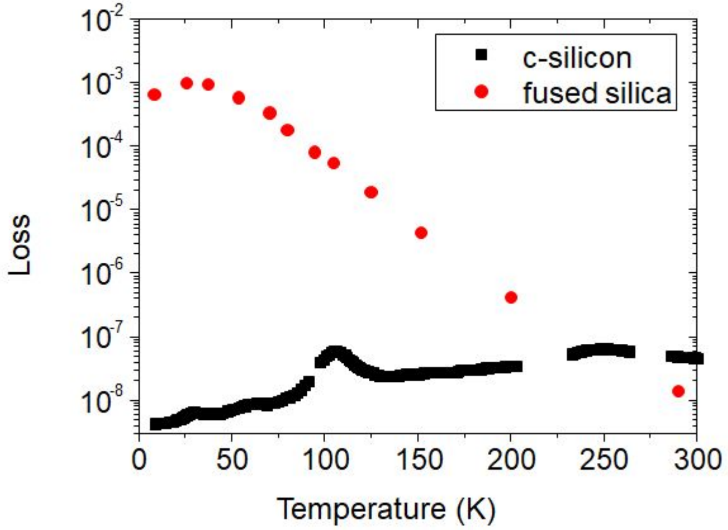
J. Steinlechner 28th Feb 2024

Silicon Substrates

- mass: ~ 200kg ⟶ motivated by IFO noise reduction
- diameter: 50cm ⟶ motivated by coating thermal noise reduction;
  - larger beam diameter reduces coating thermal noise;
  - even if we had extremely good coatings:
    minimum mirror diameter, due to laser beam
    propagation in long ET arms: 35 - 40 cm

⟶ Very large silicon blocks are required.

- requires very low mechanical loss (high Q-factor)
  - uncritical for monocrystalline material
- requires very low optical absorption
  at 1550nm/2000nm



data from Jena; published as 1/Q in [link]

Silicon: Absorption

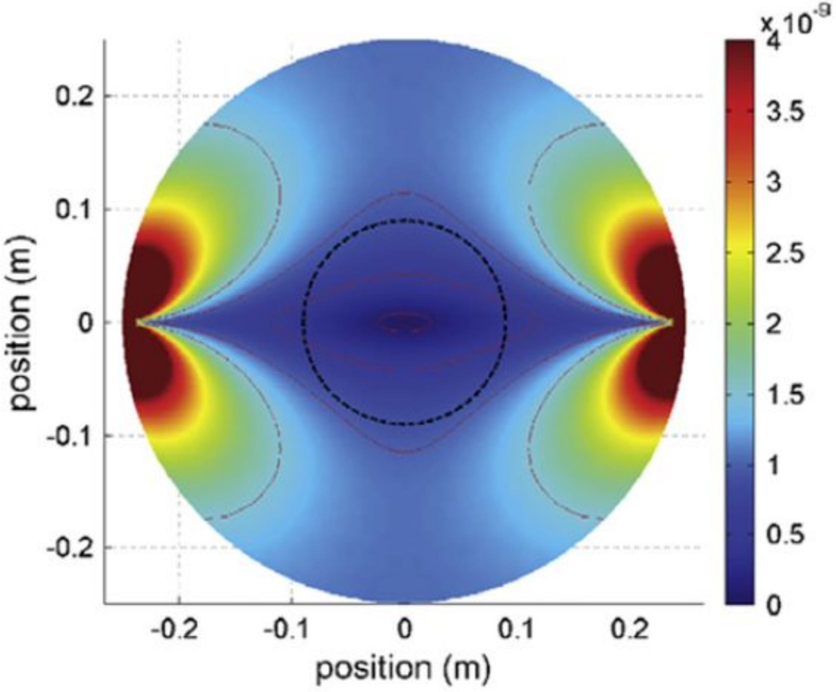
- Float zone silicon (undoped):
  - Very pure - optical absorption can be as low as few ppm/cm ✅
  - Drawback: maximum diameter ~20cm ❌
- Czochralski silicon:
  - Diameter up to 45cm (larger in principle possible) ✅
  - Significant impurities, absorption of several thousand ppm/cm or more ❌
- Magnetically purified Czochralski silicon:
  - Can have low absorption similar to float zone material ✅
  - Can in principle be produced with same diameter as standard Czochralski ?
  - Large substrates currently not available ❌
- Directional solidification
  - Very large diameter/mass available ✅
  - Significant impurities ❌

Absorption requirement: ’not as good as FZ, but much better than standard Czochralski’

Other considerations:
- Composite test masses?
- Different ITM/ETM material (at different mirror size)?

Silicon: Birefringence and other properties

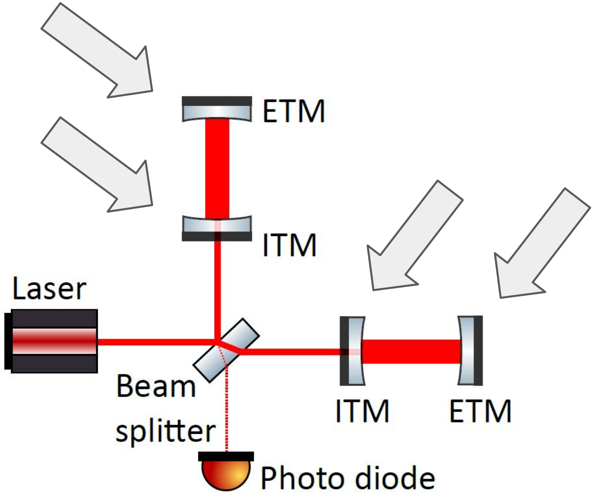
- growth, suspension and heat treatment (required for coating optimisation) lead to internal stresses such as birefringence
- heat treatment: activation of free carriers $\longrightarrow$ absorption increase
- surface absorption: can arise from polishing
- also important: thermal expansion coefficient, homogeneous refractive index, …

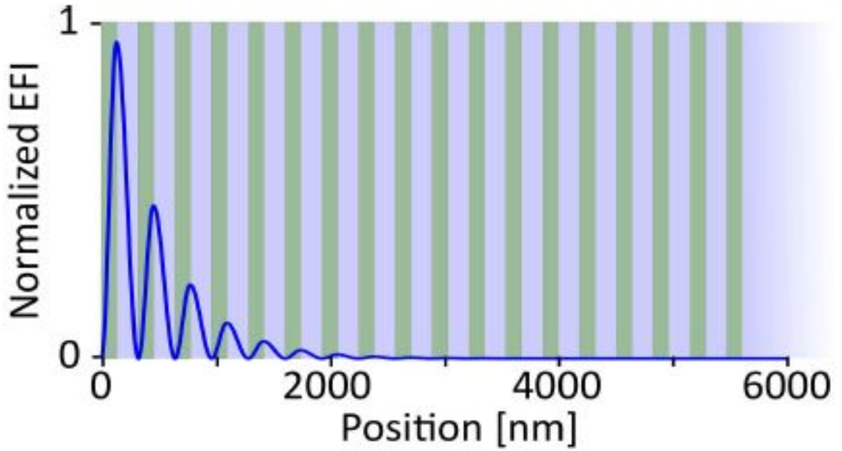


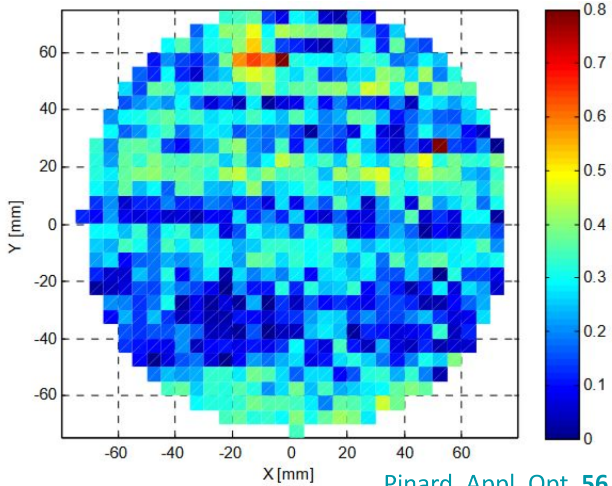
C. Krueger et al. [link]

Coatings

- high reflectivity (at 1550nm)
  - ETM → 99.9995%
  - ITM → 99.9%
- ~40 layers or more for ETMs (depending on refractive index contrast)
- total optical absorption of ~1ppm







Pinard, Appl. Opt. **56**, C11-C15, 2017

Coatings: Further requirements

material properties
[temperature dependent]

low mechanical loss/high Q factor (temperature dependent)

high refractive index contrast
→ thin coating for high reflectivity
(ETM: $R \approx 99.9995\%$, ITM: $R \approx 98$ - 99%)

low optical absorption (order of 1 ppm)

tolerates heat treatment required for low absorption and mech. loss

high laser damage threshold

very low scattering

low number of defects, point absorber etc.

homogeneous layer thickness

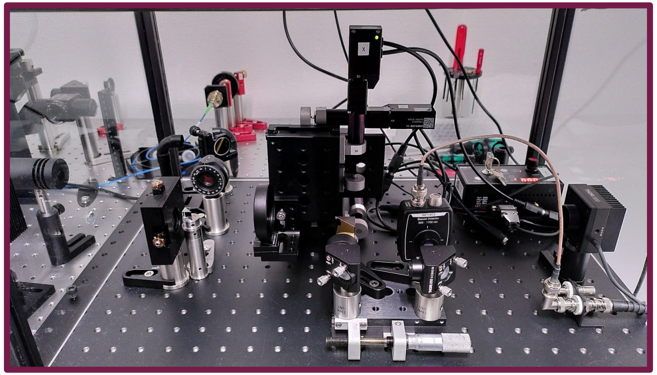
large diameters: ≈ 0.5 m

production technology

Coating Options and Materials

- Current coatings made of SiO_2/Ta_2O_5
  - mechanical loss increases at low temperatures planned for ET-LF
  - usually heat treated to ~500°C to minimize absorption and mechanical loss
- Of interest at 1550nm and low temperature:
  - a-Si - absorption reduction required
  - SiN - combination with a-Si being explored
  - SiO_2:HfO_2 - early development phase
  - TiO_2 - crystallizes easily during heat treatment
  - …
- Other coating concepts
  - monocrystalline multilayers (e.g. AlGaAs)
  - crystalline/amorphous hybrid coatings (e.g. crystalline toplayer)
  - dombination of more than two materials in a multilayer stack (Multimaterial coatings)
  - nanolayers (to suppress crystallisation)
  - ion implantation of reflective layers
  - …

What the ET Coatings Community can do



Measurements of:

- ➢ Optical absorption
  - ○ usually on fused silca substrates, 1” in diameter
- ➢ Mechanical loss
  - ○ Room temperature: usually on fused silica substrates, 2 or 3” in diameter, 1mm thick
  - ○ Cryogenics: silicon or sapphire samples, 2” in diameter, between 1 and 5mm thick
- ➢ Spectrophotometry: refractive index and thickness needed to analyse mechanical loss and absorption
- ➢ Various cycles of heat treatments

→ characterisation of samples can take weeks to months (depending on what we want to know/optimise)