Large optics for next generation gravitational wave detectors
The 3 ingredients of a mirror:
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My perfect mirror:

**Substrate**
- as big as I want
- no optical loss
- no mechanical loss
- heavy
- easy to polish
- ...

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**Polishing**
- perfect curvature
- no roughness
- arbitrary shape
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**Coating**
- as big as I want
- no optical loss
- no mechanical loss
- maintain the polishing quality
- ...

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- no mechanical loss
- heavy
- easy to polish
- ...

Polishing
- perfect curvature
- no roughness
- arbitrary shape
- ...

Coating
- as big as I want
- no optical loss
- no mechanical loss
- maintain the polishing quality
- ...

And all of that for a good price and with a quick delivery!
This morning session

I will not talk about coating thermal noise since it has some dedicated talks:

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<td>11:10</td>
<td>Large optics for next generation gravitational wave detectors</td>
<td>DEGALLAIX Jerome</td>
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<td>11:40</td>
<td>LISA optical metrology challenges</td>
<td>PENKERT Daniel</td>
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<td>12:00</td>
<td>The VIRGO coating collaboration: research lines and preliminary results of a detailed study on thermoelasticity in crystalline materials</td>
<td>CESARINI Elisabetta</td>
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<td>12:20</td>
<td>The VIRGO coating collaboration: a new deposition facility and preliminary results on nano-layered coatings</td>
<td>PRINCIPE Maria</td>
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More this afternoon also at 2:30
The substrate’s choice
The king: fused silica

THE test mass substrate for the room temperature first and second generations of gravitational wave detectors

A well justified choice:

- extremely good optical properties
  - bulk absorption < 1 ppm/cm @ 1064 nm
  - birefringence < 1 nm / cm
  - excellent homogeneity $\Delta n < 2 \times 10^{-6}$
  - 3D isotropic

- available in large size
- polishing and coating well mastered
Fused silica plate of 550 mm diameter (40 kg)
The king: fused silica

Some more properties particularly relevant to GW detectors:

- very low bulk thermal noise
- possibility of monolithic suspension

Reduction of the undesired displacement of the surface mirror due to thermal noise
Fused silica substrate for next generations

2 days ago, visit to Heraeus one of the main providers of very high purity fused silica.

What we learned:

- for 1D functional materials (IM, EM, PR,...):
  100kg or 200 kg, 600 mm diameter : no problem
  limit: handling tool, roof of the factory

- for 3D functional materials (BS):
  limited to 40 kg due to the homogenisation process
  will investigate how to go further, but no promise
We may need something else for low T

Crystalline materials have lower substrate mechanical loss at low temperature.

![Mechanical loss vs Temperature graph](image)
The cool outsider: sapphire

- crystalline material
- not available in large size for high purity (Ø 220 mm for Kagra)
- relatively high absorption (~ 20 ppm/cm at best)
- high thermal conductivity
- implemented in KAGRA with monolithic suspension (talk at 14:50)
For third generation detectors...

Longer arm length \(\rightarrow\) larger beam size
\(\rightarrow\) looking for larger substrates

- For room temperature: keep the fused silica
- For low temperature, we would like:
  - the size and optical properties of fused silica
  - the mechanical / thermal properties of sapphire

Is silicon the answer?
Transmission spectra

Not transparent at 1064 nm → new laser, likely 1550 nm

High refractive index, $n=3.45$ → uncoated: reflectivity of 30%
Absorption as a function of the doping (Troom)

- Absorption is due to the free carrier
- Free carrier concentration is equal to dopant concentration
- Absorption as low as 5 ppm/cm has been measured

![Graphs showing absorption as a function of free carrier concentration for p-doped and n-doped silicon at 1550 nm.](image-url)
Size and absorption

- Size and absorption are linked (due to the fabrication process)
- High purity Si achieved on smaller samples (Float Zone)
- Magnetic Czochralski crystal growth (MCz) may provide 450 mm diameter substrate with absorption as low as 5 ppm/cm

300 mm and 450 mm diameter wafer  
Temperature simulation during Si growth
Absorption vs temperature

With different dopant:
- Phosphorus
- Boron
- Gallium

Same magnitude of the optical absorption at cryogenic temperature! could be an issue if not pure material
The polishing
Second generation achievement

Outstanding polishing capabilities for fused silica!

Radius of curvature within 2 meters accuracy (over 1.5 km)

Low spatial frequency surface figure:

\[ \text{RMS} < 0.2 \text{ nm} \]

over 150 mm diameter

High spatial frequency figure:

\[ \text{RMS} < 0.1 \text{ nm} \]
Sapphire and silicon polishing

- **Sapphire:**
  - Used to be difficult
  - Possibility to achieve same performances as fused silica (more expensive)

- **Silicon:**
  - No major issue, large experience in the industry
  - RMS micro-roughness slightly higher than for FS
  - Silicon more brittle, easier to damage during cleaning / handling

~ 0.5 RMS over Ø 180 mm
Final words on polishing

- Personal thoughts:
  - Currently outstanding
  - Do not expect much better performances for third generation (we are already at the atomic scale)
  - Metrology is also critical at this level
  - The larger the mirrors, the larger the cost of polishing
The last step: the coating
All test masses of LIGO, Virgo and Kagra have been coated at LMA
What has been achieved: the coating

State of the art Ion Beam Sputtering (IBS) coating:

- possibility to coat large substrates (up to \( \varnothing \) 55 cm)
- low mechanical loss (HR coating \( \varphi \) \( \sim \) 2-3\( \times \)10\(^{-4}\))
- very low absorption (< 0.3 ppm @ 1064 nm)
- Low scattering, 4 ppm (on average over 20 mirrors)
- RMS of \( \sim \) 0.5 nm for HR ETM (coating thickness: 6 \( \mu m \))

Surface over 160 mm of the 6 \( \mu m \) HR coating (\( T = 3 \) ppm)
Challenges ahead!

- Worldwide research focuses on reducing the coating thermal noise:
  - different coating technologies / parameters
  - new amorphous materials (Nb, SiN, aSi)
  - new coating design (3 material stack)
  - crystalline coating
  - ... (not an exhaustive list)

- But we should also keep an eye on the optical performances (absorption, scattering) and the technology scaling for large mirrors
Research on the coating process at LMA

- Research on large coating size ($\Omega > 350$ mm):
  - coating one piece at a time
  - simple rotation
  - goal: coating uniformity 0.1% up to 550 mm
  - post deposition corrective coating

- Transmission matching will be crucial
  - in-situ optical monitoring improvement
  - post deposition corrective coating

Legend: 
- work in progress
Research on the coating process at LMA

- Ultra-low antireflective coating
  - state of the art \( R < 100 \) ppm @ 1064nm AOI 0°
  - goal: \( R < 50 \) ppm @ 1064 nm AOI 0°
  - and same performances for other wavelength and AOI
  - in-situ optical monitoring improvement

- Reduce the optical scattering
  - nature and origin of the defect?
  - 5 months internship has started
Conclusion

- Extremely satisfying optics for second generation have been achieved
- For next generation, substrates* and polishing will be suitable, everyone is looking at progresses on the coating front
- Heavier constraint on the metrology

* a large substrate for cryogenic detector has still to be demonstrated
Sources and credit

Title slide photos and pages 2-3
- left: https://upload.wikimedia.org/wikipedia/ru/7/72/Chohralsky_Silicon_Crystal_Growth.jpg
- middle: surface flatness EM01 AdV
- right: ©Cyril FRESILLON/LMA/CNRS Photothèque

Slide 11
- Picture taken at LMA during the cleaning of the Advanced Virgo beamsplitter

Slide 12
- Pic from the Virgo Collaboration
- From the Virgo logbook post 31956

Slide 14
- “Silicon and Sapphire - mechanical, thermal and optical properties” by R. Nawrodt, P8 (ET-0002A-15 )

Slide 15
- From Kagra logbook post 3613
- From Kagra logbook post 3073

Slide 17-18
- Measurement done at LMA
Sources and credit

Slides 19
- https://wccftech.com/foundries-tsmc-companies-shift-300mm-wafers/
- Simulations of silicon cz growth in a cusp magnetic field - C.-H. Lin et al.

Slide 20
- “Optical measurements at cryogenic temperatures” - J. Komma – GWADW 2013

Slide 22
- Data taken from the polishing reports for the Advanced Virgo arm cavity end mirrors

Slide 23
- “Development of a cryogenic mirror system for the KAGRA GW detector” E. Hirose 2014

Slide 26
- Le Grand Coated ©Cyril FRESILLON/LMA/CNRS Photothèque

Slide 27
- L. Pinard et al, Mirrors used in the LIGO interferometers for first detection of gravitational waves  Applied Optics Vol. 56, No. 4