Glasgow update: Thermal conductivity measurements of silicon and HCB and other relevant properties.

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The ears (to provide welding horns) are hydroxide catalysis bonded to the sides of the silica masses.

Silicon: Mechanical dissipation decreases with temperature, and linear coefficient of expansion goes to zero (and thus the thermoelastic thermal noise also goes to zero) at ~120K and ~20K.

(1) Rowan et al, Test mass materials for a new generation of gravitational wave detectors. 2003
Cryogenics

At cryogenic temperatures (below ~100K) the heat is extracted from the mirror and through the suspension fibres. This includes heat extracted through the connection points and therefore through the silicate bonds.
Thermal conductivity

\[ \kappa = \frac{P \Delta x}{A \Delta T} \]

- \( P \)  Power through the sample
- \( \Delta x \)  Separation between sensors measuring the temperature
- \( A \)  Cross sectional area of the sample
- \( \Delta T \)  Temperature difference between the sensors
Thermal conductivity of silicon

<table>
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<th>Sample specs</th>
<th>Measured curve</th>
<th>Curve 25 (Touloukian)</th>
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</thead>
<tbody>
<tr>
<td>O₂ cm³</td>
<td>5.15 × 10¹⁷</td>
<td>7 × 10¹⁷</td>
</tr>
<tr>
<td>R cm³</td>
<td>6 × 10¹⁵, 4.8 × 10¹⁵, &lt; 0.01%</td>
<td>7 × 10¹⁷, 4.8 × 10¹⁵</td>
</tr>
</tbody>
</table>

- 2.32 Ω cm
- 3 Ω cm
Silicon bonded samples

5 x 5 x 20 mm silicon (100) bonded samples

Single bond 10 bonds 3 bonds
Extracting the thermal conductivity of the bond

\[
\frac{L_{\text{total}}}{\kappa_{\text{total}} A_{\text{total}}} = \frac{L_{\text{bond}}}{\kappa_{\text{bond}} A_{\text{bond}}} + \frac{L_{\text{silicon}}}{\kappa_{\text{silicon}} A_{\text{silicon}}}
\]

\[
\kappa_{\text{bond}} = \frac{L_{\text{bond}}}{\frac{L_{\text{total}}}{\kappa_{\text{total}}} - \frac{L_{\text{silicon}}}{\kappa_{\text{silicon}}}}
\]
Thermal conductivity of HCB
40 samples where strength tested using a 4 point bend tester. 10 sets of the samples were tested at various curing times: 1 week, 2 weeks, 4 weeks and 26 weeks.
Strength testing over time

Breaking type
- Bond failure
- Bond break
- Diagonal break
- Oxide break

Weakest: 4.8 MPa.
Strongest: 61.1 MPa.

\[ y = 6.6e^{-0.01x} + 24.1 \]
\[ R^2 = 0.991 \]

Pressure profile simulates the probing laser beam proposed for ET-LF\textsuperscript{[3]}

\[ P = F_0 \frac{2}{\pi r^2} \exp\left(-2 \frac{x^2}{r^2}\right) \]

- \( P \) Gaussian pressure wave applied to the face of test mass.
- \( r \) Radius of beam (9 cm\textsuperscript{[3]}).
- \( x \) Distance from optical axis (orthogonal and central to the front face of test mass).
- \( F_0 \) Constant force.

\[3\] Einstein gravitational wave telescope conceptual design study
Thermal noise for an 3G-like suspension

Prokhorov measured TN of bonds between silicon substrates at ~120 K.

Haughian measured TN of bonds between sapphire substrates at ~20 K
3G-like suspension at 20 K

FEA simulation for cool down of suspension

Taking the ET-LF concept design, the heatsink temperature will be at 5 K and an operating temperature of ~20 K. A fixed temperature of 5 K is applied at the top end of each fiber whilst the rest of the suspension is at 300 K.

Two models were taken into account:
❖ Test mass cooled though conduction only (worst case scenario).
❖ Test mass cooled through conduction and radiation (surrounding at 5 K).
Cool-down rate for ET-LF silicon mirror suspension

- 3G-like final stage of suspension
  ~35.5 days to reach 20 K.
Conclusions

- Experimental measurements for the thermal conductivity of bonds between silicon substrates was conducted, showing a thermal conductivity at 20 K of 0.05 W/m/K.

- For an 3G-like configuration with a 15 K temperature difference between the mirror (20 K) and marionette (5 K) [3], the additional temperature difference associated with the silicate bond is 14.5 $\mu$K (assuming 1ppm absorption) or 262.2 $\mu$K (assuming 20ppm absorption).

- Also for 120K test mass configuration, the thermal resistance of the bonds are negligible compare to that of the suspension elements (Voyager-like configuration gives $\Delta T$ of 0.5mK across bonds).

- Based on the strength measurements presented, for the weakest value obtained (4.8 MPa), this would leave a safety margin of a factor of $\sim 5$, further validating the use of hydroxide catalysis bonding for the construction of future, quasi-monolithic, silicon mirror suspensions.

- An FEA simulation of the cool-down rate of an ET-LF mirror using a combination of conduction and radiation was calculated. It was found that a total of 35.5 days are required to reach the desired temperature.

- All details of the experimental measurements and simulations are described in my PhD thesis[5] (available online).

[3] Einstein gravitational wave telescope conceptual design study
[4] Silicate Bonding Procedure (Hydroxide-Catalysis Bonding) LIGO-E050228-v4