Measurement of the Intrinsic Losses in Various Kinds of Fused Silica

Kenji Numata, Hidehiko Ishimoto, Shigemi Otsuka, Kazuhiro Yamamoto, Keita Kawabe, Masaki Ando, Kimio Tsubono

University of Tokyo

Giuseppe Bertolotto Bianc

National Metrology Institute of Japan

The 2nd TAMA Symposium, Univ. of Tokyo

February 6, 2002
Abstract

Activity at Univ. of Tokyo

- Direct investigation of the intrinsic loss in bulk fused silica

Experimental Procedure

- Nodal support technique

Results

- Systematic comparison of mechanical losses
- High Q measured: \( Q_{Max} = 4.3 \times 10^7 \)
- Reduction of loss by annealing
- Information about sources of loss
Contents

1. Introduction

2. Procedure
   ● Principle of nodal support technique
   ● 13 kinds of fused silica samples

3. Results
   ● Qs of Heraeus, Corning, Tosoh and Shin-etsu silica
   ● Annealing in vacuum
   ● Frequency dependence of measured loss

4. Summary
1. Introduction

What should be investigated for mirror thermal noise

- If you want to estimate thermal noise at **mirror resonance**...

  Measure quality factor of **suspended mirror** in GW detector

  *Source of dissipation at resonance*: loss occurring at whole volume including loss due to suspension and attached mechanics

- If you want to estimate thermal noise in the **observation band**

  Measure intrinsic loss of **bulk mirror substrate** & coating

  *Source of dissipation in observation band*: loss occurring near beam spot
Our Approach

- Most likely choices for test masses
  - *Fused silica* (for room temperature)
  - Sapphire (for cryogenic temperature)

- Direct evaluation of intrinsic loss in fused silica
  *This is what we should have done.*
  - Use of reliable measurement system
  - Elimination of external losses that obscure intrinsic loss
  - Active development of new fused silica in the future
2. Procedure

- **Principle of experiment to measure intrinsic loss**
  Support at the nodes of the vibrational mode by point contacts

  *Elimination of external support loss*

- **Bulk cylindrical sample**
- **Higher order \((n>1)\) mode**

This work has also been submitted to Phys. Lett. A.
Photograph ñ Setup

- Nodal support system
  - 2-mm ruby balls
  - Simple system
  - High precision in machining
  - Vacuum
  - PZT for excitation
  - Interferometer for readout
- **Commercial products**

<table>
<thead>
<tr>
<th>Company</th>
<th>Trade name</th>
<th>Type</th>
<th>Bubble class</th>
<th>Striae grade</th>
<th>Direction of homogeneity</th>
<th>Homogeneity of refraction index ($10^{-6}$)</th>
<th>OH content (ppm)</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heraeus</td>
<td>Suprasil 1</td>
<td>III 0</td>
<td>A</td>
<td>3D</td>
<td>5</td>
<td>1000</td>
<td>GEO(NM,EM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suprasil 2</td>
<td>III 0</td>
<td>A</td>
<td>1D</td>
<td>5</td>
<td>1000</td>
<td>GEO(RM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suprasil 311</td>
<td>III 0</td>
<td>A</td>
<td>3D</td>
<td>3</td>
<td>200</td>
<td>VIRGO(BS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suprasil 312</td>
<td>III 0</td>
<td>A</td>
<td>1D</td>
<td>4</td>
<td>200</td>
<td>VIRGO(NM,RM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Herasil 1</td>
<td>II 0</td>
<td>A</td>
<td>1D</td>
<td>4</td>
<td>150</td>
<td>VIRGO(EM)</td>
<td></td>
</tr>
<tr>
<td>Corning</td>
<td>7980 0A</td>
<td>III 0</td>
<td>A</td>
<td>1D</td>
<td>1</td>
<td>800-1000</td>
<td>LIGO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7980 0F</td>
<td>III 0</td>
<td>A</td>
<td>1D</td>
<td>5</td>
<td>800-1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7980 5F</td>
<td>III 5</td>
<td>A</td>
<td>1D</td>
<td>5</td>
<td>800-1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tosoh</td>
<td>ES</td>
<td>III -</td>
<td>A</td>
<td>1D</td>
<td>-</td>
<td>1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ED-A</td>
<td>V -</td>
<td>A</td>
<td>3D</td>
<td>-</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ED-C</td>
<td>V -</td>
<td>A</td>
<td>3D</td>
<td>-</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shin-etsu</td>
<td>Suprasil P-10</td>
<td>III 0</td>
<td>A</td>
<td>3D</td>
<td>2</td>
<td>1200</td>
<td>TAMA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suprasil P-30</td>
<td>III 0</td>
<td>C-D</td>
<td>3D</td>
<td>20</td>
<td>1200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*VIRGO and GEO use custom made Suprasil called SV grade.

- Intrinsic Qs of 13 kinds of fused silica were measured.
- Each of them has different properties.
- 5 samples of them were annealed in vacuum.
Photograph ñ Sample

- **Measured sample**
  - Cylindrical samples*
  - Height : 6cm, Diameter : 7cm
  - Commercially polished by the same company
  - 50 resonances below 100kHz
  - 25 higher order modes
  - 45-deg. beveling

*We have also tried a block sample. Cylindrical shape is not a necessary condition for our support system.
3. Results

- Heraeus
- Corning
- Tosoh Quartz
- Shin-etsu Quartz Products
- Annealing in vacuum
- Comparison with each other
- Origin of measured frequency dependence
World highest Qs among bulk fused silica

- Suprasil-311, -312
  \[ Q_{\text{Max}} = 3.4 \times 10^7 \]

- Suprasil-1, -2
  \[ Q_{\text{Max}} \approx 1 \times 10^7 \]

- Herasil-1
  \[ Q_{\text{Max}} = 7.2 \times 10^5 \]

(Except for Herasil)

The Qs were observed to be lower at higher frequency.
Similar mechanical-losses in different grades

- 7980-0A*
- 7980-0F
- 7980-5F

✓ TYPE III, OH 800-1000ppm
✓ Same chemical contents
✓ Different homogeneity of refraction index and bubble class

\[ Q_{\text{Max}} \approx 1 \times 10^7 \]

Degraded with increase in frequency

*All of them are standard grade.
Different quality factors obtained

- **ED-A** (VAD*: OH 100ppm)
  \[ Q_{\text{Max}} = 1.9 \times 10^7 \]

- **ED-C** (VAD*: OH 1ppm)
  \[ Q_{\text{Max}} = 8.8 \times 10^6 \]

- **ES** (TYPE III: OH 1300ppm)
  \[ Q_{\text{Max}} = 4.6 \times 10^6 \]

---

Amount of OH is not a only factor that dominates intrinsic loss

*Vapor-phase Axial Deposition method*
Shin-etsu Quartz Products

- Lower quality factors observed than other samples

- Suprasil P-10
  - TYPE III, OH 1200ppm
  - $Q_{Avg} = 3.0 \times 10^6$

- Suprasil P-30
  - TYPE III, OH 1200ppm
  - Glass with most striae
  - $Q_{Avg} = 1.0 \times 10^6$

Qs of TYPE III silica ranged from $10^6$ to over $10^7$

(Diameter : 10cm, Height : 6cm)
Annealing System

- Vacuum electric furnace
- Furnace & vacuum system

Sample in the furnace

Temperature vs. Time graph
Increase in Qs observed in every annealed sample

- **7980-5F**
  - Before: $Q_{Before} = 1.0 \times 10^7$
  - After: $Q_{After} = 2.1 \times 10^7$

- **Suprasil-312**
  - Before: $Q_{Before} = 3.4 \times 10^7$
  - After: $Q_{After} = 4.3 \times 10^7$

Thermal treatment is important and promising.
### Intrinsic loss and optical properties

<table>
<thead>
<tr>
<th>Company</th>
<th>Trade name</th>
<th>Type</th>
<th>Bubble class</th>
<th>Striae grade</th>
<th>Direction of homogeneity</th>
<th>Homogeneity of refraction index (\times 10^{-6})</th>
<th>OH content (ppm)</th>
<th>Maximum Q (before anneal)</th>
<th>Maximum Q (after anneal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heraeus</td>
<td>Suprasil 1</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>3D</td>
<td>5</td>
<td>1000</td>
<td>1.1x10^7</td>
<td>2.1x10^7/3.3x10^7</td>
</tr>
<tr>
<td></td>
<td>Suprasil 2</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>1D</td>
<td>5</td>
<td>1000</td>
<td>1.3x10^7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suprasil 311</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>3D</td>
<td>3</td>
<td>200</td>
<td>3.4x10^7</td>
<td>4.1x10^7</td>
</tr>
<tr>
<td></td>
<td>Suprasil 312</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>1D</td>
<td>4</td>
<td>200</td>
<td>3.4x10^7</td>
<td>4.3x10^7</td>
</tr>
<tr>
<td></td>
<td>Herasil 1</td>
<td>II</td>
<td>0</td>
<td>A</td>
<td>1D</td>
<td>4</td>
<td>150</td>
<td>7.2x10^5</td>
<td>9.7x10^5</td>
</tr>
<tr>
<td>Corning</td>
<td>7980 0A</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>1D</td>
<td>1</td>
<td>800-1000</td>
<td>1.1x10^7</td>
<td>2.1x10^7</td>
</tr>
<tr>
<td></td>
<td>7980 0F</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>1D</td>
<td>5</td>
<td>800-1000</td>
<td>1.1x10^7</td>
<td>2.1x10^7</td>
</tr>
<tr>
<td></td>
<td>7980 5F</td>
<td>III</td>
<td>5</td>
<td>A</td>
<td>1D</td>
<td>5</td>
<td>800-1000</td>
<td>1.0x10^7</td>
<td>2.1x10^7</td>
</tr>
<tr>
<td>Tosoh</td>
<td>ES</td>
<td>III</td>
<td>-</td>
<td>A</td>
<td>1D</td>
<td>-</td>
<td>1300</td>
<td>4.6x10^6</td>
<td>8.8x10^6</td>
</tr>
<tr>
<td></td>
<td>ED-A</td>
<td>V</td>
<td>-</td>
<td>A</td>
<td>3D</td>
<td>-</td>
<td>100</td>
<td>1.9x10^7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ED-C</td>
<td>V</td>
<td>-</td>
<td>A</td>
<td>3D</td>
<td>-</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shin-etsu</td>
<td>Suprasil P-10</td>
<td>III</td>
<td>0</td>
<td>A</td>
<td>3D</td>
<td>2</td>
<td>1200</td>
<td>3.0x10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suprasil P-30</td>
<td>III</td>
<td>0</td>
<td>C-D</td>
<td>3D</td>
<td>20</td>
<td>1200</td>
<td>1.0x10^6</td>
<td></td>
</tr>
</tbody>
</table>

- Difference of TYPE (raw material, manufacturing process, etc.) is crucial.
- TYPE III tend to show higher Qs, if OH content is less.
- Bubble class, direction of homogeneity do not affect Qs.
- Homogeneity of refraction index doesn’t affect Qs.
- Qs could be degraded by the amount of striae.
Origin of Frequency Dependence

Several possibilities

- Loss due to support
  - We have measured $Q_s$ of $1 \times 10^8$ in silicon, $6 \times 10^7$ in sapphire.
  - No frequency dependence of support loss has been observed in lower order modes.

- Loss due to surface
  - This effect is strongly dependent on each modal shape, not on resonant frequency.
  - The polish for curved surface was good enough.

- Loss due to beveled edge
  - This effect is also dependent on each modal shape rather than the resonant frequency.
  - Beveled block gave the same results as the edge-rounded cylinder.

- Frequency-dependent material intrinsic loss
  - Possible, because no one has observed directly real intrinsic loss in material.
Origin of Frequency Dependence

Several possibilities

- Loss due to support
  - We have measured $Q_s$ of $1 \times 10^8$ in silicon, $6 \times 10^7$ in sapphire.
  - No frequency dependence of support loss has been observed in lower order modes.

- Loss due to surface
  - This effect is strongly dependent on each modal shape, not on resonant frequency.
  - The polish for curved surface was good enough.

- Loss due to beveled edge
  - This effect is also dependent on each modal shape rather than the resonant frequency.
  - Beveled block gave the same results as the edge-rounded cylinder.

- Frequency-dependent material intrinsic loss
  - Possible, because no one has observed directly real intrinsic loss in material.
Origin of Frequency Dependence

■ Several possibilities

● Loss due to support
  ✓ We have measured Qs of $1 \times 10^8$ in silicon, $6 \times 10^7$ in sapphire.
  ✓ No frequency dependence of support loss has been observed in lower order modes.

● Loss due to surface
  ✓ This effect is strongly dependent on each modal shape, not on resonant frequency.
  ✓ The polish for curved surface was good enough.

● Loss due to beveled edge
  ✓ This effect is also dependent on each modal shape rather than the resonant frequency.
  ✓ Beveled block gave the same results as the edge-rounded cylinder.

● Frequency-dependent material intrinsic loss
  ✓ Possible, because no one has observed directly real intrinsic loss in material.
Origin of Frequency Dependence

Several possibilities

- Loss due to support
  - We have measured Qs of $1 \times 10^8$ in silicon, $6 \times 10^7$ in sapphire.
  - No frequency dependence of support loss has been observed in lower order modes.

- Loss due to surface
  - This effect is strongly dependent on each modal shape, not on resonant frequency.
  - The polish for curved surface was good enough.

- Loss due to beveled edge
  - This effect is also dependent on each modal shape rather than the resonant frequency.
  - Beveled block gave the same results as the edge-rounded cylinder.

- Frequency-dependent material intrinsic loss
  - Possible, because no one has observed directly real intrinsic loss in material.
Frequency Dependent Intrinsic Loss?

- Comparison with the data from the other groups
  - No contradiction with the Qs measured at low frequency

  Is thermal noise no longer a problem?

- Further experiments
  - Measurement at lower & higher frequency

Suprasil-2
- Numata [Before annealing]
- Numata [After 900C annealing]
- Penn & Saulson (gr-qc/0009035)
- Gretarsson & Harry (RSI70(1999)4081)

Suprasil-311
- Numata [After 900C annealing]
4. Summary

■ Our approach
  ● Resultant Q does not matter for mirror thermal noise.
  ● Our prime concern should be an intrinsic loss in material.
  ● Fused silica is the most promising at room temperature.

■ Nodal support technique
  ● The best way to measure intrinsic loss by now
  ● Removal of support loss that has been a serious problem
  ● Reliable measurement based on a simple principle
  ● Measured Qs distributed on a straight line
Conclusion & Future Work

- Measurement of 13 kinds of bulk fused silica
  - First systematic comparison of various kinds of fused silica
  - Clear differences were observed in different grades.
  - Maximum Q reached $4.3 \times 10^7$ after vacuum annealing.
  - Knowledge about sources of loss was expanded.
  - Circumstantial evidences support freq-dependent intrinsic loss.

- Future work
  - Identification of sources of loss (use of spectroscopy etc.)
  - Thermal treatment, expansion of measurement band...
  - Active development of new fused silica
Loss due to Support - 2

Estimation using measured Qs in lower order mode

- Basic idea
  \[
  \frac{1}{Q_{\text{Support}}} \propto u_{\text{center}}^2 \varphi_{\text{eff}}
  \]

- Measured Qs in lower order modes
- Imperfection of support system etc.

Upgrade of support system is in preparation to confirm this.
Support loss should be negligible in our results on fused silica.
Loss due to Surface

Main effect of surface loss

- Standard model

\[ \frac{1}{Q_{\text{Measured}}} = \frac{E_{\text{Bulk}}}{E_{\text{Total}}} + \frac{E_{\text{Surface}}}{E_{\text{Total}}} \approx \varphi_{\text{Bulk}} + \varphi_{\text{Surface}} h \int \varepsilon^2 dS \int \varepsilon^2 dV \]

- Strongly dependent on each mode

Shin-etsu Suprasil P-30 with poorly polished lateral surface

\[ \text{Scattering around main trend} \]

Surface loss is not responsible for uniform decrease in Qs.
Loss due to Beveled Edge

- Removal of beveling
  - No significant change observed

Existence of edge is considered unimportant.
Block Sample

- Tosoh ED-A block sample

- Flat surfaces

- Sample on the system
Effect of Edge & Curved Surface

Comparison with block sample*

- Virtually no difference observed

Non-degenerate modes

28.6kHz 80.2kHz

Curved surface is not a limiting factor.

Tosoh ED-A

- Edge-rounded Cylinder -
  - n=0, even
  - n=0, odd
  - n=1, even
  - n=1, odd
  - n=2, even
  - n=2, odd
  - n=3, even
  - n=3, odd
  - n=4, even
  - n=4, odd
  - n=5, even
  - n=5, odd

- Edge-beveled Block -
  - Non-degenerate Mode
  - Longitudinal Mode
  - Degenerate Mode

*5cmx5cmx6cm