Lecture 8, Part 1: Vacuum-ultraviolet transparency of silica glass and its relation to processes involving mobile interstitial species - UV transparency of silica glass

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Jan. 10, 2008
Winter School on New Functionalities in Glass

Vacuum-ultraviolet transparency of silica glass and its relation to processes involving mobile interstitial species

Tokyo Metropolitan University
Koichi Kajihara
Overview

1. Introduction

2. Structure and optical properties of defects
   - Strained Si-O-Si bonds
   - Network modifiers (≡SiX)
   - Interstitial hydrogen molecules (H₂)

3. Improvement of UV-VUV transparency of silica glasses
   (a) Effects of structural disorder (strained Si-O-Si bonds) on VUV transparency
   (b) Removal of strained Si-O-Si bonds by doping with network modifiers
   (c) Role of mobile interstitial H₂ molecules

4. Silica glasses for UV-VUV spectral region
   - Silica glasses for excimer laser photolithography
   - Deep-UV optical fibers

5. Interstitial oxygen in silica glass
1. Introduction

Why silica glass?

- One of the simplest light metal amorphous oxides
- Large-size crystalline polymorph (α-quartz) is available
- Good mechanical properties and chemical stability
- High purity products are commercially available
- Various practical applications
  - Optical components
  - Gate dielectric films
  - Catalysts and catalyst supports
1. Introduction

Silica glass (amorphous SiO$_2$) – A promising UV optical material

1. Largest bandgap among glasses commercially available (absorption edge $\sim$8eV)
2. Good shape workability
3. Good physical and chemical properties

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Photon energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>3</td>
</tr>
<tr>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
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<tr>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td>170</td>
<td>7</td>
</tr>
<tr>
<td>150</td>
<td>8</td>
</tr>
<tr>
<td>140</td>
<td>9</td>
</tr>
</tbody>
</table>

- Hg i line
- XeCl
- KrF
- ArF
- F$_2$

Wavelength of various optical materials:

- VIS
- UV
- Deep-UV (DUV)
- Vacuum-UV (VUV)

- CaF$_2$
- Al$_2$O$_3$
- $\alpha$-quartz (c-SiO$_2$)
- SiO$_2$ glass

Mercury UV lamp

Glass plate

Luminescent glass
1. Introduction  Characteristic types of silica glasses [after Brückner(1998)]

Fused silica . . . Prepared from natural quartz

Good thermal stability; for crucibles and reactor chambers.

- Type I  Electric melting in crucibles. Contain metallic impurities (e.g. Al, Na), low ($<5$ppm) OH concentration.

- Type II  Crucible-free $\text{H}_2\text{-O}_2$ flame fusion. Concentrations of metallic impurities are lower than Type I. Medium ($\sim100$ppm) OH concentration.

From product catalog, Covalent Materials Co.
1. Introduction  Characteristic types of silica glasses [after Brückner(1998)]

**Synthetic silica** … Prepared by vapor-phase decomposition of silane compounds
High purity, various doping techniques; for optical components

- **Type III**  Directly deposited by $\text{H}_2\text{-O}_2$ hydrolysis.
  High ($\sim1,000\text{ ppm}$) OH concentration.

- **Type IIIa,b**  Prepared by “soot”-remelting.
  Suitable for dehydration and doping.

- **Type IV**  Prepared by $\text{O}_2\text{-Ar}$ plasma CVD method.
  Nealy OH-free but contains $\text{O}_2$ molecules.

There are various types of silica glasses!
1. Introduction

Effect of point defects (color centers)

- Different types of silica glasses
  - different optical properties . . . different concentrations of point defects
  - Control of point defects is important!


Absorption spectra

![](image1.png)

Induced absorption spectra

![](image2.png)
### 1. Introduction

Optical properties of silica glass is often influenced by **trace amounts of defects!**

<table>
<thead>
<tr>
<th>log[Conc.(cm(^{-3}))]</th>
<th>Defect concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>Lattice atom (O: 4.4×10(^{22})cm(^{-3}))</td>
</tr>
<tr>
<td>21</td>
<td>Solubility limit of fluorine (SiF) (several wt%)</td>
</tr>
<tr>
<td>20</td>
<td>SiOH in “wet” silica glass (∼1000wtppm, ∼10(^{20})cm(^{-3}))</td>
</tr>
<tr>
<td>19</td>
<td>H(_2) in H(_2)-loaded silica, chlorine (SiCl) in dry silica</td>
</tr>
<tr>
<td>18</td>
<td>SiOH in silica glass for KrF and ArF photolithography (10-100wtppm)</td>
</tr>
<tr>
<td>17-16</td>
<td>Detection limit by IR and Raman spectroscopy (bulk glasses)</td>
</tr>
<tr>
<td>17-15</td>
<td>Common radiation-induced defects</td>
</tr>
<tr>
<td>15-14</td>
<td>Detection limit by PL and EPR spectroscopy (bulk glasses)</td>
</tr>
<tr>
<td>13</td>
<td>Problematic defect concentration for DUV optical fibers</td>
</tr>
</tbody>
</table>
1. Introduction

- Excellent transparency from infrared to vacuum-ultraviolet
- “Blue shift” of the main research field

---

2. Structure and optical properties of defects

Ideal structure... Corner-shared SiO$_4$ tetrahedra, built only from Si-O bonds

- Chemical defects ... Local nonstoichiometry (vacancy, interstitial, dangling bonds, impurity atoms)
- Physical defects... Topological disorder (strained Si-O-Si bonds)

Normal bond

Oxygen deficiency–related defects

Dopant–related structures

Oxygen excess–related defects

Interstitial chemical species

- E' center
- Si–Si bond
- Divalent Si
- SiOH group
- SiF group

- Strained Si–O–Si bond
- Non–bridging oxygen hole center (NBOHC)
- Peroxy radical (POR)
- Peroxy linkage (POL)
- Molecular oxygen
- Atomic oxygen
- Ozone
- Atomic hydrogen
- Molecular hydrogen
2. Structure and optical properties of defects

Optical absorption bands

Improvement of transparency and radiation hardness . . . Control of point defects

VUV absorption edge

1. Fluoride group
2. Hydride group
3. Chloride group
4. Oxygen vacancy [SiODC(I)]
5. Hydroxyl group
6. Peroxy linkage [POL]
7. E' center
8. Peroxy radical [POR]
9. Divalent Si / Oxygen divacancy [SiODC(II)]
10. Ozone molecule
11. Chlorine molecule
12. Non-bridging oxygen hole center [NBOHC]
13. Oxygen molecule
14. Self-trapped hole [STH]

Peak absorption cross section (cm$^2$)

$<10^{-19}$  $10^{-19}$−$10^{-17}$  $>10^{-17}$

Verified  Tentative

After Skuja et al., Proc.SPIE 4347, 155(2001)
3a. Strained Si-O-Si bonds

A comparison among SiO₂ polymorphs

\( \alpha \)-quartz (ordered SiO₄ units)

Silica glass (disordered SiO₄ units)

- Larger bandgap than silica glass
- \( F_2 \) laser irradiation does not form persistent defects

<table>
<thead>
<tr>
<th>Materials</th>
<th>Band gap</th>
<th>Bandgap excitation causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amorphous silicon</td>
<td>( \sim 1.7\text{eV} )</td>
<td>Staebler-Wronski effect</td>
</tr>
<tr>
<td>Chalcogenide glasses</td>
<td>( \sim 2\text{eV} )</td>
<td>Photo darkening</td>
</tr>
<tr>
<td>Silica glass</td>
<td>( \sim 9\text{eV} )</td>
<td>?</td>
</tr>
</tbody>
</table>
3a. Strained Si-O-Si bonds

Physical disorder in silica glass

Short-range physical disorder...

**Distribution in Si-O-Si angle**

c.f. $\alpha$-quartz... No distribution in Si-O-Si and O-Si-O angles, Si-O length

*Calculated from a periodic silica structure reported in Mukhopadhyay et al., PRB70,195203 (2004)*
3a. Strained Si-O-Si bonds

Typical strained Si-O-Si bonds
... 3- and 4-membered rings


- Do not exist in α-quartz
- The concentration depends on thermal annealing (fictive) temperature

-Hosono et al., PRL 87, 175501 (2001)

  Modified based on discussion by Galeener in JNCS 49, 53 (1982)
3a. Strained Si-O-Si bonds

- \(<10 \text{mJ cm}^{-2}\) ... One-photon processes

\[
\equiv \text{Si-O-Si} \xrightarrow{h \nu (7.9 \text{eV})} \equiv \text{Si}^\bullet (E' \text{ center}) + \cdot \text{O-Si} \equiv \text{(NBOHC)}
\]

- \(>10 \text{mJ cm}^{-2}\) ... Two-photon processes (Yield \(\cdots F_2 \gg \text{KrF, ArF}\))

Strained Si-O-Si bonds ... Real intermediate states for defect formation via two-step absorption processes

Hosono et al., PRL87,175501(2001)

Kajihara et al., APL81,3164(2002)

![Graphs showing absorption coefficient and defect concentration vs. power and number of pulses]
3a. Strained Si-O-Si bonds

Elimination of strained Si-O-Si bonds

- Low temperature heating ("physical" annealing) ... time consuming
- Breaking up glass network by network modifiers (SiF, SiCl, SiOH, SiH) ("chemical" annealing)... structural relaxation by lowered viscosity

Hosono and Ikuta, NIMB166, 691(2000)
3b. Network modifiers

Types and the VUV absorption bands

<table>
<thead>
<tr>
<th>Absorption band</th>
<th>SiOH</th>
<th>SiH</th>
<th>SiF</th>
<th>SiCl</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gtrsim 7.4 \text{ eV}$</td>
<td>Not known ($\gtrsim E_g$)</td>
<td>Not known ($\gtrsim E_g$)</td>
<td>$\gtrsim 7 \text{ eV}$</td>
</tr>
</tbody>
</table>

Kajihara et al. PRB72,214112(2005)

Awazu et al. JAP69,1849(1991)
3b. Network modifiers

- Increase in SiF concentration
  - Improve VUV transparency
  - Decrease defect concentration
- Most effective at <1% SiF doping (Effects do not proportionally with SiF concentration)

Structural relaxation by SiF doping

Hosono and Ikuta, NIMB166, 691(2000)

<table>
<thead>
<tr>
<th></th>
<th>VUV OA</th>
<th>Photolysis</th>
<th>Cost</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiF</td>
<td>F-doped</td>
<td>No</td>
<td>No</td>
<td>High</td>
</tr>
<tr>
<td>SiOH  (Wet)</td>
<td>≥7.4eV</td>
<td>SiO⁺ + H⁰</td>
<td>Low-Med.</td>
<td>UV-DUV laser optics</td>
</tr>
<tr>
<td>SiCl  (Dry)</td>
<td>≥7.7eV</td>
<td>Si⁺ + Cl⁰</td>
<td>Med</td>
<td>IR optical telecom</td>
</tr>
<tr>
<td>SiH</td>
<td>No?</td>
<td>Si⁺ + H⁰?</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Absorption edge (nm) vs. Si-F concentration (mol%)
3c. Interstitial H₂ molecules

Silica glass
- Low density as compared with crystalline SiO₂, Al₂O₃... large free volume
- Easy diffusion and reaction of small chemical species
- Neutral interstitial species

- Hydrogen-related... H⁰, H₂
- Oxygen-related ... O⁰, O₂

<table>
<thead>
<tr>
<th></th>
<th>Density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica glass</td>
<td>2.21</td>
</tr>
<tr>
<td>Tridymite</td>
<td>2.33</td>
</tr>
<tr>
<td>Cristobalite</td>
<td>2.33</td>
</tr>
<tr>
<td>α-quartz</td>
<td>2.65</td>
</tr>
<tr>
<td>Soda-lime silicate</td>
<td>2.47</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>3.97</td>
</tr>
</tbody>
</table>
3c. Interstitial $\text{H}_2$ molecules

$\text{H}_2$ in silica glass... fast diffusion ($\text{He} > \text{H}_2 > \text{Ne} \gg \text{Ar, H}_2\text{O}$), high reactivity
- Hydrogen corrosion in telecom fibers ($\equiv\text{Si-O-Si}\equiv + \text{H}_2 \rightarrow \equiv\text{SiOH} + \equiv\text{SiH}$)
- Sensitization of photoencoding of Bragg gratings
- Termination of dangling bonds ($\text{R}^* + \text{H}_2 \rightarrow \text{RH} + \text{H}^0$)
- Improvement of KrF and ArF laser hardness

![Graphs showing optical loss and transmittance](image-url)
3c. Interstitial H\textsubscript{2} molecules

In-situ study of diffusion and reactions

F\textsubscript{2}-laser-irradiated “wet” silica glass

\[
\text{F}_2 \text{ laser (7.9eV)} \quad \equiv \text{SiO-H} \rightarrow \equiv \text{SiO}^* + H^0 \quad \text{(quantum yield } \sim 0.1-0.2 \text{)}
\]

\[
\text{Nd:YAG 4HG (4.7eV)} \quad \equiv \text{SiO}^* \rightarrow \equiv \text{SiO}^*(1.9eV PL)
\]

- Concentration of radiation-induced NBOHC (\equiv \text{SiO}^*) \ldots \text{insensitive to H}_2 \text{ loading}
- NBOHC does not accumulate in H\textsubscript{2}-loaded glass

Kajihara et al., APL79,1575(2001); NIMB33,323(2004); PRB74,094202(2006)
3c. Interstitial H\textsubscript{2} molecules

Various effects of interstitial H\textsubscript{2}

1. Termination of dangling bonds [≡Si\textbullet\textsuperscript{•}(5.8eV), ≡SiO\textbullet\textsuperscript{•}(4.8eV, 6.8eV)]

2. Acceleration of oxygen vacancy formation [≡Si-Si≡ (7.6eV)]
   ...Photoreduction (≡Si-O*-Si≡ + H\textsubscript{2} → ≡Si-Si≡ + H\textsubscript{2}O)

3. Crack formation ...Stress corrosion (≡Si-O-Si≡ + H\textsubscript{2}O → 2≡SiOH)

\textit{H\textsubscript{2} conc. should be strictly optimized}

Ikuta et al., APL80,3916(2002); Appl.Opt.43,2332(2004)

Termination of dangling bonds

\begin{center}
\begin{tikzpicture}
\node at (0,0) {Si};
\node[red] at (1,0) {O};
\node at (2,0) {Si};
\node[green] at (3,0) {H};
\node at (4,0) {O};
\node at (5,0) {Si};
\node[blue] at (6,0) {H};
\node at (7,0) {Si};
\draw[->, green] (2,0) -- (3,0);
\draw[->, green] (4,0) -- (5,0);
\end{tikzpicture}
\end{center}

\begin{center}
\textbf{Photon energy (eV)}
\begin{tabular}{cccc}
3 & 4 & 5 & 6 & 7 & 8 \\
0 & 0.05 & 0.1 & 0.15 & 0 & 0.15 \\
\end{tabular}
\end{center}

\begin{center}
\begin{tabular}{cccc}
\textbf{Photon energy (eV)} & \textbf{ΔAbsorption coefficient (cm\textsuperscript{-1})} \\
\hline
3 & 4 & 5 & 6 & 7 & 8 \\
0 & 0.05 & 0.1 & 0.15 & 0 & 0.15 \\
\end{tabular}
\end{center}

(a) ArF, OH-doped, H\textsubscript{2}-free
\begin{itemize}
\item H\textsubscript{2}-im (193nm)
\end{itemize}

(b) F\textsubscript{2}, OH-free, H\textsubscript{2}-free
\begin{itemize}
\item H\textsubscript{2}-im (157nm)
\end{itemize}

\textbf{Termination of dangling bonds}

\textbf{Photo-reduction of Si–O–Si bond}
4. Silica glasses for UV-VUV spectral region

<table>
<thead>
<tr>
<th>Type</th>
<th>Defect species</th>
<th>Conventional applications</th>
<th>7.9eV Transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>SiOH</td>
<td>UV optics</td>
<td>Poor (OA by SiOH)</td>
</tr>
<tr>
<td>Dry</td>
<td>SiCl, Si-Si</td>
<td>IR telecom. fibers</td>
<td>Poor (OA by Si-Si)</td>
</tr>
<tr>
<td>F-doped</td>
<td>SiF</td>
<td>X- and $\gamma$-resistant fibers</td>
<td><strong>Good</strong></td>
</tr>
</tbody>
</table>

Fluorine-doped silica . . . Suitable for photomask substrates in F₂ laser photolithography

Hosono et al. APL74,2755(1999), Mizuguchi et al. JVSTB17,3280(1999)
4. Silica glasses for UV-VUV spectral region

Conventional fibers (Ge-doped core and pure-silica cladding)
- Not transparent for UV light
- High viscosity – drawing-induced defects
- High radiation sensitivity

1. F-doped core and cladding
2. Defect annihilation by $H_2$ impregnation

4. Silica glasses for UV-VUV spectral region

- End sharpening by chemical etching in hydrofluoric acid
  ... Possible application to scanning nearfield optical microscopy (SNOM)

HF etching

Core: SiF 200ppm
Clad: SiF 10,000ppm
Δn = 0.7%
5. Interstitial oxygen in silica glass

- Oxygen-deficiency related defects...Si-Si, ≡Si•, –Si–, ...
  - Main color centers in DUV fibers
- Oxygen-excess related defects...≡SiOO•, O₂, Si-O-O-Si, ...
  - May be used to oxidize oxygen-deficiency related color centers
  - Chemical and optical properties remain largely unclear
5. Interstitial oxygen in silica glass

Interstitial O$_2$... The most common form of excess oxygen in silica glass

- Nassau and Shiever (1975) Preparation of low-OH $a$-SiO$_2$ by plasma-CVD method
- Heitmann et al. (1983) Sharp loss bands of unknown origin in telecom fibers by PCVD
- Carvalho et al. (1985) Identification of interstitial O$_2$ by Raman spectroscopy
- Awazu et al. (1990) Observation of VUV absorption band of interstitial O$_2$
5. Interstitial oxygen in silica glass  
Detection by photoluminescence

- Shikama et al. (1994)  Discovery of 1270nm PL band in optical fiber in an nuclear reactor
- Skuja et al. (1996)  PL detection of interstitial O\textsubscript{2} via 1064nm excitation
- Skuja et al. (1998)  PL detection of interstitial O\textsubscript{2} via 765nm excitation

Sensitive, selective, and non-destructive detection of interstitial O\textsubscript{2} in $\alpha$-SiO\textsubscript{2}

![Graph showing optical radiation intensity vs. wavelength](image)

**O\textsubscript{2} energy level**

- $b^1\Sigma_g^+$
- $a^1\Delta_g$
- $X^3\Sigma_g^-$

**O\textsubscript{2} 2p\pi^***

- 765nm (Ti:Al\textsubscript{2}O\textsubscript{3})
- 1064nm (Nd:YAG)
- 1272nm

Cherenkov radiation
5. Interstitial oxygen in silica glass

- O₂ PL measurements of silica glasses thermally annealed in air

  ... Solubility and diffusion coefficient of interstitial O₂ in silica glass


Oxidant in the thermal oxidation of silicon is interstitial O₂
5. Interstitial oxygen in silica glass

- Thermal desorption spectroscopy

\[ 8.3 \times 10^{16} \text{ molecules} \sim 22\% \text{ decrease of PL intensity} \]

\[ \text{O}_2 \text{ concentration} \sim 2.7 \times 10^{16} \text{ cm}^{-3} \]

\[ \Delta A_{\text{PL peak}} / A_{\text{Raman@1200 cm}^{-1}} \]

Kajihara et al. JNCS, in press
5. Interstitial oxygen in silica glass

- Simultaneous measurement of VUV absorption and O\textsubscript{2} concentration changes
  1. **Red-shift** of VUV absorption edge
  2. **Increase** in absorption intensity

  Weak attractive interaction between O\textsubscript{2} and \textit{a}-SiO\textsubscript{2} framework

Kajihara et al. JAP98, 013527 (2005)

![Graph showing absorption coefficient and photon energy relationship](image1)

![Graph showing log(Absorption cross section) vs. Photon energy relationship](image2)
5. Interstitial oxygen in silica glass

- Reaction of $\alpha$-SiO$_2$ with H$_2$ . . . Cracking of Si-O bond
  \[ \equiv \text{Si-O-Si} \equiv + \text{H}_2 \rightarrow \equiv \text{SiOH} + \text{HSi} \equiv \]

- Shelby (1980) SiOH creation with little accompanying SiH formation in O$_2$-rich $\alpha$-SiO$_2$
  Two-step reactions
  1. \[ \frac{1}{2}\text{O}_2 + \text{H}_2 \rightarrow \text{H}_2\text{O} \]
  2. \[ \equiv \text{Si-O-Si} \equiv + \text{H}_2\text{O} \rightarrow \equiv \text{SiOH} \]

Shelby, JAP51,2589(1980)

Kajihara, JAP98,043515(2005)

![Graph showing absorption coefficient (cm$^{-1}$) and normalized emission intensity](image)
5. Interstitial oxygen in silica glass

Reactions (2)

- Reaction with Si-Si bonds: $\equiv\text{Si-Si}{}\equiv + \frac{1}{2}\text{O}_2 \rightarrow \equiv\text{Si-O-Si}{}\equiv$
- Reaction with $E'$ center: $\equiv\text{Si}^\cdot + \text{O}_2 \rightarrow \equiv\text{SiOO}^\cdot$
- Reaction with SiCl: $\frac{1}{2}\text{O}_2 + 2\equiv\text{SiCl} \rightarrow \equiv\text{Si-O-Si}{}\equiv + \text{Cl}_2$
- Reaction with $H^0$: $\text{O}_2 + H^0 \rightarrow \text{HO}_2^\cdot$

Pfeffer (1998)

Kajihara, JAP98,043515(2005)
5. Interstitial oxygen in silica glass

Configuration... Peroxy linkage form

e.g. Hamann, PRL81,3447(1998)
Szymanski et al. PRB63,224207(2001)

Formation

1. Radiolytic decomposition of Si-O-Si bonds
\[ \equiv \text{Si}-\text{O}-\text{Si} \xrightarrow{h\nu} \equiv \text{Si}-\text{Si} + O^0 \text{ (or } 1/2O_2) \]

2. VUV photolysis of interstitial O$_2$
\[ O_2 \xrightarrow{h\nu} 2O^0 \]

3. UV photolysis of peroxy radical
\[ \equiv \text{SiOO} \xrightarrow{h\nu} \equiv \text{SiO}^* + O^0 \]

- Anion part of the Frenkel pair
- Low-temperature oxidant of silicon
e.g. Ishikawa et al. JJAP31,1148(1992)
5. Interstitial oxygen in silica glass  

Optical absorption and diffusivity

\[
\text{O}_2 \overset{\text{Heat}}{\leftrightarrow} \text{2} \text{O}^0
\]

- Optical absorption... Use \(O^0\)-rich sample prepared by \(F_2\) laser irradiation
- Diffusivity ... Probe \(O_2\) generated by recombination of \(O^0\)

Skuja et al. NIMB191,127(2002)

5. Interstitial oxygen in silica glass

\[ \equiv \text{SiOO}^\bullet \xrightleftharpoons{h\nu(\sim 5\text{eV})} \text{Heat} \equiv \text{SiO}^\bullet + \text{O}^0 \]

Kajihara et al. PRL92,015504(2004)

5. Interstitial oxygen in silica glass Absorption cross section “map”

log[Absorption cross section (cm$^2$)]

Photon energy (eV)

-20 -19 -18 -17 -16 -15

E’ center
NBOHC
Si-Si
SiOH
O$_2$
H$_2$O
Si-O-O-Si

3 4 5 6 7 8
Summary

1. Optical isotropy
   - Process engineering
     - Raw material
     - Production method
     - Fiber drawing
   - Optical spectroscopy
     - EPR
     - Simulation
   - Deep-UV optics
     - Photomasks
     - Hard pellicles
     - Lenses
   - Optical fibers
     - DUV fibers
     - Bragg grating devices
     - Fiber lasers
2. Wide-gap α-quartz
   - Network topology
   - Stoichiometry
   - Doping (H, F, P, RE, ...)
3. Workability
   - Structural modification
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- Dr. Yoshiaki Ikuta (Asahi Glass Company Co. Ltd.)
- Dr. Masanori Oto (Showa Device Technology Co. Ltd.)