Lecture 8, Part 2: Vacuum-ultraviolet transparency of silica glass and its relation to processes involving mobile interstitial species, continued

Koichi Kajihara

Tokyo Metropolitan University, Japan

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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 ($\alpha$-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 SiO₂) – A promising UV optical material

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

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

- VIS
- UV
- deep–UV (DUV)
- vacuum–UV (VUV)

O₂ Schumann–Runge band

Mercury UV lamp

Glass plate

Luminescent glass

Window glass

SiO₂ glass

CaF₂

Al₂O₃

α–quartz (c–SiO₂)
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 (<5ppm) OH concentration.
- **Type II** Crucible-free $\text{H}_2\text{-O}_2$ flame fusion. Concentrations of metallic impurities are lower than Type I. Medium (~100ppm) 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 H₂-O₂ hydrolysis.
  High (∼1,000 ppm) OH concentration.
- **Type IIIa,b**  Prepared by “soot”-remelting.
  Suitable for dehydration and doping.
- **Type IV**  Prepared by O₂-Ar plasma CVD method.
  Nealy OH-free but contains O₂ 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

Induced absorption spectra
## 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: $4.4 \times 10^{22}$ 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 ($\sim 1000$wtppm, $\sim 10^{20}$ cm$^{-3}$)</td>
</tr>
<tr>
<td></td>
<td>Detection limit by X-ray fluorescence spectroscopy</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></td>
<td>Metallic impurities (e.g. Al) in fused silica</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></td>
<td>SiOH in optical telecom fibers</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)
2. Structure and optical properties of defects

Optical absorption bands

Improvement of transparency and radiation hardness...

Control of point defects

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

A comparison among SiO$_2$ polymorphs

**α-quartz** (ordered SiO$_4$ units)  

Silica glass (disordered SiO$_4$ 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$1.7eV</td>
<td>Staebler-Wronski effect</td>
</tr>
<tr>
<td>Chalcogenide glasses</td>
<td>$\sim$2eV</td>
<td>Photo darkening</td>
</tr>
<tr>
<td>Silica glass</td>
<td>$\sim$9eV</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. α-quartz... No distribution in Si-O-Si and O-Si-O angles, Si-O length

Si-O-Si angle

O-Si-O angle

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 $\alpha$-quartz
- The concentration depends on thermal annealing (fictive) temperature

Modified based on discussion by Galeener in JNCS 49, 53 (1982)

Hosono et al., PRL 87, 175501 (2001)
3a. Strained Si-O-Si bonds

- $<10\text{mJ cm}^{-2}$ ... One-photon processes
  \[ \equiv \text{Si-O-Si} \equiv h\nu(7.9\text{eV}) \rightarrow \equiv \text{Si}^* (E' \text{ center}) + \cdot \text{O-Si} \equiv \text{(NBOHC)} \]

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

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)
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>Hydrogen-related species</th>
<th>Hydrogen-related species</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiOH group</td>
<td>SiH group</td>
</tr>
<tr>
<td>SiF group</td>
<td>SiCl group</td>
</tr>
</tbody>
</table>

Kajihara et al. PRB72,214112(2005)

Absorption cross section, $\sigma (10^{-18} \text{cm}^2)$

- SiOH $\gtrsim 7.4 \text{eV}$
- SiH Not known ($\gtrsim E_g$)
- SiF Not known ($\gtrsim E_g$)
- SiCl $\gtrsim 7 \text{eV}$

Awazu et al. JAP69,1849(1991)

Absorption coefficient (cm$^{-1}$)

- Sintered in He
- Treated in CCl$_4$, Sintered in He
- Treated in Cl$_2$/He=5/10
- Treated in Cl$_2$/He=1/10

**Graphs:**

- Photon energy vs. log Absorption cross section
- Photon energy vs. log Absorption coefficient

**Notes:**

- Sintered in He
- Treated in CCl$_4$, Sintered in He
- Treated in Cl$_2$/He=5/10
- Treated in Cl$_2$/He=1/10

Morimoto et al. (1999)
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 (F-doped)</td>
<td>No</td>
<td>No</td>
<td>High</td>
<td>Excimer laser lithography, DUV fiber</td>
</tr>
<tr>
<td>SiOH (Wet)</td>
<td>≥7.4eV</td>
<td>SiO$^*$ + H$^0$</td>
<td>Low-Med.</td>
<td>UV-DUV laser optics</td>
</tr>
<tr>
<td>SiCl (Dry)</td>
<td>≥7.7eV</td>
<td>Si$^*$ + Cl$^0$</td>
<td>Med</td>
<td>IR optical telecom</td>
</tr>
<tr>
<td>SiH</td>
<td>No?</td>
<td>Si$^*$ + H$^0$?</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
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 H₂ molecules

H₂ in silica glass... fast diffusion (He > H₂ > Ne >> Ar, H₂O), high reactivity
- Hydrogen corrosion in telecom fibers (≡Si-O-Si≡ + H₂ → ≡SiOH + ≡SiH)
- Sensitization of photoencoding of Bragg gratings
- Termination of dangling bonds (R⁺ + H₂ → RH + H⁰)
- Improvement of KrF and ArF laser hardness

![Graphs showing optical loss and transmittance](image-url)
3c. Interstitial $\text{H}_2$ molecules

In-situ study of diffusion and reactions

$\text{F}_2$-laser-irradiated “wet” silica glass

- $\text{F}_2$ laser (7.9eV)  
  $\equiv\text{SiO-H} \rightarrow \equiv\text{SiO}^\bullet + \text{H}^0$ (quantum yield $\sim0.1-0.2$)
- Nd:YAG 4HG (4.7eV)  
  $\equiv\text{SiO}^\bullet \rightarrow \equiv\text{SiO}^\bullet$(1.9eV PL)

- Concentration of radiation-induced NBOHC($\equiv\text{SiO}^\bullet$) ... insensitive to $\text{H}_2$ loading
- NBOHC does not accumulate in $\text{H}_2$-loaded glass

Kajihara et al., APL79,1575(2001); NIMB33,323(2004); PRB74,094202(2006)
3c. Interstitial $\text{H}_2$ molecules

Various effects of interstitial $\text{H}_2$

1. Termination of dangling bonds [$\equiv \text{Si}^\bullet (5.8\text{eV}), \equiv \text{SiO}^\bullet (4.8\text{eV}, 6.8\text{eV})$]

2. Acceleration of oxygen vacancy formation [\$\equiv \text{Si-Si} \equiv (7.6\text{eV})\$]

   ... **Photoreduction** ($\equiv \text{Si-O}^\bullet - \text{Si} \equiv + \text{H}_2 \rightarrow \equiv \text{Si-Si} \equiv + \text{H}_2\text{O}$)

3. Crack formation ... **Stress corrosion** ($\equiv \text{Si-O-Si} \equiv + \text{H}_2\text{O} \rightarrow 2\equiv \text{SiOH}$)

$\text{H}_2$ conc. should be strictly optimized

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

Termination of dangling bonds

Photo-reduction of Si–O–Si bond

$\text{Si} \text{O} \text{Si} + \text{H}_2 \rightarrow \text{Si} \text{H} \text{Si}$

$\text{Si} \text{O} \text{Si} + \text{H}_2 \rightarrow \text{Si} \text{Si} \text{H} \text{Si}$

$\text{Si} \text{O} \text{Si} + \text{H}_2 \rightarrow \text{Si} \text{Si} \text{Si} \text{O} \text{H}$

$\text{Si} \text{O} \text{Si} + \text{H}_2 \rightarrow \text{Si} \text{Si} \text{Si} \text{Si} \text{O} \text{H}$

$\Delta$Absorption coefficient ($\text{cm}^{-1}$)

Photon energy (eV)

(a) $\text{ArF}, \text{OH-doped, H}_2\text{-free}$

(b) $\text{F}_2, \text{OH-free, H}_2\text{-free}$

$\text{H}_2\text{-im}$

$\Delta$Absorption coefficient ($\text{cm}^{-1}$)

Photon energy (eV)

$\Delta$Absorption coefficient ($\text{cm}^{-1}$)

Photon energy (eV)

$\Delta$Absorption coefficient ($\text{cm}^{-1}$)

Photon energy (eV)

(157nm)

(193nm)
### 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 γ-resistant fibers</td>
<td>Good</td>
</tr>
</tbody>
</table>

**Fluorine-doped silica**

... Suitable for photomask substrates in F$_2$ laser photolithography

Hosono et al. APL74, 2755(1999), Mizuguchi et al. JVSTB17, 3280(1999)

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**Graph:**

- **X-axis:** Wavelength (nm)
- **Y-axis:** Transmittance
- **Legend:**
  - Dry
  - Wet
  - F-doped

**Graph Annotation:**

- Reflection loss at (7.9eV)
- Transmittance at (157nm)
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

\[ \Rightarrow \]

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
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 $\text{O}_2$... The most common form of excess oxygen in silica glass

- Nassau and Shiever (1975) Preparation of low-OH $a$-$\text{SiO}_2$ 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 $\text{O}_2$ by Raman spectroscopy
- Awazu et al. (1990) Observation of VUV absorption band of interstitial $\text{O}_2$

![Graph showing attenuation and wavelength](image-url)
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 $\text{O}_2$ via 1064nm excitation
- Skuja et al. (1998)  PL detection of interstitial $\text{O}_2$ via 765nm excitation

Sensitive, selective, and non-destructive detection of interstitial $\text{O}_2$ in $\alpha$-SiO$_2$

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

### $\text{O}_2$ energy level

- $b^1\Sigma^+_g \rightarrow 0$
- $a^1\Delta_g \rightarrow 0$
- $X^3\Sigma^-_g \rightarrow 0$

Excitation wavelengths:
- $765\text{nm} (\text{Ti:Al}_2\text{O}_3)$
- $1064\text{nm} (\text{Nd:YAG})$
- $1272\text{nm}$

Cherenkov radiation
5. Interstitial oxygen in silica glass

- O$_2$ PL measurements of silica glasses thermally annealed in air

**Oxidant in the thermal oxidation of silicon is interstitial O$_2$**
5. Interstitial oxygen in silica glass

Concentration calibration

- Thermal desorption spectroscopy

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

\[ O_2 \text{ concentration} \sim 2.7 \times 10^{16} \text{ cm}^{-3} \]

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

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

- Simultaneous measurement of VUV absorption and O$_2$ concentration changes
  1. **Red-shift** of VUV absorption edge
  2. **Increase** in absorption intensity

⇒ Weak attractive interaction between O$_2$ and $a$-SiO$_2$ framework

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Kajihara et al. JAP98,013527(2005)

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**Graphs:**
- **Absorption coefficient (cm$^{-1}$)**
  - Photon energy (eV)
  - O$_2$-loaded and O$_2$-desorbed curves
  - O$_2$ band (1539 cm$^{-1}$)

- **Log(Absorption cross section (cm$^2$))**
  - Photon energy (eV)
  - This study and Gaseous O$_2$ curves
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)
5. Interstitial oxygen in silica glass

Reactions (2)

- Reaction with Si-Si bonds: $\equiv Si-Si\equiv + \frac{1}{2}O_2 \rightarrow \equiv Si-O-Si\equiv$
- Reaction with $E'$ center: $\equiv Si^\bullet + O_2 \rightarrow \equiv SiOO^\bullet$
- Reaction with SiCl: $\frac{1}{2}O_2 + 2\equiv SiCl \rightarrow \equiv Si-O-Si\equiv + Cl_2$
- Reaction with $H^0$: $O_2 + H^0 \rightarrow HO_2^\bullet$

Pfeffer (1998)

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

Configuration... Peroxy linkage form

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

Formation

1. Radiolytic decomposition of Si-O-Si bonds

\[ \equiv \text{Si-O-Si} \xrightarrow{h\nu} \equiv \text{Si-Si} + \text{O}^0 \text{ (or 1/2O}_2) \]

2. VUV photolysis of interstitial O\textsubscript{2}

\[ \text{O}_2 \xrightarrow{h\nu} 2\text{O}^0 \]

3. UV photolysis of peroxy radical

\[ \equiv \text{SiOO}^\bullet \xrightarrow{h\nu} \equiv \text{SiO}^\bullet + \text{O}^0 \]

Interstitial oxygen atoms

- 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

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

- Optical absorption... Use \( \text{O}^0 \)-rich sample prepared by \( \text{F}_2 \) laser irradiation
- Diffusivity ... Probe \( \text{O}_2 \) generated by recombination of \( \text{O}^0 \)

Skuja et al. NIMB191,127(2002)

5. Interstitial oxygen in silica glass

Conversion of dangling bonds

$$\equiv \text{SiOO}^* \xrightarrow{h\nu(\sim 5\text{eV})} \text{Heat} \xrightarrow{\equiv \text{SiO}^* + O^0}$$

Kajihara et al. PRL 92, 015504 (2004)

5. Interstitial oxygen in silica glass

Absorption cross section “map”

- Log[Absorption cross section (cm$^2$)] vs. Photon energy (eV)

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

- **Optical isotropy**
  - Process engineering
    - Raw material
    - Production method
    - Fiber drawing
  - Deep-UV optics
    - Photomasks
    - Hard pellicles
    - Lenses

- **Wide-gap α-quartz**
  - Fundamental research
    - Optical spectroscopy
    - EPR
    - Simulation
  - Network topology
  - Stoichiometry
  - Doping (H, F, P, RE, ...)

- **Workability**
  - Structural modification
    - Optical fibers
    - DUV fibers
    - Bragg grating devices
    - Fiber lasers

- **Production method**
  - Raw material
  - Production method
  - Fiber drawing

- **Simulation**
  - EPR
  - Simulation
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