Mechanical Properties of Microelectronics Thin Films: Silicon DiOxide ($\text{SiO}_2$)

Fariborz Maseeh, Sean M. Gelston, and Stephen D. Senturia

Abstract

Mechanical design of microfabricated devices requires knowledge of mechanical material properties. Thin film material properties are sensitively process dependent, and should therefore be organized accordingly. A relational database of material properties is under development as part of a general micro-electro-mechanical CAD environment. A computerized literature search through the published values for Silicon DiOxide ($\text{SiO}_2$) properties under various processing conditions resulted in the following document.
Acknowledgements

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Author Information


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PROPERTIES OF MICROELECTRONIC SILICON DIOXIDE 
(SiO₂) 

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Introduction

There is a growing need for the ability to perform mechanical analysis of microelectronic devices, both in assuring structural reliability against failure of thin film layers, and in evaluating the effects of various external loads including temperature and humidity effects. In addition, with the development of increasingly sophisticated micromechanical devices, including microsensors, pumps, valves, and micromotors, and with the increasing performance demands being placed on these devices, notably in the precision and accuracy of microsensors, there is a critical need for computer-aided-design (CAD) tools which will permit rational design of these devices. The present program is directed towards creation of a suitable CAD environment for micromechanical analysis of microfabricated deformable structures utilized for measuring the mechanical properties of thin films, and static analysis of which can be utilized for reliability investigations.

There are two fundamental problems that confront the designer \[\ast,\ast\ast\]: (1) the need to construct a three-dimensional solid model from a description of the mask set and process sequence to be used in fabrication of a micromechanical device; and (2) the need to be able to predict the mechanical properties of each of the constituent materials in a device, including possible process dependences of these properties. With such a 3-D model in hand, with appropriate properties for each material, prediction of mechanical behavior could be done with existing finite-element modeling (FEM) programs. However, at the present time, there is no CAD system, either mechanical or microelectronic, which successfully addresses these problems in a coherent way. Koppelman [\***\] has developed a program called OYSTER which permits construction of a 3-D polyhedral-based solid model from a mask set and primitive process description, but as yet, there is no provision for linking to FEM tools or to standardly used layout and process modeling tools, and no database for prediction of mechanical properties from the process sequence.
An architecture for a micro-electro-mechanical CAD system in which these two critical problem areas can be the focus of simultaneous and parallel development work is presented in Fig. 1. The basic idea is to provide three different levels of user interaction: (1) at the conventional microelectronic level, with access to mask layout and process specification; (2) at the mechanical CAD level, for direct construction of 3-D solid models which can then be analyzed with FEM; and (3) at the mechanical-property database level, for entry of mechanical property data as it is acquired and documented. There are then two specific development tasks: (1) development of a 3-D solid modeling tool, which we call the "structure simulator", and which takes mask layout data and a realistic process description and builds a 3-D solid model in a format compatible with the mechanical CAD system (an extension of what OYSTER now does); and (2) the development of a mechanical property database using iterative measurements on deformable micromechanical structures (such as diaphragms, beams, and resonant structures) together with careful FEM studies of the dependence of their behavior on mechanical properties.

We have implemented this architecture in a Sun 4 host, drawing on existing codes wherever possible. The primary interface for mechanical modeling is through PATRAN, a mechanical CAD package which provides for manual construction of 3-D solid models, graphical display, and interfacing with FEM packages (we are using ABAQUS). The 3-D solid model resides in the PATRAN Neutral File, and we have elected to use the material-property format of the Neutral File as a first version of the Mechanical Property Database. Layout is provided through KIC, and process description through the process-flow representation (PFR) is created with a standard text editor. SUPREM III and SAMPLE are installed to provide depth and cross-sectional modeling capabilities. The structure simulator (under development) will accept KIC and PFR files as input, draw on SUPREM
III and SAMPLE as needed, and will output a 3-D solid model in the format of the PATRAN Neutral File. PATRAN will then be able to pick up the model, provide for FEM analysis and graphical display of behavior. The present status is that all of the commercially available codes (solid boxes in Fig. 1) are installed and operating. The first entries into the Mechanical Property Database have been made for silicon dioxide and silicon nitride as a result of the literature review enclosed.

This document is the result of a computerized literature search (done at MIT CLSS) to locate published mechanical property data for silicon dioxide, SiO$_2$. Investigating some 120+ references, a group of 45 was selected and the mechanical properties of SiO$_2$ were extracted under both thermal growth and chemical vapor deposition (CVD). The cited values were arranged by different mechanical property headings, and then by the deposition methods as subheadings. The boldface values indicate results of experimental measurements (from references), and the italic value correspond to when a reference cites results from other references without measurements, or when no reference experiment was indicated to support the cited values. Most values were traced to their original measurement (experiment) when possible. Averages of the cited properties have been entered in our mechanical property database.

References

* S. D. Senturia, "Microfabricated structures for the measurement of mechanical properties and adhesion of thin films", Transducers ’87, Tokyo, 1987, pp. 11-16.


Microelectronic CAD

User Interface

- Mask Layout (KIC)
- Layout Description (CIF)
- Structure Simulator (under development)
- Process Models (SUPREM-III, SAMPLE)

User Interface

- File Editor
- Process Description (PFR)

Mechanical CAD

User Interface

- Mechanical Property Database
- 3-D Solid Model (PATRAN Neutral File)
- CAD graphics
  Geometry, FEM input & output construction (PATRAN)
- FEM Input Interface (PATRAN)
- FEM Output Interface (PATRAN)
- FEM Simulation (ABAQUS)

Fig. 1

CAD architecture for micro-electro-mechanical design
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1 Young’s Modulus

1.1 Thermal Oxide

- 50 GPa, [3] oxide grown from 550° C to 1000° C.

- 100 GPa, [5].

- 70 GPa, [18].

- 66 GPa [27] for dry oxide grown between 875° C and 1200° C on (100) and (111) oriented Si.

- 76 GPa, [34].

- 57 GPa [36] for wet oxide grown at 960° C.

- 67 GPa [36] for dry oxide grown at 960° C.

- 110 x 10^5 psi [38].

1.2 PECVD Oxide

No values obtained for the Young’s Modulus, \( E \), of PECVD SiO\(_2\).
2 Poisson's Ratio

2.1 Thermal Oxide

- 0.15 [3], for oxide grown between 550°C and 1000°C
- 0.20 [18], no conditions available.
- 0.17 [21], no conditions available.
- 0.164 [34], no conditions available.

2.2 PECVD Oxide

No data was retrieved for the Poisson's ratio of PECVD silicon oxide.

2.3 Bulk Oxide

- 0.18 [27].
3 Biaxial Modulus

3.1 Thermal Oxide

- 100 GPa [14]
- 63.3 GPa [30] for oxide grown at 1200°C
- 70 GPa [36] for steam oxide
- 82 GPa [36] for dry oxide

3.2 PECVD Oxide

- Biaxial modulus variant with precursor gas ratio.

This data reproduced from [23]

Conditions:
Substrates: Glass, Steel, and Quartz
Temperature: 250°C
Pressure: 500 mTorr
Rf Frequency: 13.56 MHz
Rf Power Density: 0.02 W cm$^{-2}$

- 42 GPa [23] for the conditions immediately above, when gas ratio exceeds 5

- Biaxial modulus variant with deposition temperature

<table>
<thead>
<tr>
<th>Deposition Temperature, °C</th>
<th>Biaxial Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>42</td>
</tr>
<tr>
<td>200</td>
<td>42</td>
</tr>
<tr>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>100</td>
<td>43</td>
</tr>
</tbody>
</table>

Data reproduced from [23]

Conditions:
N$_2$O flow: 165 sccm
N$_2$O/SiH$_4$ ratio: 12:1
Pressure: 500 mTorr
Temperature: variable
Rf frequency: 13.56 MHz
Power Density: 0.02 W cm$^{-2}$
Substrates: glass, steel, quartz

- 46.6 GPa and 51.5 GPa.

This data collected from [30].

Conditions:
Temperature: 250°C
Pressure: n/a
Rf frequency: n/a
Rf Power: n/a
SiH$_4$ (5 % in Ar): 100 cc min$^{-1}$
O$_2$: 10 cc min$^{-1}$
N$_2$ flow: 4000 cc min$^{-1}$
Substrates: Si and GaAs
- 75 GPa CVD-SiO₂ deposited at 490 A/min

- 100 GPa CVD SiO₂, deposited at 1900 A/min

Data collected from [37].

**Conditions:**
- **Temperature:** 450°C
- **Substrate:** (111) Si
- **Reagents:** SiH₄ and O₂
- **Pressure:** n/a
- **Deposition rates:** 490 A/min & 1900 A/min.

### 3.3 Bulk Oxide

- 88 GPa [15].
4 Density

4.1 Thermal Oxides

- Density versus oxidation temperature and pressure for several samples of dry oxide

<table>
<thead>
<tr>
<th>Growth Temperature, °C</th>
<th>Pressure, atm</th>
<th>Density, g cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1</td>
<td>2.47</td>
</tr>
<tr>
<td>800</td>
<td>500</td>
<td>2.41</td>
</tr>
<tr>
<td>800</td>
<td>1</td>
<td>2.42</td>
</tr>
<tr>
<td>1000</td>
<td>500</td>
<td>2.35</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>2.26</td>
</tr>
</tbody>
</table>

This data collected from [8].

Conditions:
- Substrates: (111) and (100) Si.
- Ambient: pure dry O₂, for low pressure, ultradry for high pressure.
- Initial oxidation for high-pressure oxides: 1000°C, ultradry O₂, for a thickness of 1 nm.

- 2.38 g cm⁻³ [10] for dry oxide grown at 500 atm, 800°C
- 2.26 g cm⁻³ [10] for dry oxide grown at 1 atm, 1000°C
- 2.208 g cm⁻³ [22] for dry oxide grown at 1150°C
- 2.268 g cm⁻³ [22] for dry oxide grown at 700°C

- Density varying with oxidation temperature, for dry oxide.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Density, g cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>600*</td>
<td>2.286</td>
</tr>
<tr>
<td>700*</td>
<td>2.265</td>
</tr>
<tr>
<td>750</td>
<td>2.257</td>
</tr>
<tr>
<td>800</td>
<td>2.253</td>
</tr>
<tr>
<td>900</td>
<td>2.236</td>
</tr>
<tr>
<td>1000</td>
<td>2.224</td>
</tr>
<tr>
<td>1150</td>
<td>2.208</td>
</tr>
</tbody>
</table>
• The results of anneals on higher density SiO₂ films.

<table>
<thead>
<tr>
<th>Anneal</th>
<th>Density, g cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>2.265</td>
</tr>
<tr>
<td>N₂ 20 min, at 1000°C</td>
<td>2.209</td>
</tr>
<tr>
<td>N₂ 16 hr, at 600°C</td>
<td>2.209</td>
</tr>
<tr>
<td>None</td>
<td>2.270</td>
</tr>
<tr>
<td>N₂ 16 hr, at 700°C</td>
<td>2.260</td>
</tr>
<tr>
<td>N₂ H₂O, 20 hr, 700°C</td>
<td>2.220</td>
</tr>
</tbody>
</table>

This data collected from [35].

Conditions:
Oxidation Temperature: 700°C
Pressure: 5000 psi
Ambient: Dry O₂

• 2.2 g cm⁻³ for wet oxide grown at 960°C [36]

• 2.25 g cm⁻³ for dry oxide grown at 960°C [36]

4.2 PECVD Oxide

• Effects of gas flow rate and annealing on oxide density

<table>
<thead>
<tr>
<th>Gas Flow Rate (sccm)</th>
<th>ρ (g cm⁻³)</th>
<th>ρ* (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.09</td>
<td>2.22</td>
</tr>
<tr>
<td>1</td>
<td>2.07</td>
<td>2.24</td>
</tr>
<tr>
<td>0.7</td>
<td>2.07</td>
<td>2.26</td>
</tr>
<tr>
<td>0.6</td>
<td>2.02</td>
<td>2.28</td>
</tr>
<tr>
<td>0.5</td>
<td>1.98</td>
<td>2.30</td>
</tr>
</tbody>
</table>

* Films annealed at 1000°C for 30 min in N₂ ambient
These values collected from [20].
Conditions:
SiH₄ (1.5 % in Ar) flow rate : 0.3 sccm
O₂ flow rate : variable
Temperature : 350° C
Pressure : 1.5 Torr
Rf frequency: 13.562 MHz
Rf Power : 50W.

- Density varying with gas ratio

![Graph showing density varying with gas ratio]

This data reproduced from [23].

Conditions:
Substrates: Glass, Steel, and Quartz
Temperature : 250° C
Pressure : 500 mTorr
Rf Frequency : 13.56 MHz
Rf Power Density : 0.02W cm⁻²
N₂O Flow : 165 sccm
SiH₄ Flow : variable, to suit gas ratio (see above)

- Density varying with deposition temperature.

![Graph showing density varying with deposition temperature]

This data reproduced [29].

Conditions:
Temperature : variable
Pressure : 1 Torr
Gas Ratio, N₂O / SiH₄ : 65
Rf frequency : 13.56 MHz
Rf Power : 24W.
• 1.97 (+/- 0.02) g cm⁻³ [32]

Conditions
N₂O / SiH₄ ratio: 12:1
Temperature: variable

4.3 Bulk Oxide

2.2 g cm⁻³, [33] at temperature = 300K
5 Coefficient of Thermal Expansion

5.1 Thermal Oxide

- $6 \times 10^{-7} \degree C^{-1} [14]$.

- $3.5 \times 10^{-7} \degree C^{-1} [22]$ dry grown from 950 - 1150° C.

- $5 \times 10^{-7} \degree C^{-1} [30]$ for oxide grown at 1200° C

- $6 \times 10^{-7} \degree C^{-1} [38]$ for dry oxide grown at 1200° C

- Thermal expansion coefficient vs. temperature

This data reproduced from [42]

**Conditions:**
Oxidation Temperature : 1050° C  
Measurement Temperature : see above  
Oxidation Pressure : n/a  
Ambient : Steam  
Substrate : (100) oriented Si  
Film Thickness : 4000A
5.2 PECVD Oxide

- Coefficient of thermal expansion, $\alpha$, variant with gas ratio.

![Graph showing linear expansion coefficient versus deposition temperature.]

Data reproduced from [23]

Conditions for PECVD:
Precursor gases: SiH$_4$ and N$_2$O
Substrates: quartz, steel, and glass
Temperature: 250°C
Pressure: 500 mTorr
Rf frequency: 13.56 MHz
Rf Power Density: 0.02 W cm$^{-2}$
Total Gas flow: 200 sccm.

- Measurements of thermal expansion coefficients for varying deposition temperatures.

<table>
<thead>
<tr>
<th>Deposition Temperature, °C</th>
<th>$\alpha \times 10^{-6} \text{ °C}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>2.3</td>
</tr>
<tr>
<td>200</td>
<td>2.6</td>
</tr>
<tr>
<td>150</td>
<td>2.2</td>
</tr>
<tr>
<td>100</td>
<td>2.2</td>
</tr>
</tbody>
</table>

This data reproduced from [24]

Conditions:
N$_2$O flow: 165 sccm
N$_2$O/SiH$_4$ ratio: 12:1
Pressure: 500 mTorr
Temperature: variable
Rf frequency : 13.56 MHz
Power Density : 0.02 W cm\(^{-2}\)
Substrates : glass, steel, quartz.

- \(3.9 \times 4.1 \times 10^{-6} \degree C^{-1}\) [30]

  **Conditions**:
  - Temperature : 250\(^\circ\) C
  - SiH\(_4\) (5 \% in Ar) : 100 cc min\(^{-1}\)
  - O\(_2\) flow : 10 cc min\(^{-1}\)
  - N\(_2\) flow : 4000 cc min\(^{-1}\)

- \(5.5 \times 10^{-7} \degree C^{-1}\) [37]

  **Conditions**:
  - Temperature : 450\(^\circ\) C
  - Substrate : (111) Si
  - Reagents : SiH\(_4\) and O\(_2\)
  - Pressure : n/a:
  - Deposition rates : 490 A/min & 1900 A/min.

5.3 Bulk Oxide

- \(5.2 \times 10^{-7} \degree C^{-1}\) [15].
6 Thermal Conductivity

6.1 Thermal Oxide

No values obtained for thermal oxide.

6.2 PECVD Oxide

No values obtained for PECVD oxide.

6.3 Bulk SiO₂

- Coefficient of thermal conductivity for bulk SiO₂, variant with temperature.

This data reproduced from [33].
7 Stress

7.1 Thermal Oxide

- 600 MPa, [3] oxide grown at 700° C.

- Schematic distribution of stress in the oxide film and its substrate.

This data reproduced from [6].

Conditions:
Oxidation Temperature : 1200° C
Growth Substrate : 2-6 Ω-cm p-type (111) Si
Anneal : 400° C. in N₂ and H₂ Annealing Duration : n/a
Calculated stress in SiO$_2$ variant with oxidation temperature.

This data reproduced from [4].

Conditions:
Substrate: 2-6 Ω·cm p-type (111) Si
Anneal: 400°C in N$_2$ and H$_2$, duration n/a

Calculated variation of stress with oxide thickness

This data reproduced from [6].

Conditions:
Growth Temperature: 1200°C
Substrate: 2-6 Ω·cm p-type (111) Si
Anneal: 400°C in N$_2$ and H$_2$, duration n/a
- Calculated variation of stress with substrate thickness

![Graph showing variation of stress with substrate thickness.]

This data reproduced from [6].

Conditions:
Growth Temperature: 1200° C
Substrate: 2-6 Ω-cm p-type (111) Si
Anneal: 400° C, in N₂ and H₂, duration n/a

- Residual Stress Measurements for Pressure-Oxides, and Normal 1 atm Oxide.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Oxide.</td>
<td></td>
</tr>
<tr>
<td>500 atm, 800° C</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>280</td>
</tr>
<tr>
<td>Average:</td>
<td>310</td>
</tr>
<tr>
<td>Controls,</td>
<td></td>
</tr>
<tr>
<td>1 atm, 1000° C</td>
<td>410</td>
</tr>
<tr>
<td></td>
<td>420</td>
</tr>
</tbody>
</table>

This data collected from [8].

Conditions:
Substrates: (100) and (111) Si
H₂O content: < 1 ppm
• 350 MPa [9], average compressive stress at room temperature for dry oxides grown at 1000°C.

• 310 - 340 MPa [11], average compressive stress for dry oxide grown at 500 atm, 800°C.

• Intrinsic stress variant with film thickness.

This data reproduced from [12]

Conditions:
Substrate: (100) p-type Si
Oxidation Ambient: dry O₂ with <5 ppm H₂O and <0.5 ppm hydrocarbons.
- Intrinsic stress variant with film thickness for etched oxide.

\[ \text{Oxidation Temperatures} \]
\[ 700^\circ C \ (\text{a}) \]
\[ 800^\circ C \ (\text{b}) \]
\[ 1000^\circ C \ (\text{c}) \]

This data reproduced from [12].

Conditions:
Substrate : (100) p-type Si
Oxidation Ambient : dry O\(_2\) with <5 ppm H\(_2\)O and <0.5 ppm
Etching : in HF solution, (NH\(_4\))\(_2\)HF \(= 50:1\) hydrocarbons.


- Total stress for dry oxides grown on two Si substrates at different temperatures.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Temperature, (^\circ) C</th>
<th>Total Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+ (10^{-2}\ \Omega\text{cm Si})</td>
<td>850</td>
<td>150</td>
</tr>
<tr>
<td>p+ (10^{-2}\ \Omega\text{cm Si})</td>
<td>1090</td>
<td>290</td>
</tr>
<tr>
<td>p 1 (\Omega\text{cm Si})</td>
<td>850</td>
<td>80</td>
</tr>
<tr>
<td>p 1 (\Omega\text{cm Si})</td>
<td>1090</td>
<td>260</td>
</tr>
</tbody>
</table>

This data collected from [13].
Stress varying with oxidation temperature for four Si orientations.

This data reproduced from [15].

**Conditions**
- Ambient: dry O₂, with <5 ppm H₂O, and <0.5 ppm hydrocarbons
- Pressure: 1 atm
• Stress varying with oxidation temperature for (100) Si.

![Graph](image_url)

This data reproduced from [15].

**Conditions:**
Ambient: dry O\textsubscript{2} with <5 ppm H\textsubscript{2}O, and <0.5 ppm hydrocarbons
Pressure: 1 atm
Annealed: 1000\degree C. in N\textsubscript{2}

• Stress varying with oxidation temperature for (111) Si.

![Graph](image_url)

This data reproduced from [15].

**Conditions:**
Ambient: dry O\textsubscript{2} with <5 ppm H\textsubscript{2}O, and <0.5 ppm hydrocarbons
Pressure: 1 atm
Annealed: 1000\degree C. in N\textsubscript{2}
• Stress varying with oxidation temperature for dry oxide.

![Graph showing stress variation with oxidation temperature.]

2' Maximum Stress
1 Thermal Stress
2 Minimum Stress

This data reproduced from [21].

Conditions: n/a.

• Stress distribution over the thickness for dry oxide.

![Graph showing stress distribution over thickness.]

This data reproduced from [21].

Conditions: n/a.
- Intrinsic and thermal stresses varying with oxidation temperature for dry oxide.

\[ \sigma (\text{MPa}) \]

Thick data reproduced from [21].

Conditions: n/a.

- Stress measurements from beam experiment.

\[ \text{STRESS (GPa)} \]

This data reproduced from [27].

Conditions:
Substrates: (111) and (100) - oriented Si
Oxidation: Dry
• Stress measurements from balloon experiment.

This data reproduced from [27].

Substrates: (111) and (100) - oriented Si
Oxidation: Dry

• Stress vs. strain for typical oxide balloon

Substrates: (111) and (100) - oriented Si
Oxidation: Dry
This data reproduced from [27].

• 340 MPa [30] measured at room temp., grown at 700° C.

• 400 MPa compressive [35], grown at 700° C.

• 50 MPa tensile [35], grown at 1150° C.
• 220 - 360 MPa compressive, [37] measured at room temp., grown at 1100°C.

• Total film stress, measured at room temperature, vs. oxide thickness

![Graph showing the relationship between oxide thickness and film stress](image)

This data reproduced from [41].

**Conditions:**
Oxidation Temperature: see above.
Oxidation Pressure: 1 atm
Ambient: Dry O₂
Substrate: p-type (100) oriented Si
Components of stress vs. oxidation temperature

\[
\text{STRESS} = E \cdot \text{EQMA} - \text{EXPANS}...
\]

Intrinsic stress vs. oxidation temperature

\[
\text{INTRINSIC STRESS (dyn/cm}^2\text{)}
\]

This data reproduced from [41]

Conditions For Both Graphs:
Oxidation Temperature: see above
Measurement Temperature: room temperature
Oxidation Pressure: 1 atm (unless otherwise specified)
Ambient: Dry \(\text{O}_2\)
Substrate: p-type (100) oriented Si

- Stress vs. temperature
This data reproduced from [42].

Conditions:
- Oxidation Temperature: 1050°C
- Measurement Temperature: see above
- Oxidation Pressure: n/a
- Ambient: Steam
- Substrate: (100) oriented Si
- Film Thickness: 4000Å

- Change in curvature induced by stress, vs. oxide thickness

This data reproduced from [44].

Dash line represents the expected curvature change for SiO₂ stress level of 700MPa.

Conditions:
- Oxidation Temperature: see above
- Measurement Temperature: ox. temp.
- Oxidation Pressure: n/a
- Ambient: wet O₂
- Substrate: 1-Ω-cm P-doped (111) and (100) Si
- Film Thickness: 4000Å
• Interfacial stress at room temperature for various substrates.

<table>
<thead>
<tr>
<th>P_2O_5 Diffusion</th>
<th>Direction of Stress Measurement</th>
<th>Si Orientation</th>
<th>Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>(110)</td>
<td>(111)</td>
<td>47</td>
</tr>
<tr>
<td>No</td>
<td>(211)</td>
<td>(111)</td>
<td>450</td>
</tr>
<tr>
<td>Yes</td>
<td>(110)</td>
<td>(111)</td>
<td>250</td>
</tr>
<tr>
<td>No</td>
<td>(110)</td>
<td>(110)</td>
<td>390</td>
</tr>
<tr>
<td>No</td>
<td>(100)</td>
<td>(110)</td>
<td>390</td>
</tr>
<tr>
<td>Yes</td>
<td>(110)</td>
<td>(110)</td>
<td>260</td>
</tr>
<tr>
<td>No</td>
<td>(110)</td>
<td>(100)</td>
<td>400</td>
</tr>
<tr>
<td>No</td>
<td>(110)</td>
<td>(100)</td>
<td>380</td>
</tr>
<tr>
<td>Yes</td>
<td>(110)</td>
<td>(100)</td>
<td>240</td>
</tr>
</tbody>
</table>

This data reproduced from [45].

**Conditions:**
- Oxidation Temperature: 1200°C
- Measurement Temperature: room temperature
- Oxidation Pressure: n/a
- Ambient: wet O_2 (dew point temperature 90°C)
- Substrate: 5 Ω-cm (111), (110), and (100) Si
- Film Thickness: 8400Å
- P_2O_5 Diffusion: in N_2 for 30 min. at 920°C

• Oxide stress at room temperature for quickly and slowly cooled films

<table>
<thead>
<tr>
<th>Sample Type and Cooling</th>
<th>Film Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Oxide</td>
<td></td>
</tr>
<tr>
<td>Slowly Cooled</td>
<td>270</td>
</tr>
<tr>
<td>Quickly Cooled</td>
<td>370</td>
</tr>
<tr>
<td>Wet Oxide</td>
<td></td>
</tr>
<tr>
<td>Slowly Cooled</td>
<td>160</td>
</tr>
<tr>
<td>Quickly Cooled</td>
<td>280</td>
</tr>
</tbody>
</table>

This data reproduced from [45].

**Conditions:**
- Oxidation Temperature: 1200°C
- Measurement Temperature: room temperature
- Measurement Direction: (110) direction
- Oxidation Pressure: n/a
- Ambient: wet oxide, dew point temperature = 90°C
dry oxide, dew point temperature = -40°C
- Substrate: (110) - oriented P-doped Si
- Film Thickness: 8600-9200Å
- Cooling Duration: for quick cooling, immediate exposure to air
Cooling Duration: for quick cooling, immediate exposure to air
for slow cooling, duration = 5hr

- Oxide stress at room temperature for various doping levels of Si

<table>
<thead>
<tr>
<th>Slice Resistivity, Ω-cm</th>
<th>Doping Level, cm⁻³</th>
<th>Oxide Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>4x10¹²</td>
<td>280</td>
</tr>
<tr>
<td>5-10</td>
<td>8.5x10¹⁴ - 4x10¹⁴</td>
<td>270</td>
</tr>
<tr>
<td>0.37</td>
<td>1.6x10¹⁶</td>
<td>200</td>
</tr>
<tr>
<td>0.035</td>
<td>4.5x10¹⁷</td>
<td>260</td>
</tr>
<tr>
<td>0.0015</td>
<td>5.5x10¹⁹</td>
<td>300</td>
</tr>
</tbody>
</table>

This data reproduced from [45]

Conditions:
Oxidation Temperature: 1200°C
Measurement Temperature: room temperature
Measurement Direction: [200] direction
Oxidation Pressure: n/a
Ambient: wet oxide, dew point temperature = 90°C
Substrate: (111) - oriented P-doped Si, Film Thickness: 9200Å
7.2 PECVD Oxide

- Stress varying with temperature (not oxidation temperature).

This data reproduced from [14].
- Thermally induced stress in the oxide, as a function of the measured temperature.

This data reproduced from [23] and [24]

Conditions:
Temperature: 250°C
Pressure: 500 mTorr
N₂O / SiH₄: 12:1
Total gas flow rate: 200 sccm
Rf frequency: 13.56 MHz
Rf Power Density: 0.02 W cm⁻²
Substrates: quartz, steel, glass.

- Tension in the film as a function of film thickness.

This data reproduced from [24]
**Conditions:**

- Temperature: 250°C
- Pressure: 500 mTorr
- RF frequency: 13.56 MHz
- RF Power Density: 0.02 W cm⁻²
- N₂O/SiH₄: 12:1
- SiH₄ flow rate: 200 sccm
- Substrates: glass, steel, quartz

- Stress in a CVD SiO₂ film as a function of temperature.

**Air**

![Graph showing stress vs. temperature for air conditions.]

**Dry Air**

![Graph showing stress vs. temperature for dry air conditions.]

This data reproduced from [30].

**Conditions:**

- Deposition Temperature: 250°C
- SiH₄ (5% in Ar) flow: 100 cc/min
- O₂ flow: 10 cc/min
- N₂ flow: 4000 cc/min
- Deposition Thickness: 0.65 μm
- Substrates: GaAs and Si
- Time variation of stress in CVD SiO$_2$

Kept in air, 49% rel. humid., exposure to a dry N$_2$
ambient at 22$^\circ$ C.

Kept in dry N$_2$, upon exposure
to air, 60% RH, at 22$^\circ$ C.

This data reproduced from [30].

Conditions:
Deposition Temperature : 250$^\circ$ C
SiH$_4$ (5% in Ar) flow : 100 cc/min
O$_2$ flow : 10 cc/min
N$_2$ flow : 4000 cc/min
Deposition Thickness : 0.65 $\mu$m
Substrates : GaAs and Si
\[ \sigma(T) - \sigma(115^\circ C) \] as a function of temperature.

Solid curves represent calculated values. Measurements done in vacuum.

This data reproduced from [30].

Conditions:
Deposition Temperature : 250\(^\circ\) C
SiH\(_4\) (5\% in Ar) flow : 100 cc/min
O\(_2\) flow : 10 cc/min
N\(_2\) flow : 4000 cc/min
Deposition Thickness : 0.47 \(\mu\)m
Substrates : GaAs and Si
Time varying stress for a CVD SiO$_2$ film, previously kept in air, 48% RH, at 21°C, upon exposure to 40 μm Hg.

This data reproduced from [30].

**Conditions:**
- Deposition Temperature: 250°C
- SiH$_4$ (5% in Ar) flow: 100 cc/min
- O$_2$ flow: 10 cc/min
- N$_2$ flow: 4000 cc/min
- Deposition Thickness: 0.47 μm
- Substrates: GaAs

Stress change in CVD SiO$_2$ after heat treatments.

This data reproduced from [37].

**Conditions:**
- Deposition Temperature: 400°C - 450°C
- Deposition Pressure: n/l
- Reagent: SiH$_4$
- Substrate: (111) Si, 200μm thick
Heat Treatment Temperature: see above

- Stress in CVD films vs. ambient temperature

![Graph showing stress in CVD films vs. ambient temperature]

This data reproduced from [37].

Conditions:
Deposition Temperature: 400°C - 450°C
Deposition Pressure: n/l
Reagent: SiH₄
Substrate: (111) Si, 200μm thick

- Stress in CVD SiO₂ films vs. deposition rate

<table>
<thead>
<tr>
<th>Deposition Rate (A/min)</th>
<th>Stress after Deposition, MPa</th>
<th>Intrinsic Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 A/min</td>
<td>220</td>
<td>370</td>
</tr>
<tr>
<td>490 A/min</td>
<td>170</td>
<td>240</td>
</tr>
</tbody>
</table>

This data collected from [37].

Deposition Temperature: 400°C - 450°C
Deposition Pressure: n/l
Reagent: SiH₄
Substrate: (111) Si, 200μm thick
• Stress change of CVD SiO₂ film after various treatments.

This data collected from [37].

Conditions:
Deposition Temperature: 400°C - 450°C
Deposition Pressure: n/a
Reagent: SiH₄
Substrate: (111) Si, 200μm thick
Film Thickness: see above

• Temperature dependence of CVD SiO₂ stress on Si

This data reproduced from [42]

Conditions:
Deposition Temperature: 480°C
Deposition Pressure: n/a
Reagents: SiH₄ and O₂
Film Thickness: 6000 Å
8 Stress Relaxation Time

8.1 Thermal Oxide

• Stress relaxation time variant with temperature.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Stress Relaxation Time, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>900</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>950</td>
<td>~25-60</td>
</tr>
<tr>
<td>1000</td>
<td>~6-20</td>
</tr>
<tr>
<td>1050</td>
<td>~1-3</td>
</tr>
<tr>
<td>1100</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>1180</td>
<td></td>
</tr>
</tbody>
</table>

This data collected from [5].

Conditions:
Oxidation Temperature: see above
Oxidation Pressure: n/a.
Ambient: dry oxide.

• Stress relaxation time variant with temperature.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Stress Relaxation Time, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>5278</td>
</tr>
<tr>
<td>800</td>
<td>175</td>
</tr>
<tr>
<td>1000</td>
<td>0.2</td>
</tr>
</tbody>
</table>

This data collected from [12].

Conditions:
Substrate: (100) p-type Si
Oxidation Ambient: dry O₂ with <5 ppm H₂O and <0.5 ppm hydrocarbons.
Stress relaxation time variant with temperature.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Stress Relaxation Time, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>5100</td>
</tr>
<tr>
<td>900</td>
<td>21</td>
</tr>
<tr>
<td>1000</td>
<td>0.2</td>
</tr>
<tr>
<td>1100</td>
<td>(10 seconds)</td>
</tr>
</tbody>
</table>

This data collected from [35].

Conditions:
- Oxidation Temperature: see above
- Pressure: 1 atm
- Substrate: (111) and (100) oriented Si crystals

8.2 PECVD Oxide

No information available for PECVD oxide films.

8.3 Bulk Oxide

Stress Relaxation times for I. R. Vitreosil.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>( \tau ), hrs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>&gt;50,000</td>
</tr>
<tr>
<td>1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>1100</td>
<td>170</td>
</tr>
<tr>
<td>1200</td>
<td>24</td>
</tr>
<tr>
<td>1300</td>
<td>6</td>
</tr>
<tr>
<td>1400</td>
<td>2</td>
</tr>
</tbody>
</table>

This data collected from [39].
9 Viscosity

9.1 Thermal Oxide

- Viscosity variant with temperature.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Stress Relaxation Time, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>$&gt;&gt;10^{18}$</td>
</tr>
<tr>
<td>900</td>
<td>$&gt;10^{18}$</td>
</tr>
<tr>
<td>950</td>
<td>$~10^{18}$</td>
</tr>
<tr>
<td>1000</td>
<td>$7x10^{16}$</td>
</tr>
<tr>
<td>1050</td>
<td>$6x10^{15}$</td>
</tr>
<tr>
<td>1100</td>
<td>$5x10^{14}$</td>
</tr>
<tr>
<td>1180</td>
<td>$~10^{13}$</td>
</tr>
</tbody>
</table>

This data collected from [5].

Conditions:
Oxidation Temperature: see above
Oxidation Pressure: n/a.
Ambient: dry oxide.

- Viscosity (Poise), as a function of temperature.

This data reproduced from [40].
9.2 PECVD Oxide

No information available for PECVD Oxides.

9.3 Bulk Oxide

- Equilibrium viscosities for different types of vitreous silica.

![Equilibrium viscosities for different types of vitreous silica](image)

This data reproduced from [10].
Variation of viscosity with temperature for Vitreosil.

This data reproduced from [39].
Variation of Viscosity with temperature for Spectrosil.

Temperature in degrees Centigrade

Reciprocal of absolute temperature x 10^6

- Fictive temperature 900°C
- Fictive temperature 1000°C
- Fictive temperature 1100°C
- Fictive temperature 1200°C
- Fictive temperature 1300°C
- Equilibrium viscosity curve—bold symbols

This data reproduced from [30]
10 Refractive Index

10.1 Thermal Oxide

- Refractive Index varying with oxidation temperature.

This data reproduced from [1].

Conditions:

- $\text{H}_2 / \text{O}_2$ flow ratio: 1.8
- Ambient: dry $\text{O}_2$
- Pressure: 5.6 kg/cm$^2$.
• Refractive Index varying with oxidation pressure.

![Graph showing refractive index varying with oxidation pressure.]

This data reproduced from [1]

**Conditions:**
- \( H_2/O_2 \) flow ratio: 1.8
- Ambient: dry \( O_2 \)
- Pressure: 5.6 kg cm\(^{-2}\).

• Effect of oxidation temperature and pressure on refractive index, for dry oxide.

<table>
<thead>
<tr>
<th>Oxygen Pressure (atm)</th>
<th>Oxidation Temperature (°C)</th>
<th>Index of Refraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>1.486</td>
</tr>
<tr>
<td>1</td>
<td>800</td>
<td>1.474</td>
</tr>
<tr>
<td>1</td>
<td>850</td>
<td>1.478</td>
</tr>
<tr>
<td>1</td>
<td>900</td>
<td>1.466</td>
</tr>
<tr>
<td>1</td>
<td>1000</td>
<td>1.465</td>
</tr>
<tr>
<td>(high pressure)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>136</td>
<td>550</td>
<td>...</td>
</tr>
<tr>
<td>207</td>
<td>550</td>
<td>1.476</td>
</tr>
<tr>
<td>136</td>
<td>600</td>
<td>1.474</td>
</tr>
<tr>
<td>212</td>
<td>600</td>
<td>1.484</td>
</tr>
<tr>
<td>136</td>
<td>700</td>
<td>1.475</td>
</tr>
<tr>
<td>207</td>
<td>700</td>
<td>1.487</td>
</tr>
<tr>
<td>212</td>
<td>700</td>
<td>1.476</td>
</tr>
<tr>
<td>306</td>
<td>700</td>
<td>1.474</td>
</tr>
<tr>
<td>211</td>
<td>800</td>
<td>1.473</td>
</tr>
</tbody>
</table>

This data taken from [1]
• Index of refraction as a function of oxidation temperature.

This data reproduced from [3].

Conditions:
Pressure: 1 atm
Ambient: dry O₂.

• Refractive index versus anneal time for dry-oxide grown thermally on (111) Si at 800°C.

This data reproduced from [5].

Conditions:
Pressure: n/a.

• 1.460 for fully relaxed SiO₂ thin film. [5]

• 1.466 for an oxide, dry-grown at 1000°C. [5]
- Refractive Index values before and after relaxation.

<table>
<thead>
<tr>
<th>Growth Temperature, °C</th>
<th>Refractive Index</th>
<th>Relaxation Treatment</th>
<th>Refractive Index After Relaxation</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1.472</td>
<td>none</td>
<td>1.467</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
<td>1000°C 1 hr N₂</td>
<td>1.464</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
<td>1000°C 16 hr N₂</td>
<td>1.460</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
<td>1180°C 40 min N₂</td>
<td></td>
</tr>
<tr>
<td>1180</td>
<td>1.472</td>
<td>none</td>
<td>1.460</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
<td>1204°C 5 min O₂</td>
<td>1.460</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
<td>none</td>
<td>1.460</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
<td>1180°C 40 min Corona*</td>
<td>1.460</td>
</tr>
<tr>
<td>1000</td>
<td>1.467</td>
<td>800°C 20 min O₂</td>
<td>1.460</td>
</tr>
<tr>
<td>1000</td>
<td>1.467</td>
<td>none</td>
<td>1.460</td>
</tr>
<tr>
<td>1000</td>
<td>1.467</td>
<td>Corona*</td>
<td>1.460</td>
</tr>
<tr>
<td>1000</td>
<td>1.467</td>
<td>900°C 4 hr O₂</td>
<td>1.460</td>
</tr>
</tbody>
</table>

* Stress relaxation performed by a Corona discharge device.

This data taken from [7].

- Refractive Index measurements for Pressure Oxide, Normal Oxide, and Low Temperature Oxide.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Film Thickness, nm</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Oxide, 500 atm, 800°C</td>
<td>947.6</td>
<td>1.476</td>
</tr>
<tr>
<td></td>
<td>153.3</td>
<td>1.475</td>
</tr>
<tr>
<td></td>
<td>983.0</td>
<td>1.473</td>
</tr>
<tr>
<td></td>
<td>941.1</td>
<td>1.473</td>
</tr>
<tr>
<td></td>
<td>685.7</td>
<td>1.475</td>
</tr>
<tr>
<td></td>
<td>129.8</td>
<td>1.478</td>
</tr>
<tr>
<td></td>
<td>960.0</td>
<td>1.475</td>
</tr>
<tr>
<td></td>
<td>967.2</td>
<td>1.467</td>
</tr>
<tr>
<td></td>
<td>684.6</td>
<td>1.477</td>
</tr>
<tr>
<td><strong>Average:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Controls,</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 atm, 1000°C</td>
<td>959.0</td>
<td>1.461</td>
</tr>
<tr>
<td></td>
<td>951.4</td>
<td>1.461</td>
</tr>
<tr>
<td></td>
<td>1293.0</td>
<td>1.462</td>
</tr>
<tr>
<td><strong>Average:</strong></td>
<td></td>
<td>1.461</td>
</tr>
<tr>
<td><strong>Low Temperature Oxide,</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 atm, 800°C</td>
<td>...</td>
<td>1.468</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>1.476</td>
</tr>
</tbody>
</table>
This data reproduced from [8]

**Conditions:**
- Sustrates: (100) and (111) Si
- \( \text{H}_2\text{O} \) content: < 1 ppm

- **1.475** for oxide prepared at 500 atm. and 800\(^\circ\) C. [10]

- **1.461** for oxide prepared at 1 atm. and 1000\(^\circ\) C. [10]

- **1.462** for thermal oxide prepared at 1100\(^\circ\) C. [11]

The effect of oxidation time and annealing on refractive index and film thickness:

<table>
<thead>
<tr>
<th>Duration of</th>
<th>Thickness of</th>
<th>( \eta ) of</th>
<th>Thickness of</th>
<th>( \eta ) of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second</td>
<td>Unannealed</td>
<td>Unannealed</td>
<td>Annealed</td>
<td>Annealed</td>
</tr>
<tr>
<td>Oxidation, hrs</td>
<td>Film, A</td>
<td>Film</td>
<td>Film, A</td>
<td>Film</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>1.474</td>
<td>23</td>
<td>1.463</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>1.475</td>
<td>44</td>
<td>1.465</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>1.475</td>
<td>83</td>
<td>1.465</td>
</tr>
<tr>
<td>9</td>
<td>78</td>
<td>1.474</td>
<td>163</td>
<td>1.464</td>
</tr>
<tr>
<td>19</td>
<td>178</td>
<td>1.473</td>
<td>267</td>
<td>1.464</td>
</tr>
</tbody>
</table>

Data taken from [17].

Both oxidations were conducted in pure dry \( \text{O}_2 \) at 800\(^\circ\) C. The annealing was performed for 1 hour at 1000\(^\circ\)C in pure Ar.
- Refractive Index as it depends upon density.

\[ T \, ^{\circ}C: \]

\[ \text{DRY O}_2 \]

\[ \nu \]

\[ \rho \, (g \, cm^{-3}) \]

Reproduced from [22].
Refractive Index versus deposition temperature for thermal oxides grown on two different silicon substrates.

(111) Silicon

(100) Silicon

Reproduced from [34].

Variation of refractive index with oxidation temperature for thermally grown SiO₂ films.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>600*</td>
<td>1.480</td>
</tr>
<tr>
<td>700*</td>
<td>1.475</td>
</tr>
<tr>
<td>750</td>
<td>1.473</td>
</tr>
<tr>
<td>800</td>
<td>1.472</td>
</tr>
<tr>
<td>900</td>
<td>1.468</td>
</tr>
<tr>
<td>1000</td>
<td>1.465</td>
</tr>
<tr>
<td>1150</td>
<td>1.461</td>
</tr>
</tbody>
</table>

* These samples grown at 5000 psi O₂, all others at 1 atm O₂.

Reproduced from [35]
- Index of refraction vs. oxidation temperature

Conditions:
Oxidation Temperature: see above
Ambient: 95°C saturated water vapor
Substrates: (111) and (100) lightly doped Si
10.2 PECVD Oxide

- Table of values of refractive index and deposition parameters.

<table>
<thead>
<tr>
<th>Deposition Temperature, °C</th>
<th>Flow Rates N₂O:SiH₄:He, sccm</th>
<th>Deposition Rate, A/min</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>500:200:0</td>
<td>510</td>
<td>1.462</td>
</tr>
<tr>
<td>350</td>
<td>500:200:0</td>
<td>510</td>
<td>1.465</td>
</tr>
<tr>
<td>350</td>
<td>200:80:1000</td>
<td>150</td>
<td>1.469</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>60</td>
<td>1.472</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>60</td>
<td>1.464</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>50</td>
<td>1.471</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>80</td>
<td>1.471</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>80</td>
<td>1.471</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>60</td>
<td>1.471</td>
</tr>
<tr>
<td>350</td>
<td>100:40:2000</td>
<td>60</td>
<td>1.474</td>
</tr>
<tr>
<td>275</td>
<td>100:40:2000</td>
<td>60</td>
<td>1.474</td>
</tr>
</tbody>
</table>

This data collected from [4].

Conditions:
- Temperature: see above
- Pressure: 1 Torr
- Flow Rates: see above
- Rf Power: 25 W (0.03 W cm⁻²)
- Rf Freq: 13.56 MHz

- Refractive Index dependent upon Deposition Temperature, Pressure, Rate, and Anealing.

<table>
<thead>
<tr>
<th>Deposition Temperature, °C</th>
<th>Deposition Pressure</th>
<th>Deposition Rate, A/min</th>
<th>Anneal Performed</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>1 Torr</td>
<td>60</td>
<td>No</td>
<td>1.471 (+/- 0.001)</td>
</tr>
<tr>
<td>350</td>
<td>1 Torr</td>
<td>60</td>
<td>Yes</td>
<td>1.463 (+/- 0.002)</td>
</tr>
<tr>
<td>275</td>
<td>1 Torr</td>
<td>60</td>
<td>No</td>
<td>1.473 (+/- 0.002)</td>
</tr>
<tr>
<td>275</td>
<td>1 Torr</td>
<td>60</td>
<td>Yes</td>
<td>1.463 (+/- 0.002)</td>
</tr>
<tr>
<td>350</td>
<td>1 Torr</td>
<td>520</td>
<td>No</td>
<td>1.467 (+/- 0.004)</td>
</tr>
<tr>
<td>350</td>
<td>1 Torr</td>
<td>520</td>
<td>Yes</td>
<td>1.463 (+/- 0.003)</td>
</tr>
<tr>
<td>700</td>
<td>1 atm</td>
<td>50</td>
<td>No</td>
<td>1.444 (+/- 0.001)</td>
</tr>
<tr>
<td>700</td>
<td>1 atm</td>
<td>50</td>
<td>Yes</td>
<td>1.454 (+/- 0.001)</td>
</tr>
</tbody>
</table>

Data collected from reference N° 4.

Deposition Conditions
- Temperature: see above
- Pressure: see above
- N₂O/SiH₄ ratio: 125 (for atmosphere pressure deposition only)
Rf frequency : 13.56 MHz.
Rf Power : 25 W (0.03 W cm^{-2}).

Annealing Conditions
Temperature : 1000°C
Ambient : N₂
Duration : 30 min.

- 1.461 - 1.465 for oxide prepared at 500°C, 10 mTorr, Rf frequency of 0.5-3.0 MHz, and Rf Power of 1 kW. Gas data : n/a. [16]

- Refractive index, before and after annealing for PECVD oxide.

![Graph showing refractive index before and after annealing for PECVD oxide.](image)

This data reproduced from [20]

Deposition Conditions
Reagents: SiH₄, O₂, Ar
Rf frequency : 13.562 MHz
Rf Power : 50 W
Temperature : 350°C
Pressure : 1.5 Torr
SiH₄ flow : 0.3 sccm
O₂ flow rate : variable
Substrate : Al.

Annealing Conditions :
30 min. in N₂, at 1000°C
- Refractive index as it varies with reagent gas ratio, for PECVD oxide.

![Graph reproduced from [25]](image)

**Conditions:**
- Temperature: n/a
- Pressure: n/a
- Rf frequency: 13.56 MHz
- Rf Power: n/a
- Substrate: Si wafer
- Gas ratio: variable.

- Refractive index vs. gas ratio for photo-enhanced CVD SiO$_2$.

![Graph reproduced from [26]](image)

**Conditions:**
- SiH$_4$ flow rate: 1 sccm
- N$_2$O flow rate: 70 sccm
- Pressure: 1 mbar
- Temperature: 275°C
- Power density: 0.1 mW cm$^{-2}$
- N$_2$ flow rate: 30 sccm.
- Refractive index vs. gas ratio for glow-discharge deposited SiO$_2$.

Graph reproduced from [28]

Conditions:
Temperature: <40°C
Pressure: 45 mTorr
Rf frequency: 13.56 MHz
Power Density: 0.2-0.5 W cm$^{-2}$
Reagents: N$_2$O and SiH$_4$.

- Refractive index vs. deposition temperature for PECVD SiO$_2$.

Reproduced from [20]

Conditions:
Temperature: variable
Pressure: 1 Torr
Gas Ratio, N$_2$O / SiH$_4$: 65
Rf frequency: 13.56 MHz
Rf Power: 24W
Refractive index vs. gas ratio for PECVD SiO$_2$.

Reproduced from [31].

**Conditions:**
- Temperature: 300°C
- Pressure: 53 Pa
- RF frequency: 57 kHz
- RF Power Density: 0.05 W cm$^{-2}$.

Refractive index vs. rf power, for PECVD SiO$_2$.

Reproduced from [31].

**Conditions:**
- Temperature: 300°C
- Pressure: 53 Pa
- RF frequency: 57 kHz
- Gas Composition, N$_2$O: 98%, SiH$_4$: 2%.
10.3 Bulk Oxide

1.46 for bulk SiO₂. [33]
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