Mechanical Properties of Microelectronics Thin Films: Silicon Nitride ($\text{Si}_3\text{N}_4$)

Fariborz Maseeh, Miles Arnone, 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 Nitride ($\text{Si}_3\text{N}_4$) properties under various processing conditions resulted in the following document.
Acknowledgements

This research was supported in part by the Defense Advanced Research Project Agency under contract number MDA-972-88-K-0008.

Author Information


Copyright© 1989 MIT. Memos in this series are for use inside MIT and are not considered to be published merely by virtue of appearing in this series. This copy is for private circulation only and may not be further copied or distributed, except for government purposes, if the paper acknowledges U. S. Government sponsorship. References to this work should be either to the published version, if any, or in the form “private communication.” For information about the ideas expressed herein, contact the author directly. For information about this series, contact Microsystems Technology Laboratories, Room 39-321, MIT, Cambridge, MA 02139; (617) 253-0292.
DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.
PROPERTIES OF MICROELECTRONIC SILICON NITRIDE (Si₃N₄)

FARIBORZ MASEEH, MILES ARNONE, STEPHEN D. SENTURIA

MICROSYSTEMS TECHNOLOGY LABORATORIES
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING & COMPUTER SCIENCE
CAMBRIDGE, MA, USA

OCTOBER 1989

Sponsored by
Defense Advanced Research Projects Agency
DARPA/ISTO
"Computer-Aided Fabrication of Integrated Circuits"
ARPA Order No. 6510, PCN 8E20
Program Code No. HAD011
Issued by DARPA/CMO under Contract No.
MDA-972-88-k-0008.
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 [*,**]: (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 nitride, Si₃N₄. Investigating some 100+ references, a group of 36 was selected and the mechanical properties of Si₃N₄ were extracted under different chemical vapor depositions (CVD) and sputter depositions. The cited values are arranged by different mechanical property headings, and then by the deposition method as subheadings. The boldface values indicate results of experimental measurements (from references), and the italic values 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 implemented in our mechanical properties 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.


Fig. 1

CAD architecture for micro-electro-mechanical design
# Table of Contents

## Density

- P.E.C.V.D.  
  - Gas Flow - Density Relationships  
  - Gas Ratios and Composition - Density Relationships  
  - R.F. Frequency - Density Relationships  
  - R.F. Power and Density Relationships  
  - Pressure - Density Relationships  
  - Temperature - Density Relationships  
  - Density Values

- Various Depositions  
  - Density Values

- Sputtering  
  - Density Values

- Bulk Material  
  - Density Values

## Elastic Stiffness (Biaxial Modulus)

- C.V.D.  
  - Thermal Expansion Coefficient - Elastic Modulus Relationships  
  - Elastic Stiffness Values

- A.P.C.V.D.  
  - Elastic Stiffness Values

- P.E.C.V.D.  
  - Elastic Stiffness Values

## Fracture

- P.E.C.V.D.  
  - Annealing - Fracture Relationships  
  - Crack Resistance  
  - Density - Fracture Relationships  
  - Thickness - Fracture Relationships

- Poisson's Ratio
Sputtering
  Poisson's Ratio Values

Bulk Material
  Poisson's Ratio Values

Refractive Index

L.P.C.V.D.
  Refractive Index Values
  Gas Flow - Refractive Index Relationships
  Residual Stress - Refractive Index Relationships
  R.F. Power - Refractive Index Relationships
  Pressure - Refractive Index Relationships
  Refractive Index Values

A.P.C.V.D.
  Refractive Index Values

P.E.C.V.D.
  Annealing - Refractive Index Relationships
  Gas Flow - Refractive Index Relationships
  Gas Ratio - Refractive Index Relationships
  R.F. Power - Refractive Index Relationships
  Position - Refractive Index Relationships
  Pressure - Refractive Index Relationships
  Temperature - Refractive Index Relationships
  Refractive Index Values

Various Depositions
  Refractive Index Values

Residual Stress

L.P.C.V.D.
  Residual Stress Values
  Gas Ratio - Residual Stress Relationships

C.V.D.
  Annealing - Residual Stress Relationships
  Gas Flow - Residual Stress Relationships
  Temperature - Residual Stress Relationships

A.P.C.V.D.
  Annealing - Residual Stress Relationships
  Film Depth - Residual Stress Relationships
  Film Thickness - Residual Stress Relationships
  Residual Stress Values
Density

P.E.C.V.D.

Gas Flow - Density Relationships

Fig. 1: Gas flow vs. film density.

Conditions: Gases: Ar, NH₃ and SiH₄;
SiH₄ concentration = 1.7 %; SiH₄/NH₃ = 0.71;
T = 275 °C; P = 127 Pa; R.F. Power = 250 W
Taken from Sinha [31]
Density

P.E.C.V.D.
Gas Ratios and Composition - Density Relationships

![Density vs. SiH₄/ΝH₃ and SiH₄ concentration](image)

---

Fig. 2: Density vs. SiH₄/ΝH₃ and SiH₄ concentration.

**Conditions:**
- Gases: Ar, ΝH₃ and SiH₄
- SiH₄ concentration = 1.7 %, SiH₄/ΝH₃ = 0.71
- T = 275 C, P = 127 Pa, R.F. power = 250 W
- Taken from Sunhe [31]

---

![Effect of NH₃/SiH₄ upon density](image)

---

Fig. 3: Effect of NH₃/SiH₄ upon density.

**Conditions:**
- \( \phi_{N_2} = 90 \text{ sccm}; \phi_{NH_3} = 50 \text{ sccm}; \)
- R.F. power = 1 kW; P = 33 Pa; T = 200 C

- \( \phi_{NH_3} = 50 \text{ sccm}; \) R.F. power = 1 kW;
- P = 33 Pa, T = 200 C

- \( \phi_{Ar} = 90 \text{ sccm}; \phi_{NH_3} = 50 \text{ sccm}; \)
- R.F. power = 1 kW; P = 33 Pa, T = 200 C

- Taken from Tessier [32]

---

![Effect of NH₃/SiH₄ upon density](image)

---

Fig. 4: Effect of NH₃/SiH₄ upon density.

**Conditions:**
- Gases: N₂, ΝH₃ and SiH₄
- \( \phi_{NH_3} = 50 \text{ sccm}; \) R.F. power = 1 kW; P = 33 Pa
- A: T = 25 C
- B: T = 100 C
- C: T = 200 C
- D: T = 250 C
- Taken from Tessier [33]

---

![Effect of Si/N composition upon density](image)

---

Fig. 5: Effect of Si/N composition upon density.

**Conditions:**
- Gases: N₂ and SiH₄
- R.F. power = 0.64 W/cm²; P = 767 Pa
- T = 270 C
- Taken from Zhou [36]
Fig. 6: Relationship between R.F. frequency and density. 
P = 130 Pa; T = 300 C; R.F. power = 50 W; 
\( \phi_{\text{SiH}_4} = 100 \text{ sccm}; \phi_{\text{N}_2} = 700 \text{ sccm}; \phi_{\text{N}_2H_3} = 700 \text{ sccm}. 
Taken from Claassen [5].
Density

P.E.C.V.D.

R.F. Power - Density Relationships

Fig. 7: Effect of R.F. power upon density.
Reacting gases SiH$_4$, NH$_3$ and Ar; T = 275 C;
SiH$_4$ conc. = 1.78 %; SiH$_4$/NH$_3$ = 0.79
Gas flow = 2320 sccm; R.F. Power = 300 W;
P = 127 Pa
Taken from Sinha [31].
Density

P.E.C.V.D.

Pressure - Density Relationships

![Graph showing pressure vs. density relationship](image)

**Fig. 2:** Effect of increased pressure upon density.

**Conditions:**
- **Gases:** $N_2$, $NH_3$, and $SiH_4$; $\phi_{N_2} = 300$ sccm;
- $\phi_{NH_3} = 1100$ sccm; $\phi_{SiH_4} = 100$ sccm; R.F. frequency = 310 kHz;
- R.F. power = 50 W; $T = 300$ C
- Taken from Claassen [5]

![Graph showing relation between gas pressures and density](image)

**Fig. 9:** Relation between gas pressures and density.

**Conditions:**
- **Gases:** $Ar$, $NH_3$ and $SiH_4$;
- $SiH_4$ concentration = 1.78 %; $SiH_4/NH_3 = 0.71$;
- $\phi = 2320$ sccm; $T = 275$ C; R.F. Power = 250 W
- Taken from Sinha [31]

![Graph showing relation between pressure and density](image)

**Fig. 10:** Relation between pressure and density.

**Conditions:**
- **Gases:** $N_2$, $NH_3$ and $SiH_4$;
- $\phi_{NH_3:N_2} = 1400$ sccm; $\phi_{SiH_4} = 100$ sccm;
- R.F. frequency = 310 kHz; R.F. power = 50 W;
- $P = 65$ Pa; $T = 300$ C
- Taken from Claassen [5]
Density

P.E. C.V.D.

Temperature - Density Relationships

Fig. 11: Density as a function of temperature.

Conditions: Gases: N₂, NH₃ and SiH₄; \( \Phi_{\text{N₂}} = 200 \text{ sccm} \); 
\( \Phi_{\text{NH₃}} = 1200 \text{ sccm} \); \( \Phi_{\text{SiH₄}} = 100 \text{ sccm} \); 
R.F. frequency = 310 kHz; R.F. power = 50 W; 
P = 130 Pa 
Taken from Claassen [5]

Fig. 12: Effect of substrate temperature upon density.

Conditions: Gases: Ar, NH₃ and SiH₄; 
SiH₄ concentration = 1.7 %; SiH₄/NH₃ = 0.71; 
P = 127 Pa; R.F. Power = 250 W 
Taken from Sinha [31]
Density

P.E.C.V.D.

Density Values

2.55 (g/cm$^3$) [19]

Conditions: Plasma Technology Model 80 Reactor.
Taken from Kember [19]

3.02 - 3.21 (g/cm$^3$) [8]

Conditions: Gases: H$_2$, NH$_3$ and SiH$_4$; $\phi_{H2} = 4$ liters/min.
SiH$_4$/NH$_3$ = 1 to 20 - 40; T = 750 - 1100 C
Taken from Doo [8]

2.7 +/- 0.10 (g/cm$^3$) [7]

Conditions: Gases: N$_2$, NH$_3$ and SiH$_4$ (2%); $\phi_{N2} = 1375$ cm$^3$/min;
$\phi_{NH3} = 6$ cm$^3$/min; $\phi_{SiH4} = 35$ cm$^3$/min; R.F. Power = 400 W;
R.F. Frequency = 50 kHz; P = 33.3 Pa; T = 325 C
Taken from Dharmedhikari [7]

2.5 +/- 0.10 (g/cm$^3$) [7]

Conditions: Gases: N$_2$, NH$_3$ and SiH$_4$ (100%); $\phi_{N2} = 1000$ cm$^3$/min;
$\phi_{NH3} = 400$ cm$^3$/min; $\phi_{SiH4} = 150$ cm$^3$/min; R.F. Power = 400 W;
R.F. Frequency = 50 kHz; P = 26.7 Pa; T = 325 C
Taken from Dharmedhikari [7]
## Density

### Various Depositions

### Density Values

Table 1: Typical density values for various depositions as reported by Morosanu in his review of the literature. [26]

<table>
<thead>
<tr>
<th>Preparation Method</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVD: SiH$_2$ - NH$_3$</td>
<td>2.78</td>
</tr>
<tr>
<td>CVD: SiCl$_4$ - NH$_3$</td>
<td>3.1</td>
</tr>
<tr>
<td>CVD: SiH$_2$ - N$_2$</td>
<td>3.11</td>
</tr>
<tr>
<td>CVD: SiH$_2$Cl$_2$ - NH$_3$</td>
<td>3.1</td>
</tr>
<tr>
<td>RFCD: SiH$_4$ - NH$_3$</td>
<td>3.1</td>
</tr>
<tr>
<td>RFCD: SiH$_4$ - N$_2$</td>
<td>3.1</td>
</tr>
<tr>
<td>LPCVD: SiH$_2$ - NH$_3$</td>
<td>3.1</td>
</tr>
<tr>
<td>LPCVD: SiH$_2$Cl$_2$ - NH$_3$</td>
<td>3.1</td>
</tr>
<tr>
<td>Direct F Sputtering</td>
<td>3</td>
</tr>
<tr>
<td>Reactive F Sputtering</td>
<td>2.8</td>
</tr>
<tr>
<td>CVD: Si$_2$O$_3$N$_2$</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Density

Sputtering

2.8 - 3.0 (g/cm$^3$) [26].

Conditions: The deposition conditions are not elaborated upon.
Taken from Morosenu [26]

Bulk Material

3.2 (g/cm$^3$) [23].
Elastic Stiffness

C.V.D.
Thermal Expansion Coefficient - Elastic Modulus Relationships

Fig. 1: Elastic stiffness as a function of thermal expansion coefficient for quartz and silicon substrates.

Conditions: Nitrox Reactor at 800 C.
Taken from Retajczyk [29]
Elastic Stiffness (Biaxial Modulus)

C.V.D.

Elastic Stiffness Values

$3.7 \times 10^{12}$ (dyn/cm$^2$) [29].

Conditions: Nitrox Reactor; $T = 800$ C, thickness = 2000 angstroms [29]

A.P.C.V.D.

Elastic Stiffness Values

$1.5 \times 10^{12}$ (dyn/cm$^2$) [27].

Conditions: Gases: SiH$_4$, NH$_3$ and Ar; SiH$_4$/NH$_3$ $= 0.2$;
Net gas flow is constant; $P = 133$ Pa;
$T = 700$ - 800 C [27]

P.E.C.V.D.

Elastic Stiffness Values

$3 \times 10^{12}$ (dyn/cm$^2$) [14].

Conditions: Gases: SiH$_4$, NH$_3$ and N$_2$; 1% SiH$_4$ in N$_2$;
NH$_3$/SiH$_4$ $> 10$; $T = 700$ - 1000 C [14]
Fracture

P.E.C.V.D.

Annealing - Fracture Relationships

Doo [8] found that cracks occur in films thicker than one micron that have been annealed.

Conditions: Gases: \( H_2 \), \( NH_3 \) and \( SiH_4 \); \( \Phi_{H_2} = 4 \) liters/min;
\( SiH_4/NH_3 = 1 \div 20 \cdot 40; \ T = 750 \div 1100; \)
Annealed for 15 minutes at 1200 C
Taken from Doo [8]

Isomae [16] found the following relationship for the force required to initiate fracture in annealed films:

\[
F_f = 10.5 \exp(Q/kT)
\]

\( T = \) annealing temperature; \( 600 < T < 1200 \) C
\( Q = 0.25 \) eV

Conditions: Gases: \( N_2 \), \( NH_3 \) and \( SiH_4 \);
\( SiH_4/NH_3 = 0.007; \ T = 950; \)
Taken from Isomae [16]
Fracture

P.E.C.V.D.

Crack Resistance

Kember [19] observed a crack resistance of less than 500 C in nitride thin films.

Conditions: Plasma Technology Model PD80 Reactor
Taken from Kember [19]
Fracture

P.E.C.V.D.

Density - Fracture Relationships

Sinha [31] observed brittle behavior in films with low densities.

Conditions: Gases: Ar, NH₃, and SiH₄; SiH₄ conc. = 1.7%;
SiH₄/NH₃ = 0.71; φ = 2320 sccm; P = 127 Pa; T = 275 C

Taken from Sinha [31]
Fracture

P.E.C.V.D.

Thickness - Fracture Relationships

Tamura [32] observed cracking in films with thicknesses over one half micron.

Conditions: Gases: \( N_2 \), \( NH_3 \) and \( SiH_4 \); \( \Phi_{NH_3} = 1000 \) cc/min;
\( T = 940 \) C;
Taken from Tamura [32]
Poisson's Ratio

Sputtering

Poisson's Ratio Values

0.25 [25].

Conditions: Gases: H\textsubscript{2}, N\textsubscript{2} and Ar; Si/N = 0.75 - 7;
Power density = 3.20 W/cm\textsuperscript{2} [25]

Bulk Material

Poisson's Ratio Values

0.27 - 0.28 [23].
Refractive Index

L.P.C.V.D.

Gas Flow - Refractive Index Relationships

Fig. 1: The effect of increased SiH₄ flow rate upon refractive index (L.P.C.V.D.)

Conditions: Gases: SiH₄ and N₂; 0.65 = 15 sccm.
R.F. power: 150 W; P = 0.12 Pa
Taken from Hirao [13]
Refractive Index

L.P.C.V.D.
Residual Stress - Refractive Index Relationships

Fig. 2: Relation between residual stress (tensile) and Refractive Index.

Conditions: Gases: NH$_3$ and SiH$_2$Cl$_2$; P = 66.75 Pa;
T = 750, and 850 °C
Taken from Sekimoto [30]
Fig. 3: Effect of R.F. power on Refractive index.

**Conditions:**
- Gases: SiH₄ and N₂; \( \Phi_{N₂} = 15 \text{ sccm} \)
- \( \Phi_{SiH₄} = 6 \text{ sccm} \)
- \( P = 0.12 \text{ Pa} \)

Taken from Hisao [13]
Refractive Index

L.P.C.V.D.

Pressure - Refractive Index Relationships

![Graph showing the relationship between gas pressure and refractive index.](image)

Fig. 4. Effect of gas pressure upon Refractive index.

**Conditions:**

- Gases: SiH₄ and N₂; O₂/N₂ = 15 sccm;
- 6SiH₄ = 5 sccm; R.F. power = 150 W
- Taken from Hirao [13]
Refractive Index

L.P.C.V.D.

Refractive Index Values

1.99 +/- 0.02 [28].

Conditions: Gases: NH$_3$ and SiH$_2$Cl$_2$; $\Phi_{\text{SiH}_2\text{Cl}_2} = 15$ sccm;
T = 770 C [28]
Refractive Index

A.P.C.V.D.

Refractive Index Values

1.95 - 1.96 [27].

Conditions: Gases: Ar, NH₃ and SiH₄; SiH₄/NH₃ = 0.2;
Net gas flow is constant: P = 133 Pa; T = 650 - 850 C [28]

1.98 - 1.99 [27].

Conditions: Gases: Ar, NH₃ and SiH₄; SiH₄/NH₃ = 0.2;
Net gas flow is constant: P = 133 Pa; T = 650 - 850 C;
Annealed at 1000 C [28]
Refractive Index

P.E.C.V.D.

Annealing - Refractive Index Relationships

Fig. 5: The effect of annealing upon refractive index.

Conditions: Gases: NH$_3$ and SiH$_4$; R.F. frequency = 400 kHz; R.F. power = 26 - 100 W; P = 267 Pa; T = 200, 380°C
Taken from Ishii [15]
Refractive Index

P.E.C.V.D.

Gas Flow - Refractive Index Relationships

Fig. 6: The effect of SiH₄ flow on refractive index.

Conditions: Gases: N₂, NH₃ and SiH₄; R.F. frequency = 13.56 MHz;
R.F. power = 300 - 500 W; P = 267 - 668 Pa; T = 260 - 400 °C
Taken from Chang [3].

Fig. 7: Dependence of refractive index upon NH₃/SiH₄ flow ratio

Conditions: Gases: NH₃ and SiH₄; R.F. frequency = 400 kHz;
R.F. power = 26 - 100 W; P = 267 Pa; T = 200, 380 °C
Taken from Ishii [15]

Fig. 8: Refractive index as a function of nitrogen flow.

Conditions: Gases: N₂, NH₃ and SiH₄; NH₃ = 40 sccm.
SiH₄ = 30 sccm; R.F. power = 100 W; P = 267 Pa; T = 300 °C
Taken from Khanq [10]
Refractive Index

P.E.C.V.D.

Gas Flow - Refractive Index Relationships

Fig. 9: Refractive Index vs. N₂O flow.

Conditions: N₂, N₂O and NH₃; 0.8 SiH₄ (in N₂) = 2950 cm³/min;
R.F. frequency = 380 kHz; R.F. power = 700 W; P = 48 Pa
Taken from Knoelle [21]

Fig. 10: Refractive index as a function of SiH₄ flow rate.

Conditions: Gases: N₂ and SiH₄; 0.8N₂ = 30 sccm;
R.F. frequency = 13.56 MHz; R.F. power = 0.64 W/cm²;
P = 53.3 Pa; T = 270 C
Taken from Zhou [36]

Figure 11: Refractive index as a function of gas ratio.

Conditions: Gases: N₂, NH₃, and SiH₄; R.F. Frequency = 13.56 MHz;
R.F. power = 100 W; P = 257 Pa; T = 300 C
Taken from Khalilq [26]
**Refractive Index**

**P.E.C.V.D.**

Gas Flow - Refractive Index Relationships

Table 1: Refractive index as a function of $N_2O$ flow and Temperature.

<table>
<thead>
<tr>
<th>$N_2O$ flow (cm$^3$/min)</th>
<th>Temp. (C)</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>2.01</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>1.94</td>
</tr>
<tr>
<td>30</td>
<td>200</td>
<td>1.85</td>
</tr>
<tr>
<td>60</td>
<td>200</td>
<td>1.77</td>
</tr>
<tr>
<td>90</td>
<td>200</td>
<td>1.70</td>
</tr>
<tr>
<td>0</td>
<td>250</td>
<td>2.06</td>
</tr>
<tr>
<td>10</td>
<td>250</td>
<td>1.98</td>
</tr>
<tr>
<td>30</td>
<td>250</td>
<td>1.85</td>
</tr>
<tr>
<td>60</td>
<td>250</td>
<td>1.75</td>
</tr>
<tr>
<td>90</td>
<td>250</td>
<td>1.68</td>
</tr>
<tr>
<td>0</td>
<td>300</td>
<td>2.15</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>2.05</td>
</tr>
<tr>
<td>30</td>
<td>300</td>
<td>1.89</td>
</tr>
<tr>
<td>60</td>
<td>300</td>
<td>1.78</td>
</tr>
<tr>
<td>0</td>
<td>350</td>
<td>2.27</td>
</tr>
<tr>
<td>10</td>
<td>350</td>
<td>1.97</td>
</tr>
<tr>
<td>20</td>
<td>350</td>
<td>1.81</td>
</tr>
</tbody>
</table>

Conditions: $N_2$, $N_2O$ and NH$_3$: SiH$_4$ (in N$_2$) = 2950 cm$^3$/min; R.F. frequency = 380 kHz; R.F. power = 700 W, P = 48 Pa

Taken from Knolle [21]
Refractive Index

P.E.C.V.D.

Gas Ratio - Refractive Index Relationships

Figure 12: Refractive index as a function of Si-N/N-H ratio.

Conditions: N₂, N₂O and NH₃; 6SiH₄ (in N₂) = 2950 cm³/min;
R.F. frequency = 380 kHz; R.F. power = 700 W; P = 48 Pa
Taken from Knolle [21]

Figure 13: Refractive index vs. Si-H content.

Conditions: N₂, N₂O and NH₃; 6SiH₄ (in N₂) = 2950 cm³/min;
R.F. frequency = 380 kHz; R.F. power = 700 W; P = 48 Pa
Taken from Knolle [21]

Fig. 14: Refractive index vs. SiH₂Cl₂/NH₃ ratio.

Conditions: Gases: NH₃ and SiH₂Cl₂; P = 66.75 Pa
T = 750, 800 and 850°C
Taken from Sekimoto [30]

Fig. 15: Effect of gas composition on Refractive index.

Conditions: H₂, N₂ and SiH₄; 6SiH₄ (in N₂) = 2950 cm³/min;
R.F. frequency = 13.56 MHz; R.F. power density = 0.8 W/cm²;
P = 400 - 933 Pa; T = 300°C
Taken from Watanabe [35]
Refractive Index

P.E.C.V.D.

Gas Ratio - Refractive Index Relationships

Fig. 16: Refractive index as a function of Si-N/H bond ratio.

Conditions: Plasma Technology Model PD80 Reactor
Taken from Kember [19]
Refractive Index

P. E. C. V. D.

R. F. Power - Refractive Index Relationships

Fig. 17: Effect of R. F. power on Refractive index.

Conditions: Gases: NH₃ and SiH₄, R. F. frequency = 400 kHz.
R. F. power = 26 - 100 W; P = 267 Pa; T = 200, 380°C
Taken from Ishi [15]
Refractive Index

P.E.C.V.D.

Position - Refractive Index Relationships

Fig. 18: Refractive index as a function of position across a 5 cm wafer.

Conditions: Gases: NH₃ and SiH₄; R.F. frequency = 400 kHz; R.F. power = 26 - 100 W; P = 267 Pa; T = 200, 380 C
Taken from Ishii [15]
Refractive Index

P.E.C.V.D.
Pressure - Refractive Index Relationships

Fig. 19: Effect of gas pressure upon Refractive index.

Conditions: H₂, N₂ and SiH₄; Ψ SiH₄ in N₂) = 2950 cm³/min;
R.F. frequency = 13.56 MHz; R.F. power density = 0.8 W/cm²;
T = 270 C
Taken from Watanabe [35]

Fig. 20: Relationship between gas pressure and Refractive index.

Conditions: Gases: N₂ and SiH₄; Ψ N₂ = 30 sccm;
Ψ SiH₄ = 30 sccm; R.F. frequency = 13.56 MHz;
R.F. power = 0.64 W/cm²; T = 270 C
Taken from Zhou [36]

Fig. 21: Relationship between NH₃ gas pressure and Refractive index.

Conditions: Gases: N₂, NH₃ and SiH₄; R.F. Frequency = 310 KHz;
P = 65 Pa; T = 300 C
Taken from Claessen [5]
Refractive Index

P.E.C.V.D.

Temperature - Refractive Index Relationships

![Graph showing temperature vs. refractive index relationship]

Fig. 22: Relationship between temperature and Refractive index.

Conditions: Gases: \( \text{N}_2, \text{NH}_3 \) and \( \text{SiH}_4 \); \( \text{NH}_3/\text{SiH}_4 = 1000 \)

Taken from Hezel [12]

![Graph showing refractive index vs. temperature relationship]

Fig. 23: Refractive index as a function of deposition temperature.

Conditions: \( \text{N}_2, \text{N}_2 \text{O} \) and \( \text{NH}_3 \); \( \text{SiH}_4 \) (in \( \text{N}_2 \)) = 2950 cm\(^3\)/min.

R.F. frequency = 380 kHz, R.F. power = 700 W, \( P = 48 \text{ Pa} \)

Taken from Knolle [21]
# Refractive Index

## P.E.C.V.D.

## Refractive Index Values

Table 2: Refractive index as a function of deposition characteristics. [18]

<table>
<thead>
<tr>
<th>System</th>
<th>P (W cm⁻²)</th>
<th>T (°C)</th>
<th>P (Torr)</th>
<th>SiH₄</th>
<th>NH₃</th>
<th>Gas Flow (sccm)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13.56 M</td>
<td>0.44</td>
<td>120</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.80</td>
</tr>
<tr>
<td>B</td>
<td>13.56 M</td>
<td>0.58</td>
<td>240</td>
<td>200</td>
<td>0.5</td>
<td>22</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>370</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>370</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.20</td>
</tr>
<tr>
<td>C</td>
<td>13.56 M</td>
<td>0.02</td>
<td>100</td>
<td>250</td>
<td>0.12</td>
<td>170</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>320</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>400</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.09</td>
</tr>
<tr>
<td>D</td>
<td>13.56 M</td>
<td>0.05</td>
<td>100</td>
<td>250</td>
<td>0.45</td>
<td>1400</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.41</td>
</tr>
<tr>
<td>E1</td>
<td>50 W</td>
<td>350</td>
<td>100</td>
<td>250</td>
<td>0.45</td>
<td>380</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.05</td>
</tr>
<tr>
<td>E2</td>
<td>150 W</td>
<td>350</td>
<td>100</td>
<td>500</td>
<td>0.6</td>
<td>380</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.12</td>
</tr>
</tbody>
</table>

33
Refractive Index

P.E.C.V.D.

Refractive Index Values

2.0 - 2.06 [8].

*Conditions:* Gases: \( \text{H}_2, \text{NH}_3 \) and \( \text{SiH}_4 \); \( \phi_{\text{H}_2} = 4 \) liters/min;
\( \text{SiH}_4/\text{NH}_3 = 1 \) to \( 20 - 40 \); \( T = 750 - 1100 \)
Taken from Doo [8]

2.05 [19].

*Conditions:* Plasma Technologies Model PD80 Reactor
Taken from Kember [19]

1.95 +/- 0.028 [7].

*Conditions:* Gases: \( \text{N}_2, \text{NH}_3 \) and \( \text{SiH}_4 \) (2%); \( \phi_{\text{N}_2} = 1375 \) cm\(^3\)/min,
\( \phi_{\text{NH}_3} = 6 \) cm\(^3\)/min; \( \phi_{\text{SiH}_4} = 35 \) cm\(^3\)/min; R.F. power = 400 W;
R.F. frequency = 50 kHz; \( P = 26.7 \) Pa; \( T = 325 \) C
Taken from Dharmadhikari [7]

2.03 +/- 0.030 [7].

*Conditions:* Gases: \( \text{N}_2, \text{NH}_3 \) and \( \text{SiH}_4 \) (100%); \( \phi_{\text{N}_2} = 1000 \) cm\(^3\)/min;
\( \phi_{\text{NH}_3} = 400 \) cm\(^3\)/min; \( \phi_{\text{SiH}_4} = 150 \) cm\(^3\)/min; R.F. power = 400 W;
R.F. frequency = 50 kHz; \( P = 26.7 \) Pa; \( T = 325 \) C
Taken from Dharmadhikari [7]
Refractive Index

Various Depositions

Refractive Index Values

Table 3: Typical refractive index values as reported by Morosanu in a review of other literature. [26]

<table>
<thead>
<tr>
<th>Preparation method</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVD. SiH$_4$ + NH$_3$</td>
<td>1.926</td>
</tr>
<tr>
<td>CVD. SiCl$_4$ + NH$_3$</td>
<td>2.028</td>
</tr>
<tr>
<td>CVD. SiH$_4$ + N$_2$H$_4$</td>
<td>2.021</td>
</tr>
<tr>
<td>CVD. SiH$_2$Cl$_2$ + NH$_3$</td>
<td>1.921</td>
</tr>
<tr>
<td>RFGD SiH$_4$ + NH$_3$</td>
<td>1.926</td>
</tr>
<tr>
<td>RFGD SiH$_4$ + N$_2$</td>
<td>2.025</td>
</tr>
<tr>
<td>LPCVD. SiH$_4$ + NH$_3$</td>
<td>1.95208</td>
</tr>
<tr>
<td>LPCVD. SiH$_2$Cl$_2$ + NH$_3$</td>
<td>2.000</td>
</tr>
<tr>
<td>Direct r.f sputtering</td>
<td>1.9708</td>
</tr>
<tr>
<td>Reactive r.f sputtering</td>
<td>2.221</td>
</tr>
<tr>
<td>CVD. Si$_3$O$_2$N$_x$</td>
<td>1.44203</td>
</tr>
</tbody>
</table>
Residual Stress

L. P. C. V. D.

Gas Ratio - Residual Stress Relationships

Fig. 1: Residual stress vs. SiH₂Cl₂/NH₃ ratio.

Conditions: Gases: NH₃ and SiH₂Cl₂; P = 66.75 Pa;
T = 750, 800 and 850 °C
Taken from Sekimoto [30]

Fig. 2: Residual stress vs NH₃/SiH₂Cl₂ ratio.

Conditions: Gases: NH₃ and SiH₂Cl₂; SiH₂Cl₂ = 15 sccm
Taken from Pan [28]
Residual Stress

L.P.C.V.D.

Residual Stress Values

Table 1: Residual stress and change in residual stress as a function of deposition conditions. [9]

<table>
<thead>
<tr>
<th>NO SiH₄</th>
<th>$\frac{\rho_S}{(\rho_S + \rho_N)}$</th>
<th>Atomic Fraction Si</th>
<th>T (cm x 10⁻³)</th>
<th>t A</th>
<th>Days after prep</th>
<th>Avg. P</th>
<th>$\sigma$ × 10⁻⁹ cm²</th>
<th>$\Delta\sigma$ × 10⁻⁹ cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>0.54</td>
<td>17.9</td>
<td>(750)</td>
<td>4</td>
<td>31.5</td>
<td>-47.7</td>
<td>-133</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14.3</td>
<td>-104</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.062</td>
<td>0.54</td>
<td>6.27</td>
<td>5500</td>
<td>2</td>
<td>7.81</td>
<td>-35.3</td>
<td>-43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.86</td>
<td>-43</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>4.21</td>
<td>-77.0</td>
<td>-65.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>4.21</td>
<td>-77.0</td>
<td>-65.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>8.85</td>
<td>-116</td>
<td>-137</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.127</td>
<td>0.54</td>
<td>6.27</td>
<td>0</td>
<td>0</td>
<td>20.9</td>
<td>-10.9</td>
<td>-9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23.6</td>
<td>-7.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>49.8</td>
<td>-4.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46.2</td>
<td>-4.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>60.9</td>
<td>-1.4</td>
<td>-0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>70.3</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55</td>
<td>174</td>
<td>4.3</td>
<td>9.6</td>
<td>-137</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>174</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>66</td>
<td>174</td>
<td>1.3</td>
<td>9.6</td>
<td>-137</td>
</tr>
<tr>
<td>15</td>
<td>0.17</td>
<td>0.34</td>
<td>3.43</td>
<td>3780</td>
<td>4</td>
<td>2.40</td>
<td>50</td>
<td>-36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.65</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.30</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.46</td>
<td>14</td>
<td>-36</td>
</tr>
<tr>
<td>3</td>
<td>0.33</td>
<td>0.34</td>
<td>7.80</td>
<td>3400</td>
<td>4</td>
<td>5.34</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.34</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.86</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.06</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.18</td>
<td>132</td>
<td>4.7</td>
</tr>
<tr>
<td>1</td>
<td>0.42</td>
<td>0.38</td>
<td>7.80</td>
<td>2875</td>
<td>4</td>
<td>6.63</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.63</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.43</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.43</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.40</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.40</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>-*</td>
<td>1</td>
<td>0.43</td>
<td>8.38</td>
<td>2200</td>
<td>1</td>
<td>1.34</td>
<td>880</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.34</td>
<td>880</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.34</td>
<td>880</td>
<td>-5</td>
</tr>
</tbody>
</table>

*Pyrolytic SiN₄ from SiH₄ + NH₃

Conditions: Gases: N₂, NH₃ and SiH₄; T = 850 C

Taken from Drum [9]
Residual Stress

C.V.D.

Annealing - Residual Stress Relationships

Fig. 3: Residual stress vs. annealing temperature.

Conditions: Gases: N₂, NH₃ and SiH₄;
T = 940°C
Taken from Tamura [32]
Residual Stress

C.V.D.

Gas Flow - Residual Stress Relationships

Fig. 4: Effect of NH$_3$ flow upon residual stress.

Conditions: Gases: N$_2$, NH$_3$ and SiH$_4$;
T = 940 C
Taken from Tanura [32]
Residual Stress

C.V.D. Temperature - Residual Stress Relationships

Fig. 5: Residual stress vs. temperature at measurement for increasing (up) and decreasing (down) temperatures.

Conditions: Gases: N₂, NH₃ and SiH₄; 6NH₃ = 1000 cc/min;
T = 940 C; (100) Si wafer
Taken from Tamura [32]

Fig. 6: Residual stress vs. temperature at measurement for increasing (up) and decreasing (down) temperatures.

Conditions: Gases: N₂, NH₃ and SiH₄; 6NH₃ = 1000 cc/min;
T = 940 C; (111) Si wafer
Taken from Tamura [32]
Residual Stress

C.V.D. Temperature - Residual Stress Relationships

Fig. 7: Residual stress vs. deposition temperature.

Conditions: Gases: N₂, NH₃ and SiH₄; \( \phi \)NH₃ = 1000 cc/min.
Taken from Tamura [32]
Residual Stress

A.P.C.V.D.

Annealing - Residual Stress Relationships

Fig. 8: The effect of annealing upon residual stress.

Conditions: Gases: Ar, NH₃ and SiH₄, SiH₄/NH₃ = 0.2
Net gas flow is constant: P = 133 Pa
Taken from Noskov [27]
Residual Stress

A.P.C.V.D.

Film Depth - Residual Stress Relationships

Fig. 9: Residual stress as a function of depth in film.

Conditions: Gases: Ar, NH₃ and SiH₄:SiH₄/NH₃ = 0.2
Net gas flow is constant; P = 133 Pa
Taken from Noskov [27]
Residual Stress

A.P.C.V.D.

Film Thickness - Residual Stress Relationships

Fig. 10: Residual stress as a function of film thickness.

Conditions: Gases: Ar, NH₃ and SiH₄; SiH₄/NH₃ = 0.2
Net gas flow is constant; P = 133 Pa
Taken from Noskov [27]
Residual Stress

A.P.C.V.D.

Residual Stress Values

\((1.1 \pm 1.2) \times 10^{10} \text{ (dyn/cm}^2\) \text{)} [27].

Conditions: Gases: \(\text{Ar, NH}_3\) and \(\text{SiH}_4\); \(\text{SiH}_4/\text{NH}_3 = 0.2\).
Net gas flow is constant; \(P = 133 \text{ Pa}\).
Taken from Noskov [27]
Residual Stress

P.E.C.V.D.
Annealing - Residual Stress Relationships

Fig. 1: Residual stress vs. annealing temperature.

Conditions: Gases: N₂, NH₃ and SiH₄; \( \Phi_{NH_3} = 1200 \) sccm;
\( \Phi_{SiH_4} = 100 \) sccm; \( \Phi_{N_2} = 200 \) sccm; R.F. frequency = 310 kHz
\( P = 130 \) Pa
Taken from Claassen [5]
Residual Stress

P.E.C.V.D.

Film Thickness - Residual Stress Relationships

![Graph showing residual stress as a function of film thickness.](image)

**Fig. 12:** Residual stress (tensile) as a function of film thickness.

Conditions: Gases: N₂, NH₃ and SiH₄; 1% SiH₄ in N₂;
NH₃/SiH₄ = 10; T = 900 - 1000 °C
Taken from [Irene](#) [14]

---

47
Residual Stress

P.E.C.V.D.

Gas Flow - Residual Stress Relationships

Fig. 13: Residual stress vs. SiH₄ flow and SiH₄/NH₃ ratio.

Conditions: Gases: Ar, NH₃ and SiH₄; SiH₄ conc. = 1.75%;
φ = 2320 sccm; R.F. power = 250 W;
P = 127 Pa; T = 275°C
Taken from Sinha [31]

Fig. 14: Effect of SiH₄ flow upon residual stress.

Conditions: Gases: N₂, NH₃ and SiH₄, R.F. frequency = 13.56 MHz;
R.F. power = 300 - 500 W; φ = 267 - 668 sccm; T = 265 - 400°C
Taken from Cheng [3]

Fig. 15: Residual stress vs. net gas flow.

Conditions: Gases: Ar, NH₃ and SiH₄;
SiH₄/SiH₃ = 0.71; R.F. power = 250 W;
P = 127 Pa; T = 275°C
Taken from Sinha [31]
Table 2: Refractive index as a function of N\textsubscript{2}O flow and Temperature.

<table>
<thead>
<tr>
<th>N\textsubscript{2}O flow (cm\textsuperscript{3}/min)</th>
<th>Temp. (C)</th>
<th>Compressive residual stress (10\textsuperscript{9} dyne/cm\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>3.6</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>3.7</td>
</tr>
<tr>
<td>30</td>
<td>200</td>
<td>3.0</td>
</tr>
<tr>
<td>60</td>
<td>200</td>
<td>2.0</td>
</tr>
<tr>
<td>90</td>
<td>200</td>
<td>1.2</td>
</tr>
<tr>
<td>0</td>
<td>250</td>
<td>3.0</td>
</tr>
<tr>
<td>10</td>
<td>250</td>
<td>2.3</td>
</tr>
<tr>
<td>30</td>
<td>250</td>
<td>1.6</td>
</tr>
<tr>
<td>60</td>
<td>250</td>
<td>0.9</td>
</tr>
<tr>
<td>90</td>
<td>250</td>
<td>1.0</td>
</tr>
<tr>
<td>0</td>
<td>300</td>
<td>3.1</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>2.3</td>
</tr>
<tr>
<td>30</td>
<td>300</td>
<td>1.2</td>
</tr>
<tr>
<td>60</td>
<td>300</td>
<td>0.7</td>
</tr>
<tr>
<td>0</td>
<td>350</td>
<td>2.1</td>
</tr>
<tr>
<td>10</td>
<td>350</td>
<td>0.5</td>
</tr>
<tr>
<td>20</td>
<td>350</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Conditions: N\textsubscript{2}, N\textsubscript{2}O and NH\textsubscript{4}; SiH\textsubscript{4} (in N\textsubscript{2}) = 2950 cm\textsuperscript{3}/min; R.F frequency = 380 kHz; R.F. power = 700 W, P = 48 Pa; Taken from Knolle [21]
Residual Stress

P.E.C.V.D.

Gas Ratios - Residual Stress Relationships

Fig. 16: Residual stress vs. $\text{NH}_3/\text{SiBr}_4$ ratio.

**Conditions:** Gases: $\text{NH}_3$ and $\text{SiBr}_4$; $T = 800 ^\circ \text{C}$
Taken from Aoad [1]

Fig. 17: Residual stress vs. $\% \text{N}_2$ in flow.

**Conditions:** Gases: $\text{Ar}$, $\text{N}_2$, $\text{NH}_3$ and $\text{SiH}_4$; $\text{SiH}_4$ conc. = 1.7%;
$\phi = 2320 \text{ sccm}$; R.F. power = 250 W;
P = 127 Pa; $T = 275 ^\circ \text{C}$
Taken from Sinha [31]

Fig. 18: The effect of $\text{O}_2$ addition on residual stress.

**Conditions:** Gases: $\text{Ar}$, $\text{NH}_3$, $\text{O}_2$ and $\text{SiH}_4$; $\text{SiH}_4$ conc. = 1.7%,
$\text{SiH}_4/\text{NH}_3 = 0.71$; $\phi = 2320 \text{ sccm}$; R.F. power = 250 W;
P = 127 Pa; $T = 275 ^\circ \text{C}$
Taken from Sinha [31]
Residual Stress

P.E.C.V.D.

Gas Ratios - Residual Stress Relationships

Fig. 19: Residual stress vs. partial pressures of component gases.

**Conditions:** Gases: N₂, NH₃ and SiH₄; R.F. frequency = 50 kHz;
P = 40 Pa; T = 300 C
Taken from Claassen [5]
Residual Stress

P.E.C.V.D.

Hydrogen Content - Residual Stress Relationships

Fig. 20: Residual stress vs. hydrogen content.

**Conditions:** Gases: NH$_3$ and SiH$_4$.

<table>
<thead>
<tr>
<th>System</th>
<th>Frequency (Hz)</th>
<th>P (w/cm$^2$)</th>
<th>T (°C)</th>
<th>Gas flow (scem)</th>
<th>P (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SiH$_4$</td>
<td>NH$_3$</td>
</tr>
<tr>
<td>A</td>
<td>13.56 MHz</td>
<td>0.04</td>
<td>?</td>
<td>?</td>
<td>40</td>
</tr>
<tr>
<td>B</td>
<td>13.56 MHz</td>
<td>0.38</td>
<td>22</td>
<td>80</td>
<td>56</td>
</tr>
<tr>
<td>C</td>
<td>13.56 MHz</td>
<td>3.02</td>
<td>17</td>
<td>120</td>
<td>42.7</td>
</tr>
<tr>
<td>D</td>
<td>187.5 kHz</td>
<td>0.06</td>
<td>1400</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td>E1</td>
<td>50 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>450 kHz</td>
<td>150 W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>50 kHz</td>
<td></td>
<td>333</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>450 kHz</td>
<td></td>
<td>333</td>
<td>280</td>
<td></td>
</tr>
</tbody>
</table>

Taken from Kamacki [18]
Residual Stress

P.E.C.V.D.
Ion Implantation - Residual Stress Relationships

Fig. 21: Ion implantation induced residual compressive stress.

Conditions:

- Film A: 5% oxygen, T = 750 C, thickness = 2300 Angstroms
- Film B: 0% oxygen, T = 750 C, thickness = 2600 Angstroms
- Film C: 0% oxygen, T = 1000 C, thickness = 2900 Angstroms

Taken from Eernisse [10]
Residual Stress

P.E.C.V.D.

Refractive Index - Residual Stress Relationships

Fig. 22: Residual stress as related to refractive index.

Conditions: Gases, $N_2$, $NH_3$, and $SiH_4$ (1%); $\text{N}_2 = 125$ ml/min;
$\text{SiH}_4 = 83$ ml/min; $NH_3/\text{SiH}_4 = 10$. $T = 725, 910$ C

Taken from: [14]
Residual Stress

P.E.C.V.D.

R.F. Frequency - Residual Stress Relationships

Fig. 23: Residual stress as a function of R.F. frequency.

Conditions: Gases: $N_2$, $NH_3$ and $SiH_4$: $\phi_{NH_3} = 1200$ sccm;
$\phi_{SiH_4} = 100$ sccm; $\phi_{N_2} = 200$ sccm; $P = 130$ Pa

Taken from Claassen [6]
Residual Stress

P.E.C.V.D.

R.F. Power - Residual Stress Relationships

Fig. 24: Residual stress vs. R.F. power.

**Condition:**
- Gases: Ar, N\textsubscript{2} \textsubscript{3}, O\textsubscript{2} and SiH\textsubscript{4}; SiH\textsubscript{4} conc. = 1.7\%;
- SiH\textsubscript{4}/NH\textsubscript{3} = 0.71; \phi = 2320 sccm; P = 127 Pa; T = 275 C
- Taken from Stuhs [31]

Fig. 25: Residual stress as a function of R.F. power.

**Conditions:**
- Gases: N\textsubscript{2}, NH\textsubscript{3} and SiH\textsubscript{4}; R.F. frequency = 50 kHz
- P = 40 Pa; T = 300 C
- Taken from Claassen [5]
Residual Stress

P.E.C.V.D. Pressure - Residual Stress Relationships

Fig. 26: Residual stress as a function of deposition pressure.

Conditions: Gases: N\textsubscript{2}, NH\textsubscript{3} and SiH\textsubscript{4}; \( \phi\text{NH}_3 = 1200 \) sccm,
\( \phi\text{SiH}_4 = 100 \) sccm; \( \phi\text{O}_2 = 260 \) sccm; R.F. frequency = 310 kHz
\( P = 130 \) Pa
Taken from Claassen [6]

Fig. 27: Residual stress vs. pressure.

Conditions: Gases: Ar, NH\textsubscript{3}, O\textsubscript{2} and SiH\textsubscript{4}; SiH\textsubscript{4} conc. = 1.7%,
SiH\textsubscript{4}/NH\textsubscript{3} = 0.71; \( \bullet = 2320 \) sccm; \( T = 275 \) C
Taken from Suh [91]
Residual Stress

P.E.C.V.D.

Temperature - Residual Stress Relationships

Fig. 28: Residual stress as a function of deposition temperature.

Conditions: Gases: NH₃ and SiBr₄; SiBr₄/NH₃ = 1:13;
T = 800 °C
Taken from Aboaf [1]

Fig. 29: Residual stress vs. (deposition - room) temperature.

Conditions: Gases: N₂, NH₃ and SiH₄ (1%); Φ_NH₃ = 125 ml/min;
Φ_SiH₄ = 83 ml/min; NH₃/SiH₄ = 150; T = 700 - 1000 °C
Taken from Irene [4]
Residual Stress

P.E.C.V.D. Temperature - Residual Stress Relationships

Fig. 30: Residual stress vs. deposition temperature.

Conditions: Gases: N$_2$, NH$_3$ and SiH$_4$: $\phi_{NH_3} = 1200$ sccm; $\phi_{SiH_4} = 100$ sccm; $\phi_{N_2} = 200$ sccm; R.F. frequency = 310 kHz; $P = 130$ Pa
Taken from Claassen [5]

Fig. 31: Residual stress vs. deposition temperature.

Conditions: Gases: N$_2$, NH$_3$ and SiH$_4$; R.F. frequency = 50 kHz; $P = 40$ Pa
Taken from Claassen [5]
Residual Stress

P.E.C.V.D.

Temperature - Residual Stress Relationships

**Fig. 32:** Residual tensile stress vs. deposition temperature.

*Conditions:* Gases: Ar, NH$_3$, O$_2$ and SiH$_4$; SiH$_4$ conc. = 1.7%;
SiH$_4$/NH$_3$ = 0.71; $\phi = 2320$ sccm, $P = 127$ Pa, $T = 275$ C
Taken from Sinha [31]

**Fig. 33:** Residual stress vs. deposition temperature for differing substrates.

*Conditions:* Nirox plasma reactor
Taken from Retajczyk [49]

**Fig. 34:** Residual stress (tensile) vs. deposition temperature.

*Conditions:* Gases: N$_2$, NH$_3$ and SiH$_4$; NH$_3$/SiH$_4$ = 1000
Taken from Hezel [12]
Residual Stress

P.E.C.V.D.

Residual Stress Values

Table 2: Residual stress as a function of deposition parameters. [18]

<table>
<thead>
<tr>
<th>System</th>
<th>P (W)</th>
<th>T (°C)</th>
<th>P (m)</th>
<th>N₂H₃</th>
<th>NH₃</th>
<th>G (sccm)</th>
<th>Res (x10²) (dyn cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1350 M</td>
<td>0.04</td>
<td>120</td>
<td>250</td>
<td>0.3</td>
<td>N₂H₃</td>
<td>30</td>
<td>170</td>
</tr>
<tr>
<td>B 1350 M</td>
<td>0.3</td>
<td>100</td>
<td>250</td>
<td>0.5</td>
<td>NH₃</td>
<td>30</td>
<td>175</td>
</tr>
<tr>
<td>C 1350 M</td>
<td>0.02</td>
<td>100</td>
<td>250</td>
<td>0.32</td>
<td>17</td>
<td>120</td>
<td>310</td>
</tr>
<tr>
<td>D 1850 M</td>
<td>0.04</td>
<td>100</td>
<td>250</td>
<td>0.45</td>
<td>140°</td>
<td>--</td>
<td>140</td>
</tr>
<tr>
<td>E1 50 k</td>
<td>25 W</td>
<td>100</td>
<td>250</td>
<td>0.31</td>
<td>30</td>
<td>130</td>
<td>100</td>
</tr>
<tr>
<td>E2 450 k</td>
<td>150 W</td>
<td>100</td>
<td>250</td>
<td>0.31</td>
<td>30</td>
<td>130</td>
<td>310</td>
</tr>
<tr>
<td>F1 50 k</td>
<td>300 W</td>
<td>250</td>
<td>25</td>
<td>333</td>
<td>2000</td>
<td>311</td>
<td>-0.03</td>
</tr>
<tr>
<td>F2 450 k</td>
<td>300 W</td>
<td>250</td>
<td>25</td>
<td>333</td>
<td>2000</td>
<td>309</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

61
Residual Stress

P.E.C.V.D.

Residual Stress Values

\((0.5 - 1.0) \times 10^{10}\) <Tensile> (dyn/cm²) \([19]\).

**Conditions:** Plasma Technology Mod-1 PD80 Reactor
Taken from Kember \([19]\)

\(8.5 \times 10^9\) <Tensile> (dyn/cm²) \([9]\).

**Conditions:** Gases: \(N_2\), \(NH_3\) and \(SiH_4\); \(T = 700 - 900\) C
Taken from Evrom \([9]\)

\((8-11) \times 10^9\) <Compressive> (dyn/cm²) \([7]\).

**Conditions:** Gases: \(N_2\), \(NH_3\) and \(SiH_4\) (2%); \(\theta_{N_2} = 1575\) cm³/min;
\(\theta_{NH_3} = 6\) cm³/min; \(\theta_{SiH_4} = 35\) cm³/min; R.F. power = 400 W;
R.F. frequency = 50 kHz; \(P = 33.3\) Pa; \(T = 225\) C
Taken from Dharmanadhakari \([7]\)

\((7-9) \times 10^9\) <Compressive> (dyn/cm²) \([7]\).

**Conditions:** Gases: \(N_2\), \(NH_3\) and \(SiH_4\) (100%); \(\theta_{N_2} = 1600\) cm³/min;
\(\theta_{NH_3} = 400\) cm³/min; \(\theta_{SiH_4} = 150\) cm³/min; R.F. power = 400 W;
R.F. frequency = 50 kHz; \(P = 26.7\) Pa; \(T = 325\) C
Taken from Dharmanadhakari \([7]\)

\(1.2 \times 10^{10}\) <Tensile> (dyn/cm²) \([1]\).

**Conditions:** gases: \(NH_3\) and \(SiH_4\); \(SiH_4/NH_3 = 0.037\);
\(T = 600\) C
Taken from Aboul \([1]\)
Residual Stress

Sputtering

Composition and Temperature - Residual Stress Relationships

Fig. 35. Relationships between residual stress, Si/N ratio and hydrogen content.

Conditions: Gases: Ar, H₂ and N₂; R.F. power density = 3.29 W/cm²; T = 175 C
Taken from Martin [25]
Thermal Expansion Coefficient

C.V.D.

Thermal Expansion Coefficient Values

2.5 - 3.85 x 10^{-6} (1/C) [32].

*Conditions*: Gases: N\textsubscript{2}, NH\textsubscript{3} and SiH\textsubscript{4};
T = 940 C
Taken from Tamura [32]

3.85 x 10^{-6} (C^{-1}) [34].

*Conditions*: Gases: SiH\textsubscript{4} and NH\textsubscript{3}; T = 800 and 1000 C [34]
Thermal Expansion Coefficient

P.E.C.V.D.

Thermal Expansion Coefficient Values

\[ 1.6 \times 10^{-6} \text{ (C}^{-1} \text{)} \] [29].

**Conditions:** Ninox Plasma Reactor; \( T = 800 \) C [29]

\[ \alpha_{Si} \text{Si}_3N_4 - \alpha_{Si} = -9 \times 10^{-7} \] [14].

**Conditions:** Gases: \( \text{SiH}_4, \text{NH}_3 \) and \( \text{N}_2 \); 1\% \( \text{SiH}_4 \) in \( \text{N}_2 \);
\( \text{NH}_3/\text{SiH}_4 > 10; T = 700 - 1000 \) C [14]

Bulk Material

\[ (2.5 - 3.1) \times 10^{-6} \text{ (C}^{-1} \text{)} \] [23].
Young's Modulus

C.V.D.

Young's Modulus Values

\[ 4.0 \times 10^{12} \text{ (dyn/cm}^2\text{)} \] [34].

Conditions: Gases: SiH\textsubscript{4} and NH\textsubscript{3}, T = 800 and 1000 C [34]

Sputtering

Young's Modulus Values

\[ 1.3 \times 10^{12} \text{ (dyn/cm}^2\text{)} \] [22].

Korhonen [22] gave no details on the nitride processing used.

Bulk Material

\[ (2.96 - 3.03) \times 10^{12} \text{ (dyn/cm}^2\text{)} \] [23].
References


