EE M150: Introduction to Micromachining and MEMS

Lecture:

Thermal Processing: Oxidation

Prof. Jack W. Judy

Lecture Outline

• Reading:
  – Jaeger: 29-47 (Oxidation)
  – Madou, Chapter 3: 131-134

• Topics:
  – Mechanics of Oxidation
  – Fundamental Equations
    • Growth Regimes, Graphs, Extras
  – Processes
What is Thermal Oxidation?

- A method for growing a film of SiO$_2$ from a film or wafer of single-crystal silicon (SCS) or polysilicon
  - high temperature process (700 - 1200ºC)
  - used extensively in commercial ICs and MEMS

Why is it done?

- Electrical Isolation
- Thermal Isolation
- Sacrificial Layer
- Biocompatibility

Desired Properties

- Electrical
  - high breakdown strength
  - low amount of undesirable charges
    - trapped, interface, mobile – effects function
- Mechanical
  - no pin holes
  - uniform (thickness and density)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dc Resistivity (Ω·cm), 25ºC</td>
<td>$10^{14}$-$10^{16}$</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>2.27</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>3.8 - 3.9</td>
</tr>
<tr>
<td>Dielectric Strength (V/cm)</td>
<td>5-10x10$^6$</td>
</tr>
<tr>
<td>Energy Gap (eV)</td>
<td>~8</td>
</tr>
<tr>
<td>Etch rate in Buffered HF (Å/min)</td>
<td>1000</td>
</tr>
<tr>
<td>Infrared Absorption Peak</td>
<td>9.3 (dyne/cm$^2$)</td>
</tr>
<tr>
<td>Linear Expansion Coefficient (cm$^2$/cm$^°C$)</td>
<td>5.0x10$^{-7}$</td>
</tr>
<tr>
<td>Melting Point (ºC)</td>
<td>~1700</td>
</tr>
<tr>
<td>Molecular Weight</td>
<td>60.08</td>
</tr>
<tr>
<td>Molecules/cm$^3$</td>
<td>2.3x10$^{22}$</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.46</td>
</tr>
<tr>
<td>Specific Heat (J/gºC)</td>
<td>1.0</td>
</tr>
<tr>
<td>Stress in film on Si</td>
<td>2 - 4x10$^9$</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm$^°C$)</td>
<td>0.014</td>
</tr>
</tbody>
</table>

SELECTED PHYSICAL CONSTANTS OF THERMAL SILICON DIOXIDE
How Does Silicon Oxidize?

- **Dry Oxidation:** \( \text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \)
- **Wet Oxidation:** \( \text{Si} + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2 \)
- **Note:** Silicon is **CONSUMED**

Oxidation occurs at the Si-SiO\(_2\) **interface** **NOT** on top of the oxide!!

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Modeling Thermal Oxidation of Si

- Since oxidation occurs at the Si-SiO\(_2\) interface:
  - \( \text{O}_2 \) or \( \text{H}_2\text{O} \) must diffuse through the previously grown oxide film
  - oxidation (growth) rate will fall off with increasing time and oxide thickness

**Diffusion Limited Process**

***Fluxes:***
- \( F_1 \) = gas phase
- \( F_2 \) = through oxide
- \( F_3 \) = reaction flux

**Steady State Requires:**
- \( F_1 = F_2 = F_3 \)
Laws of Diffusion

- Fick’s first law of diffusion:

\[ J = F_1 = -D \cdot \frac{dN}{dx} = D \left( \frac{N_0 - N_i}{x_{ox}} \right) \left( \text{number of particles per cm}^2 \cdot \text{sec} \right) \]

combine with \( J = F_2 = k_i \cdot N_i \) and \( J = F_2 = F_3 \) yields

\[ J = \frac{D \cdot N_0}{\left( x_0 + \frac{D}{k_s} \right)} \]

Growth Rate

Use time dependent continuity equation:

\[ \frac{dx_{ox}}{dt} = \frac{J}{N_{ax}} = \left( \frac{D \cdot N_0}{N_{ax}} \right) \left( \frac{x_0 + \frac{D}{k_s}}{B} \right) \]

\[ t = \frac{x_{ox}^2}{B} + \frac{x_{ox}}{A} - \tau \]

\[ x_{ox}(t = 0) = x_i \]

\[ \tau = \frac{x_i^2}{B} + \frac{x_i}{A} \]

\[ A = \frac{2 \cdot D}{k_s} \]

\[ B = \frac{2 \cdot D \cdot N_0}{N_{ax}} \]

\[ x_{ox}(t) = \frac{1}{2} A \left[ \sqrt{1 + \frac{4 \cdot B}{A^2} (t + \tau)} - 1 \right] \]
**Multiple Oxidations (tracking $\tau$)**

$t = \frac{x_{ox}^2}{B} + \frac{x_{ox}}{A} - \tau$

$\tau = \frac{x_{i}^2}{B} + \frac{x_{i}}{A}$

<table>
<thead>
<tr>
<th>Step</th>
<th>Time</th>
<th>Temp</th>
<th>Type</th>
<th>Overall Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0 hr</td>
<td>-</td>
<td>-</td>
<td>0 nm</td>
</tr>
<tr>
<td>1</td>
<td>0.9 hr</td>
<td>900 ºC</td>
<td>Wet</td>
<td>190 nm</td>
</tr>
<tr>
<td>2</td>
<td>4.5 hr</td>
<td>1000 ºC</td>
<td>Dry</td>
<td>280 nm</td>
</tr>
<tr>
<td>3</td>
<td>1.6 hr</td>
<td>1100 ºC</td>
<td>Wet</td>
<td>1000 nm</td>
</tr>
</tbody>
</table>

**Growth Rate Regimes**

$x_{ox}(t) = \frac{1}{2} A \left[ \sqrt{1 + \frac{4B}{A^2}(t+\tau)} - 1 \right]$

**Short Times:** $(t+\tau) \ll \frac{A^2}{4B}$

Simplify with Taylor Series Expansion:

$x_{ox}(t) = x_{ox}(t_0) + \frac{x_{ox}'}(t_0)(t-t_0) + \frac{x_{ox}''(t_0)}{2!}(t-t_0)^2 + \ldots$

reduces to:

$x_{ox}(t) = \left( \frac{B}{A} \right) \cdot (t+\tau)$

**Long Times:** $(t+\tau) \gg \frac{A^2}{4B}$

$x_{ox}(t) = \sqrt{B \cdot (t+\tau)}$
Oxidation Rate Constants

Determined the Diffusion Coefficients

Arrhenius Relationship

$$B = B_0 \cdot e^{\frac{E_{a(b)}}{k \cdot T}}$$

$$B = \frac{B}{A_0} \cdot e^{\frac{E_{a(b/a)}}{k \cdot T}}$$

<table>
<thead>
<tr>
<th>Atmosphere (X = 0 mm)</th>
<th>Linear (B/A)</th>
<th>9.70 x 10^6 μm/hr</th>
<th>2.05 eV</th>
<th>3.71 x 10^6 μm/hr</th>
<th>2.00 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parabolic (B)</td>
<td>586 μm/hr</td>
<td>0.78 eV</td>
<td>772 μm/hr</td>
<td>1.25 eV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmosphere (X = 25 mm)</th>
<th>Linear (B/A)</th>
<th>1.63 x 10^6 μm/hr</th>
<th>2.05 eV</th>
<th>6.23 x 10^6 μm/hr</th>
<th>2.00 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parabolic (B)</td>
<td>386 μm/hr</td>
<td>0.78 eV</td>
<td>772 μm/hr</td>
<td>1.25 eV</td>
</tr>
</tbody>
</table>
Oxidation Graphs

- Quick look-up
- Used to get rough answer or confirm calculations are in the ballpark

Orientation Dependance
High Pressure Oxidation

![Graph showing oxidation thickness vs. temperature and pressure](image)

Substrate: <100>, 3-10 ohm-cm
Oxidation duration: 60 min

2-D Oxidation Profile

![Diagram showing oxidation and removal processes](image)
Oxidation Equipment

Oxidation Furnaces
Next Lecture

- Reading for next lecture:
  - Madou p. 105-116 (CVD)