Lecture Outline

- Dielectrics and Poly-Si Film Deposition Processes (CVD)
- Reactor Configurations
- Gas Safety
- Poly-Si Deposition and Doping
- SiO₂ Deposition and Properties
- Si₃N₄ Deposition and Properties

Note: The lecture slides were prepared based on the original materials written by Profs. T.P. Chow and J.-Q. Lu
Dielectric and Poly-Si Films

- Most commonly used films
  - Poly-Si, SiO₂, Si₃N₄ and SiNx

- Most commonly deposition methods
  - APCVD, LPCVD, PECVD, PVD

- Most common applications
  - Doped poly-Si as MOS gates
  - SiO₂ as interlevel dielectric (ILD)
  - Si₃N₄ as diffusion and sodium barrier
  - SiNx as chip passivation layer

Deposition Reaction Processes

<table>
<thead>
<tr>
<th>Product</th>
<th>Reactants</th>
<th>Deposition temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide</td>
<td>SiH₄ + CO₂ + H₂</td>
<td>850–950</td>
</tr>
<tr>
<td></td>
<td>SiCl₂H₂ + N₂O</td>
<td>850–900</td>
</tr>
<tr>
<td></td>
<td>SiH₄ + N₂O</td>
<td>750–850</td>
</tr>
<tr>
<td></td>
<td>SiH₄ + NO</td>
<td>650–750</td>
</tr>
<tr>
<td></td>
<td>Si(OC₂H₅)₄</td>
<td>650–750</td>
</tr>
<tr>
<td></td>
<td>SiH₄ + O₂</td>
<td>400–450</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>SiH₄ + NH₃</td>
<td>700–900</td>
</tr>
<tr>
<td></td>
<td>SiCl₂H₂ + NH₃</td>
<td>650–750</td>
</tr>
<tr>
<td>Plasma silicon nitride</td>
<td>SiH₄ + NH₃</td>
<td>200–350</td>
</tr>
<tr>
<td></td>
<td>SiH₄ + N₂</td>
<td>200–350</td>
</tr>
<tr>
<td>Plasma silicon dioxide</td>
<td>SiH₄ + N₂O</td>
<td>200–350</td>
</tr>
<tr>
<td>Polysilicon</td>
<td>SiH₄</td>
<td>575–650</td>
</tr>
</tbody>
</table>

- Silane (SiH₄) is flammable in air, colorless, toxic
**APCVD Reactor**

- **Advantages:**
  - High throughput
  - Good uniformity
  - Handle large wafers
- **Disadvantages:**
  - Fast gas flows
  - High particulate count
  - Needs frequent cleaning

**CVD**: Chemical Vapor Deposition  
**APCVD**: Atmosphere Pressure CVD

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**LPCVD Reactor**

- **Advantages:**
  - Excellent uniformity
  - Large load size
  - Hold large wafers
  - Uniform step-coverage
  - Precise control of composition & Structure
- **Disadvantages:**
  - Low deposition rates
  - Toxic, corrosive or flammable gases
  - Medium throughput (vacuum)

Poly-Si, SiO2, Si3N4
PECVD Reactor

- Advantages:
  - Low deposition temperature
- Disadvantages:
  - Limited capacity
  - Individual wafer loading
  - Easily contaminated by loosely adhering deposits falling

SiO₂, SiNx:H

Physical Vapor Deposition (PVD)

- Advantages:
  - Low deposition temperature
  - Good purity
  - Gas Safety
- Disadvantages:
  - Poor step coverage
  - High vacuum / Limited capacity
  - Limited materials (mostly for metals)
- Cryo-pump is preferred over diffusion pump for cleanliness (oil back diffusion in the latter)
Gas Safety

Properties of common gases used in CVD

<table>
<thead>
<tr>
<th>Gas</th>
<th>Formula</th>
<th>Hazard</th>
<th>Flammable limits in air (vol%)</th>
<th>Exposure limit (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>toxic, corrosive</td>
<td>16–25</td>
<td>25</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>inert</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Arsine</td>
<td>AsH₃</td>
<td>toxic</td>
<td>—</td>
<td>0.05</td>
</tr>
<tr>
<td>Diborane</td>
<td>B₃H₆</td>
<td>toxic, flammable</td>
<td>1–98</td>
<td>0.1</td>
</tr>
<tr>
<td>Dichlorosilane</td>
<td>SiH₂Cl₂</td>
<td>flammable, toxic</td>
<td>4–99</td>
<td>5</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>flammable</td>
<td>4–74</td>
<td>—</td>
</tr>
<tr>
<td>Hydrogen chloride</td>
<td>HCl</td>
<td>corrosive, toxic</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>inert</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Nitrogen oxide</td>
<td>N₂O</td>
<td>oxidizer</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>oxidizer</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Phosphine</td>
<td>PH₃</td>
<td>toxic, flammable</td>
<td>pyrophoric</td>
<td>0.3</td>
</tr>
<tr>
<td>Silane</td>
<td>SiH₄</td>
<td>flammable, toxic</td>
<td>pyrophoric</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Tetraethoxysilane (TEOS) Si(OC₂H₅)₄: liquid, stable, flammable, toxic (tetra-ethylortho-silicate)

Poly-Si Deposition: LPCVD

- Pyrolyze Silane at 575 - 650 °C

SiH₄ → Si + 2H₂

- Arrhenius Equation:
  \[ R = A \exp(-qE_a/kT) \]
  \[ E_a \sim 1.7 \text{eV (40Kcal/mol)} \]
  for poly-Si

- At high temperatures, R → constant
  * Mass-transport limited
  * Dependent on reactant conc., reactor geometry and gas flow

Deposition Rate: 10-20 nm/min
Poly-Si Deposition: LPCVD

- At low-T, the deposition is *surface reaction limited* (the rate of reaction is slower than the rate of reactant arrival)
- *Surface-reaction limited regime gives films with excellent thickness uniformity*
- Deposition rate calculation:
  \[
  \log \left( \frac{R_1}{R_2} \right) = \left( \frac{qE_a}{k} \right) \frac{(T_1 - T_2)}{(T_1 T_2)}
  \]

  If \( R_1 = 10 \text{ nm/min at 600 °C with } E_a = 1.7eV, \)
  \( R_2 = 2.5 \text{ nm/min at 550 °C} \)

Poly-Si Deposition: LPCVD

- Reactor pressure can be controlled by
  - Pumping speed
  - Nitrogen flow
  - Total gas flow with constant ratio
- Deposition *reproducibility* is best when the pressure is controlled by pumping speed
Poly-Si Deposition: LPCVD

Sequence of surface process:

\[ \text{SiH}_4(g) \leftrightarrow \text{SiH}_4(ad) \]
\[ \text{SiH}_4(ad) \leftrightarrow \text{SiH}_2(ad) + \text{H}_2(ad) \]
\[ \text{SiH}_2(ad) \leftrightarrow \text{Si} + \text{H}_2(ad) \]
\[ \text{H}_2(ad) \leftrightarrow \text{H}_2(g) \]

Rate = \( K_1 p_s^{1/2} / (1 + K_2 p_s^{1/2}) \)

\( p_s \) is the partial pressure

(g: gas, ad: adsorb)

Effect of silane concentration (non-linearity)

- Surface-reaction limited regime gives films with excellent thickness uniformity

Poly-Si Deposition: LPCVD

- Poly-Si films deposited below 580°C is amorphous
- Poly-Si films deposited above 625°C is polycrystalline and has a columnar structure
- Poor quality at >650°C

Grains formed after annealing at 700°C
The target, upon bombardment by Ar ions, ejects atoms of the target material, which then float and condense on a substrate.

Gas flow: Ar:H₂=10:6
T (Substrate): 250 °C
Deposition rate: ~10 nm/min

Poly-Si/Glass: columnar structure
Grains: 50–70 nm in diameter

Poly-Si Doping

Effect of dopants on poly-Si deposition

3 doping methods for poly-Si

Dopants: Boron, Arsenic, Phosphorus

Phosphorus-doped Poly-Si

Diffusion doping by POCl₃ or PH₃ (900-1000 °C)

\[
\begin{align*}
5\text{POCl}_3 & \rightarrow \text{P}_2\text{O}_5 + 3\text{PCl}_5 \\
4\text{PCl}_3 + 5\text{O}_2 & \rightarrow 2\text{P}_2\text{O}_5 + 10\text{Cl}_2 \\
2 \text{P}_2\text{O}_5 + 5\text{Si} & \rightarrow 5\text{SiO}_2 + 4\text{P} \\
4\text{PH}_3 + 5\text{O}_2 & \rightarrow 2\text{P}_2\text{O}_5 + 6\text{H}_2
\end{align*}
\]

- Difficult to dope poly-Si moderately, either very lightly doped or heavily doped
- Grain size is dependent on the doping method used

In situ doping for poly-Si

Amorphous to columnar transition

Resistivity (Ω·cm) vs. Temperature (°C)

Resistivity (Ω·cm) vs. Temperature (°C)

Resistivity (Ω·cm) vs. Temperature (°C)

Poly-Si Doping

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Rensselaer

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SiO₂ Deposition

\[
\text{SiH}_4 + \text{O}_2 \rightarrow \text{SiO}_2 + 2\text{H}_2
\]

\[
4\text{PH}_3 + 5\text{O}_2 \rightarrow 2\text{P}_2\text{O}_5 + 6\text{H}_2
\]

*Phosphosilicate glass (PSG)*

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**APCVD** silane-oxygen reaction at 350 °C

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SiO₂ Deposition

\[
\text{Si(OC}_2\text{H}_5\text{)}_4 \rightarrow \text{SiO}_2 + 4\text{C}_2\text{H}_4 (g) + 2\text{H}_2\text{O} (g)
\]

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**PECVD TEOS SiO₂ Deposition**

- Plasma energy to reduce the deposition T: 250 – 425 °C at pressure of 2-10 torr (*suitable for ILD*).
- O₂:TEOS in 10:1 to 20:1 to minimize C & N
- Conformal

Unlike thermal TEOS-CVD (no H detectable), PECVD TEOS oxide has 2-9% H

\[
\text{Si(OC}_2\text{H}_5)_4 + \text{O}_2 \rightarrow \text{SiO}_2 + \text{by-products}
\]

**RPI P5000 PE-TEOS SiO₂**

TEOS/O₂, 425 sccm

- @ 390 °C / 9 Torr / RF 350 W
- R \sim 500 \text{ nm/min.}

**SiO₂ Step Coverage**

- Dependent on reactant surface migration and mean free path

(a) TEOS at 700°C
(b) Silane-O₂ at 450°C and low P
(c) Silane-O₂ at 480°C and Atm. P
Properties of Deposited Oxides

<table>
<thead>
<tr>
<th>TABLE 3 Properties of silicon dioxide</th>
<th>PECVD O2:TEOS</th>
<th>SiH4 + O2</th>
<th>TEOS</th>
<th>SiCl2H2 + N2O</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
<td>Plasma</td>
<td>250–425</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition</td>
<td>SiO1.9(H)</td>
<td>SiO2(H)</td>
<td></td>
<td>SiO2(H)</td>
<td></td>
</tr>
<tr>
<td>Step coverage</td>
<td>nonconformal</td>
<td>nonconformal</td>
<td></td>
<td>nonconformal</td>
<td></td>
</tr>
<tr>
<td>Thermal stability</td>
<td>loses H</td>
<td>conformation stable</td>
<td></td>
<td>conformation stable</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.3</td>
<td>2.1</td>
<td></td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.47</td>
<td>1.44</td>
<td></td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>Stress (10⁵dyne/cm²)</td>
<td>3C–3T</td>
<td>&lt;1.5 T2C</td>
<td></td>
<td>1 C</td>
<td></td>
</tr>
<tr>
<td>Dielectric strength (10⁶V/cm)</td>
<td>3–6</td>
<td>6–7</td>
<td></td>
<td>3 C</td>
<td></td>
</tr>
<tr>
<td>Etch rate, nm/min (100:1 H2O:HF)</td>
<td>40</td>
<td>6</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>4.9</td>
<td>4.3</td>
<td></td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

SiCl₂H₂ + 2N₂O → SiO₂ + 2N₂ + 2HCl

C: compressive; T: tensile

Si₃N₄ Deposition: LPCVD

- 3SiH₄ + 4NH₃ → Si₃N₄ + 12H₂
  **APCVD:** 700 to 900 °C

- 3SiCl₂H₂ + 4NH₃ → Si₃N₄ + 6HCl + 6H₂
  **LPCVD:** 700 to 800°C

- Eₐ ~ 1.8 eV (41Kcal/mol)

- Nitride films can contain up to 8% of hydrogen
PECVD-Nitride Deposition

Concentration of Hydrogen Groups

RPI PlasmaTherm PECVD SiNx @ 300 °C / 900 mTorr / RF Power 25 W
2% SiH₄/N₂ 490 sccm / He 2250 sccm
R ~ 5 nm/min.

Properties of Deposited Nitrides

- LPCVD nitride is stoichiometric and an excellent barrier against oxidation and sodium diffusion
- PECVD nitride contains a large amount of hydrogen (can be etched with HF) and serves as a passivation layer

<table>
<thead>
<tr>
<th>TABLE 4 Properties of silicon nitride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Composition</td>
</tr>
<tr>
<td>Si/N ratio</td>
</tr>
<tr>
<td>Atom % H</td>
</tr>
<tr>
<td>Refractive index</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
</tr>
<tr>
<td>Dielectric constant</td>
</tr>
<tr>
<td>Resistivity (ohm-cm)</td>
</tr>
<tr>
<td>Dielectric strength (V/cm)</td>
</tr>
<tr>
<td>Energy gap (eV)</td>
</tr>
<tr>
<td>Stress (10⁹ dyne/cm²)</td>
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</tbody>
</table>
### Comparison of Different Deposition Methods

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric pressure CVD</th>
<th>Low temperature LPCVD</th>
<th>Medium temperature LPCVD</th>
<th>Plasma assisted CVD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature (°C)</strong></td>
<td>300 – 500</td>
<td>300 – 500</td>
<td>500 – 900</td>
<td>100 – 350</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>SiO₂</td>
<td>SiO₂</td>
<td>Poly-Si</td>
<td>SiNH</td>
</tr>
<tr>
<td></td>
<td>P-glass</td>
<td>P-glass</td>
<td>SiO₂</td>
<td>SiO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BP-glass</td>
<td>SiON</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Si₃N₄</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SiON</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SIPOS</td>
<td></td>
</tr>
<tr>
<td><strong>Uses</strong></td>
<td>Passivation, insulation</td>
<td>Passivation, insulation</td>
<td>Gate metal, insulation</td>
<td>Passivation, insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(ILD)</td>
</tr>
<tr>
<td><strong>Throughput</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
<td><strong>Step coverage</strong></td>
<td>Poor</td>
<td>Poor</td>
<td>Conformal</td>
<td>Poor</td>
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<tr>
<td><strong>Particles</strong></td>
<td>Many</td>
<td>Few</td>
<td>Many</td>
<td>Few</td>
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<tr>
<td><strong>Film properties</strong></td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
<td>Poor</td>
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<tr>
<td><strong>Low temperature</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

|                        | (PETEOS)                 | (PVD)                  | (250–425)                | (RT–300)           |
|                        | (SiO₂)                   | (Poly-Si)              | (Low)                    | (Low)              |
|                        | (Low)                    | (Conformal)            | (Poor)                   |                    |
|                        | (Few)                    | (Few)                  |                          |                    |
|                        |                          | (Good)                 | (Yes)                    |                    |

### Guidelines for IC FabLab Report

- Cover with group names and responsibility
- Acknowledgement
- Abstract
- Chapter 1: Technical Background
  - Introduction
  - Device Physics
  - Process Considerations
  - Basic NMOS Processing
  - Processing Modeling – T-SUPREM
  - Test Devices
  - Testing Techniques
- Chapter 2: Processing Procedures
  - Detailed process flows with comments/suggestions
  - Inspection results with photos
- Chapter 3: Electrical Test Results and Discussions
  - I-V, C-V, Device variations, etc., with tables/plots
- Chapter 4: Summary & Conclusions
- References & Appendix