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)₂</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

LPCVD Reactor

- **Advantages:**
  - Excellent uniformity
  - Large load size
  - Hold large wafers
  - Uniform step-coverage
  - Precise control of & 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>—</td>
</tr>
<tr>
<td>Diborane</td>
<td>B₂H₆</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-ethyl-ortho-silicate)

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Poly-Si Deposition: LPCVD

- Pyrolyze Silane at 575 - 650 °C

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

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

- At high temperatures,
  \( R \rightarrow \text{constant} \)
  * 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 \( R_1 = 10 \text{ nm/min at 600 } ^\circ\text{C} \) with \( E_a = 1.7\text{eV} \),
  \( R_2 = 2.5 \text{ nm/min at 550 } ^\circ\text{C} \)

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:

\[
\begin{align*}
\text{SiH}_4(g) & \leftrightarrow \text{SiH}_4(ad) \\
\text{SiH}_4(ad) & \leftrightarrow \text{SiH}_2(ad) + \text{H}_2(ad) \\
\text{SiH}_2(ad) & \leftrightarrow \text{Si} + \text{H}_2(ad) \\
\text{H}_2(ad) & \leftrightarrow \text{H}_2(g)
\end{align*}
\]

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

\(p_s\) is the partial pressure

\((g: \text{gas}, \ ad: \text{adsorb})\)

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

Effect of silane concentration (non-linearity)

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

Increase 600 °C

Decrease

Dopants: Boron, Arsenic, Phosphorus

Phosphorus-doped Poly-Si

3 doping methods for poly-Si

(a) Diffusion
(b) Implantation
(c) In situ

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

Boron

Phosphorus
SiO₂ Deposition

**APCVD**

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

4\( \text{PH}_3 \) + 5\( \text{O}_2 \) → 2\( \text{P}_2\text{O}_5 \) + 6\( \text{H}_2 \)

*Phosphosilicate glass (PSG)*

APCVD silane-oxygen reaction at 350 °C

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**LPCVD**

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

---

ECSE-6300 IC Fabrication Laboratory
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

\[
\text{Si(OC}_2\text{H}_5)_4 + O_2 \rightarrow \text{SiO}_2 + \text{by-products}
\]

RPI P5000 PE-TEOS SiO₂
TEOS/O₂, 425 sccm
@ 390 °C / 9 Torr / RF 350 W
R ~ 500 nm/min.

SiO₂ Step Coverage

- Dependent on reactant surface migration and mean free path
Properties of Deposited Oxides

<table>
<thead>
<tr>
<th>TABLE 3 Properties of silicon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Composition</td>
</tr>
<tr>
<td>Step coverage</td>
</tr>
<tr>
<td>Thermal stability</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
</tr>
<tr>
<td>Refractive index</td>
</tr>
<tr>
<td>Stress (10⁹ dyne/cm²)</td>
</tr>
<tr>
<td>Dielectric strength (10¹² V/cm)</td>
</tr>
<tr>
<td>Etch rate, nm/min (100:1 H2O:HF)</td>
</tr>
<tr>
<td>Dielectric constant</td>
</tr>
</tbody>
</table>

\[
\text{SiCl}_2\text{H}_2 + 2\text{N}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{N}_2 + 2\text{HCl}
\]

C: compressive; T: tensile

Si3N4 Deposition: LPCVD

- \(3\text{SiH}_4 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 12\text{H}_2\)
  APCVD: 700 to 900 °C

- \(3\text{SiCl}_2\text{H}_2 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 6\text{HCl} + 6\text{H}_2\)
  LPCVD: 700 to 800°C

- \(E_a \sim 1.8 \text{ eV (41Kcal/mol)}\)

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

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</th>
<th>Properties of silicon nitride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
<td>LPCVD</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>700–800</td>
</tr>
<tr>
<td>Composition</td>
<td>Si3N4(H)</td>
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<tr>
<td>Si/N ratio</td>
<td>0.75</td>
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<tr>
<td>Atom % H</td>
<td>4–8</td>
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<tr>
<td>Refractive index</td>
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<tr>
<td>Density (g/cm³)</td>
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<td>Dielectric constant</td>
<td>6–7</td>
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<tr>
<td>Resistivity (Ω·cm)</td>
<td>10¹⁶</td>
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<td>Dielectric strength (V/cm)</td>
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<tr>
<td>Energy gap (eV)</td>
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<tr>
<td>Stress (10⁹ dyn/cm²)</td>
<td>10 T</td>
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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>
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<tbody>
<tr>
<td>Temperature (°C)</td>
<td>300 – 500</td>
<td>300 – 500</td>
<td>500 – 900</td>
<td>100 – 350</td>
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<td>Materials</td>
<td>SiO₂</td>
<td>SiO₂</td>
<td>Poly-Si</td>
<td>SiNH</td>
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<td></td>
<td>P-glass</td>
<td>P-glass</td>
<td>SiO₂</td>
<td>SiO₂</td>
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<tr>
<td></td>
<td>BP glass</td>
<td>BP glass</td>
<td>SiO₂</td>
<td>SiON</td>
</tr>
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<td>BP-glass</td>
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<td></td>
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<td></td>
<td>Si₃N₄</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>SiON</td>
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<td>Uses</td>
<td>Passivation, insulation</td>
<td>Passivation, insulation</td>
<td>Gate metal, insulation</td>
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<tr>
<td>Throughput</td>
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<td>Step coverage</td>
<td>Poor</td>
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<td>Conformal</td>
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<td>Particles</td>
<td>Many</td>
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<td>Few</td>
<td>Many</td>
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<td>Film properties</td>
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<td>Good</td>
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<td>Poor</td>
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<td>Low temperature</td>
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<td>Yes</td>
<td>No</td>
<td>Yes</td>
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</table>

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