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 1**
Typical reactions for depositing dielectrics and polysilicon.

<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

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

ECSE-6300 IC Fabrication Laboratory
James J.-Q. Lu 4-5
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>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>—</td>
<td>—</td>
</tr>
<tr>
<td>Silane</td>
<td>SiH₄</td>
<td>flammable, toxic</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

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

Poly-Si Deposition: LPCVD

- Pyrolyze Silane at 575 - 650 °C

SiH₄ → Si + 2H₂

- Arrhenius Equation:
  \[ R = A e^{-\frac{qE_a}{kT}} \]
  \[ E_a \approx 1.7\text{eV (40Kcal/mol)} \]
  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

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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:
  \[ R = Ae^{-\frac{qE_a}{kT}} \]
  \[ E_a \approx 1.7\text{eV (40Kcal/mol)} \]
  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

- 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:

\[
\begin{align*}
SiH_4(g) & \leftrightarrow SiH_4(ad) \\
SiH_4(ad) & \leftrightarrow SiH_2(ad) + H_2(ad) \\
SiH_2(ad) & \leftrightarrow Si + H_2(ad) \\
H_2(ad) & \leftrightarrow H_2(g) \\
R &= \frac{K_1 \sqrt{p_s}}{1 + K_2 \sqrt{p_s}}
\end{align*}
\]

\(p_s\) 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
PVD Poly-Si by Ionized Magnetron Sputtering

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

Dopants: Boron, Arsenic, Phosphorus

Phosphorus-doped Poly-Si

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

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

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

---

**APCVD**

APCVD silane-oxygen reaction at 350 °C

---

**SiO₂ Deposition**

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

Si(O₂H₅)₄ + O₂ → SiO₂ + 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

(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</th>
<th>Properties of silicon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
<td>Plasma</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>Composition</td>
<td>SiO1.5(H)</td>
</tr>
<tr>
<td>Step coverage</td>
<td>nonconformal</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>loses H</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.3</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.47</td>
</tr>
<tr>
<td>Stress (10^6 dyne/cm²)</td>
<td>3C-3T</td>
</tr>
<tr>
<td>Dielectric strength (10^5V/cm)</td>
<td>3-6</td>
</tr>
<tr>
<td>Etch rate, nm/min (100:1 H2O:HF)</td>
<td>40</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>4.9</td>
</tr>
</tbody>
</table>

SiCl2H2 + 2N2O → SiO2 + 2N2 + 2HCl

Si3N4 Deposition: LPCVD

- 3SiH4 + 4NH3 → Si3N4 + 12H2
  APCVD: 700 to 900 °C
- 3SiCl2H2 + 4NH3 → Si3N4 + 6HCl + 6H2
  LPCVD: 700 to 800°C
- E_a ~ 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</th>
<th>Properties of silicon nitride</th>
</tr>
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<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>
</tr>
<tr>
<td>Si/N ratio</td>
<td>0.75</td>
</tr>
<tr>
<td>Atom % H</td>
<td>4–8</td>
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<tr>
<td>Refractive index</td>
<td>2.01</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.9–3.1</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>6–7</td>
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<tr>
<td>Resistivity (ohm-cm)</td>
<td>10¹⁶</td>
</tr>
<tr>
<td>Dielectric strength (10⁶V/cm)</td>
<td>10</td>
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<tr>
<td>Energy gap (eV)</td>
<td>5</td>
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<tr>
<td>Stress (10⁹ dyne/cm²)</td>
<td>10 T</td>
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</table>
### Comparison of Different Deposition Methods

#### TABLE 5
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>Temperature (°C)</td>
<td>300 – 500</td>
<td>300 – 500</td>
<td>500 – 900</td>
<td>100 – 350</td>
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<tr>
<td>Materials</td>
<td>SiO₂</td>
<td>SiO₂</td>
<td>Poly-Si</td>
<td>SiNH</td>
</tr>
<tr>
<td></td>
<td>P-glass</td>
<td>BP glass</td>
<td>SiO₂</td>
<td>SiO₂</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>BP-glass</td>
<td>SiO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Si₃N₄</td>
<td>SiO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SiON</td>
<td>SIO2</td>
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<tr>
<td></td>
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<td></td>
<td>SIPOS</td>
<td>Poly-Si</td>
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<tr>
<td>Uses</td>
<td>Passivation, insulation</td>
<td>Passivation, insulation</td>
<td>Gate metal, insulation</td>
<td>(ILD)</td>
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<td>(Metal gate, TFT)</td>
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<tr>
<td>Throughput</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
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<td>(Low)</td>
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<td>Step coverage</td>
<td>Poor</td>
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<td>Particles</td>
<td>Many</td>
<td>Few</td>
<td>Few</td>
<td>Many</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(Few)</td>
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<tr>
<td>Film properties</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>(Good)</td>
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<td>Low temperature</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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### 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