Announcements

• **TA’s:** Li-Wen Hung & Yang Lin
• **Office Hours:** 382 Cory
  - Li-Wen Hung: M 9-10 a.m., 1:30-2:30 p.m.
  - Yang Lin: W 11-12 a.m., 2-3 p.m.
• **Discussion Sections:**
  - Friday, 2-3 p.m., 299 Cory
  - Friday, 3-4 p.m., 299 Cory
• Everyone should already be moved from the waitlist to the class and put into a discussion section
• Check to see which discussion section you’re in
• No office hours for me on Thursday … but TA OH throughout the week
• HW#1 is posted on the course website:
  - [http://inst.eecs.berkeley.edu/~ee245/fa07/](http://inst.eecs.berkeley.edu/~ee245/fa07/)
Lecture Outline

• Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 3, 6
• Lecture Topics:
  • Film Deposition
    • Evaporation
    • Sputter deposition
    • Chemical vapor deposition (CVD)
    • Plasma enhanced chemical vapor deposition (PECVD)
    • Epitaxy
    • Atomic layer deposition (ALD)
    • Electroplating
  • Lithography
  • Etching

Atomic Layer Deposition (ALD)
Atomic Layer Deposition (ALD)

- **Fundamental Components:**
  - Self-limiting surface reactions of suitable precursor compounds A & B
  - A & B then form the desired product S in a binary reaction cycle consisting of two sequential half-reactions

**Remarks:**
- Both half-reactions must be complete and self-limiting at the monolayer level
- The total film thickness $d(tot)$ can be “digitally” controlled by the number of applied deposition cycles $N(A/B)$:
  $$d(tot) = d(mono) \cdot N(A/B)$$
- The reagents A & B in the half reactions are normally chemical reactions
  - But they don’t need to be
  - They can also represent a physical process, e.g., heating, irradiation, electrochemical conversion
**Advantages of ALD**

- Surface limited reaction
  - Excellent step coverage and refilling
- Self-limiting mechanism
  - Monolayer deposition
  - Composition control
  - Thickness control ($\propto$ # of cycles)
  - Less sensitive to flow rate & temperature

Note, though, that there's still a temperature window:

- Condensation
- Decomposition
- Re-evaporation
- Incomplete Reaction

**ALD Reactor**

200°C to 400°C needed

Must purge completely before the next pulse

Usually mixed w/ an inert gas to achieve lower effective vapor pressures → slows reaction, but needed to allow rapid pulsing & purging
In air, $H_2O$ vapor is adsorbed on most surfaces, forming a hydroxyl group. With silicon, this forms $:Si-O-H$ (s).

- Place the substrate in the reactor
- Pulse TrimethylAluminum (TMA) into the reaction chamber

TrimethylAluminum (TMA) reacts with the adsorbed hydroxyl groups, producing methane as the reaction product.

$$Al(CH_3)_3(g) + :Si-O-H(s) \rightarrow :Si-O-Al(CH_3)_2(s) + CH_4$$
TrimethylAluminum (TMA) reacts with the adsorbed hydroxyl groups, until the surface is passivated.

TMA does not react with itself, so terminates the reaction to one layer.

This leads to the perfect uniformity of ALD.

The excess TMA and methane reaction product is pumped away.

After the TMA and methane reaction product is pumped away, water vapor ($H_2O$) is pulsed into the reaction chamber.
**Al₂O₃ ALD**

* H₂O reacts with the dangling methyl groups on the new surface forming aluminum-oxygen (Al-O) bridges and hydroxyl surface groups, waiting for a new TMA pulse
* Again, methane is the reaction product

\[
2 \text{H}_2\text{O} (g) + \text{Si-O-Al(CH₃)}_2 (s) \rightarrow \text{Si-O-Al(OH)}_2 (s) + 2 \text{CH}_4
\]

* The reaction product methane is pumped away
* Excess H₂O vapor does not react with the hydroxyl surface groups
* Again, get perfect passivation to one atomic layer
**Al₂O₃ ALD**

* One TMA and one H₂O vapor pulse form one cycle
* Here, three cycles are shown, with approximately 1 Å per cycle
* Each cycle including pulsing and pumping takes, e.g., 3 sec

\[
\begin{align*}
\text{Al(CH₃)₃} & \rightarrow \text{Si-O-Al(CH₃)₂} + \text{CH₄} \\
2 \text{H₂O} & \rightarrow \text{Si-O-Al(OH)₂} + 2 \text{CH₄}
\end{align*}
\]

**ALD Video**

* Run the ALD video
**ALD Capability**

Figure 3: ALD features aspect ratio coverage performance. The SEM images show close to 100% conformality for an 80nm thick Al2O3 film which was deposited by ALD into high aspect ratio trenches with a minimum lateral dimension of 80nm and a final aspect ratio of ~60:1.

**ALD Versus CVD**

<table>
<thead>
<tr>
<th>ALD</th>
<th>CVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly reactive precursors</td>
<td>Less reactive precursors</td>
</tr>
<tr>
<td>Precursors react separately on the substrate</td>
<td>Precursors react at the same time on the substrate</td>
</tr>
<tr>
<td>Precursors must not decompose at process temperature</td>
<td>Precursors can decompose at process temperature</td>
</tr>
<tr>
<td>Uniformity ensured by the saturation mechanism</td>
<td>Uniformity requires uniform flux of reactant and temperature</td>
</tr>
<tr>
<td>Thickness control by counting the number of reaction cycles</td>
<td>Thickness control by precise process control and monitoring</td>
</tr>
<tr>
<td>Surplus precursor dosing acceptable</td>
<td>Precursor dosing important</td>
</tr>
</tbody>
</table>
### ALD Versus Other Deposition Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>ALD</th>
<th>MBE</th>
<th>CVD</th>
<th>Sputter</th>
<th>Evapor</th>
<th>PLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness Uniformity</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Film Density</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Step Coverage</td>
<td>Good</td>
<td>Poor</td>
<td>Varies</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Interface Quality</td>
<td>Good</td>
<td>Good</td>
<td>Varies</td>
<td>Poor</td>
<td>Good</td>
<td>Varies</td>
</tr>
<tr>
<td>Number of Materials</td>
<td>Fair</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
</tr>
<tr>
<td>Low Temp. Deposition</td>
<td>Good</td>
<td>Good</td>
<td>Varies</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Deposition Rate</td>
<td>Fair</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Industrial Apps.</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
</tr>
</tbody>
</table>

**Electroplating**
Metal Electroplating

- **Electroplating**: the process using electrical current to coat an electrically conductive object with a thin layer of metal
  - Useful when very thick (>1 μm) metal films are needed
  - Evaporation and sputtering generally suffer from excessive stress when films get too thick → get peeling

\[ \text{Cu}^{2+} + 2e^- \rightarrow \text{Cu} \]

1. Switch on external supply of direct current
2. Metal at anode is oxidized to form cations with a (+) charge
3. Cations are attracted to the (-) charge on the cathode
4. Cations get reduced by e\(^-\)'s at the cathode, depositing the metal (in this case, Cu)

Wafer-Level Implementation

- **Wafer Preparation**: areas where plating is to occur must have electrical access to the DC voltage source
  - Often use a seed layer that accesses all plating locations
  - Need not be the metal to be electroplated
  - Often just a platinum electrode
  - In this case, must replenish electrolytic solution after time

\[ \text{Ti} / \text{Au} \]

Al layer insures electrical contact to plating areas, despite patterned Ti/Au

\[ \text{Electrolyte Solution} \]

\[ \text{Electrical Connector} \]

\[ \text{Wafer} \]

\[ \text{Wafer Holder} \]

\[ \text{Electrolyte Solution Container} \]

\[ \text{Photoresist} \]

\[ \text{Aluminum} \]

\[ \text{Silicon Substrate} \]
Lithography
Lithography

Method for massive patterning of features on a wafer → pattern billions of devices in just a few steps

I. Radiation Source
II. Mask
III. Photoresist
IV. Exposure System

Four Main Components (that affect resolution)

- Generated from layout

I. Radiation Source

II. Mask

III. Photoresist

IV. Exposure System

The basic Process - (Positive Resist Example)

Exposed PR → converts to another form after reaction with light (e.g., (+)-resist: polymer → organic acid)

Dip or spray wafer with developer → if (+) resist, developer is often a base

Etch → PR protects film; open areas of film get etched
Lithography (cont.)

With each masking step usually comes a film deposition, implantation, and/or etch. Thus, the complexity of a process is often measured by # masks required.

- NMOS: 4-6 masks
- Bipolar: 8-15 masks
- BICMOS: ~20 masks
- CMOS: 8-28 masks
  - Multi-level metallization
- Comb-Drive Resonator: 3 masks
- GHz Disk: 4 masks

Now, take a closer look at the 4 components:

I. Radiation Source

- Several types: optical (visible, UV, deep UV light), e-beam, X-ray, ion beam
  - The shorter the wavelength → Better the resolution
  - Today’s prime choice due to cost and throughput.
  - Can expose billions of devices at once!

Optical Sources:
- Mercury arc lamp (mercury vapor discharge)
  - We have all of these in our µlab
  - I-line
  - G-line
  - For deep UV, need Excimer laser (very expensive)
  - Glass opaque, so must use quartz mask and lens
II. Mask

II. Mask → has become one of today's biggest bottlenecks!

Electronic computer representation of layout (e.g., CIF, GDSII) → A single file contains all layers

tape → mask generator

Masks for each layer

Mask Material:
- Fused silica (glass) → inexpensive, but larger thermal expansion coeff.
- Quartz → expensive, but smaller thermal expansion coeff.

III. Photoresist (optical)

Pictorial Description:

Negative

Exposed Area:

remains

Positive

Exposed Area:

removed
### III. Photoresist (optical)

#### Mechanism:

- **Negative**
  - Photoactivation
  - Polymerization (long, linked Carbon chains)
  - Developer solvent removes unexposed PR

- **Positive**
  - Photoactivation
  - Converts exposed PR to organic acid
  - Alkaline developer (e.g., KOH) removes acid (i.e., removes exposed PR)

#### Issues:

- **Negative**
  - Polymerized PR swells in solvent → bridging problem
  - Exposed and polymerized

- **Positive**
  - Doesn't adhere well to SiO₂
  - Need primer: HMDS (hexamethyl disilazane)

- Poor adhesion

- PR

- SiO₂

- Exposed and polymerized

- Good adhesion at both HMDS interfaces
Typical Procedure for Lithography

- Clean Wafer
- Dry Wafer
- Deposit HMDS
- Spin-on PR
- Soft Bake
- Align & Expose
- Develop
- Descum
- Post Bake

Very important step

30 min. @ 120°C pre-bake
(for oxide on wafer surface)

30-60 sec @ 1000-5000 rpm

2 min @ 90°C

Improve adhesion and remove solvent from PR

Oxygen plasma (low power ~ 50W)

Topography very important:

Thicker and unfocused

overexpose

underexpose

IV. Exposure System/Optics

Contact Printing

- Mask in contact with wafer
- Problem: mask pattern can become damaged with each exposure → must make a new mask after n number of exposures

• 1X printing very useful for MEMS → can expose surfaces with large topography (where reduction printers cannot)

Proximity Printing

- Mask in very close proximity but not touching
IV. Exposure System/Optics

- Dominates in IC transistor fabrication
- 5X or 10X reduction typical
- Mask minimum features can be larger than the actual printed features by the focused reduction factor → less expensive mask costs
- Less susceptible to thermal variation (in the mask) than 1X printing
- Can use focusing tricks to improve yield:
  - *Projection Printing*
  - *Step & repeat*
  - *Dust particle will be out of focus → better yield!*