Lecture Outline

• Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 3, 6
• Lecture Topics:
  - Example MEMS fabrication processes
  - Oxidation
  - Film Deposition
    - Evaporation
    - Sputter deposition
    - Chemical vapor deposition (CVD)
    - Plasma enhanced chemical vapor deposition (PECVD)
    - Epitaxy
    - Atomic layer deposition (ALD)
    - Electroplating
  - Lithography
Making Mechanical Devices

- How best does one make a mechanical product?
- Assembly line production?
  - Pick and place parts
  - Used for many macroscopic mechanical products
  - Robotic automation greatly reduces cost
- **Problem**: difficult to do this with MEMS-scale parts (but not impossible, as we’ll soon see …)
- **Solution**: borrow from integrated circuit (IC) transistor technology
  - Use monolithic wafer-level fabrication methods
  - Harness IC’s batch methods, where multiple devices are achieved all at once

Automobile Assembly Line

CMOS Integrated Circuit Wafer

Polysilicon Surface-Micromachining

- Uses IC fabrication instrumentation exclusively
- **Variations**: sacrificial layer thickness, fine- vs. large-grained polysilicon, *in situ* vs. POCL$_3$-doping

Silicon Substrate

Hydrofluoric Acid Release Etchant

Wafer

Free-Standing Polysilicon Beam

Silicon Substrate

300 kHz Folded-Beam Micromechanical Resonator
Electroplating: Metal MEMS

- Use electroplating to obtain metal μstructures
- When thick: call it “LIGA”
- Pros: fast low temp deposition, very conductive
- Cons: drift, low mech. Q but may be solvable?

Bulk Micromachining and Bonding

- Use the wafer itself as the structural material
- Adv: very large aspect ratios, thick structures
- Example: deep etching and wafer bonding

1 mm

Microrotor (for a microengine)
Thermal Oxidation of Silicon

- Achieved by heating the silicon wafer to a high temperature (~900°C to 1200°C) in an atmosphere containing pure oxygen or water vapor.
- Enabling reactions:

  For dry oxygen:
  \[ \text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \]

  For water vapor:
  \[ \text{Si} + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2 \]

  Schematically:

  ![Diagram of silicon wafer oxidation process](image)
Oxidation Modeling

(1) Initially: (no oxide @ surface)

\[ \text{gas stream} \]

\[ \text{Si} \]

\text{Growth rate determined by reaction rate @ the surface}

(2) As oxide builds up:

\[ \text{gas stream} \]

\[ \text{oxide} \rightarrow \text{Si} \]

\text{Reactant must diffuse to Si surface where the oxidation reaction takes place}

\text{Growth rate governed more by rate of diffusion to the silicon-oxide interface}

Oxidation Modeling (cont.)

\[ N_0 = \text{reactant conc. at oxide surface} \] [in cm\(^{-2}\)]

\[ N_i = \text{reactant conc. at Si-SiO}_2 \text{ interface} \]

\[ J = \text{reactant flux} = -D \frac{\partial N(x,t)}{\partial x} \] [Fick’s 1st Law of Diffusion]

Diffusion coeff. [in \(\mu\)m/hr or m/s]

\[ J = \frac{D (N_0 - N_i)}{X_{OX}} = \text{constant} \] [in # particles/(cm\(^2\)-s)]

Assumption that the reactant does not accumulate in the oxide.
Oxidation Modeling (cont.)

At the Si-SiO$_2$ interface:

Oxidation rate $\propto N_i \implies J \propto N_i \implies J = k_i N_i \quad (2)$

Combining (1) and (2):

$$N_i = \frac{J}{k_i} \implies J = D \left( \frac{N_o - J/k_s}{X_{ox}} \right)$$

$$JX_{OX} = DN_o - \frac{DJ}{k_s} \implies J \left( X_{OX} + \frac{D}{k_s} \right) = DN_o$$

$$J = \frac{DN_o}{X_{OX} + \frac{D}{k_s}} = \text{Flux of reactants}$$

Oxidation Modeling (cont.)

Find an expression for $X_{OX}(t)$:

Rate of change of oxide layer thickness w/time $\{ \frac{dX_{OX}}{dt} = \frac{J}{M} \implies J = \frac{DN_o}{X_{OX} + D/k_s} \quad (3) \}$

$\#$ of molecules of oxidizing species incorporated into a unit volume of oxide $\{ = 2.2 \times 10^{22} \text{cm}^{-3} \text{ for } O_2$

$= 4.4 \times 10^{22} \text{cm}^{-3} \text{ for } H_2O$

Solve (3) for $X_{OX}(t)$: [Initial condition $X_{OX}(t=0) = X_i$]

$$\int_{X_i}^{X_{OX}} (X_{OX} + \frac{D}{k_s}) dX_{OX} = \int_{0}^{t} \frac{DN_o}{M} \ dt$$
Oxide Thickness Versus Time

Result:

additional time required to go from $X_i \rightarrow X_{OX}$

time required to grow $X_i$ [\(X_i\) = initial oxide thickness]

\[
X_{OX}(t) = \frac{A}{2} \left[ 1 + \frac{4B}{A^2} (t + \tau) \right]^{1/2} - 1
\]

where

\[
A = \frac{2D}{k_s}, \quad \tau = \frac{X_i^2}{B} + \frac{X_i}{(B/A)}
\]

\[
B = \frac{2DN_O}{M}, \quad D = D_0 \exp \left( -\frac{E_A}{kT} \right)
\]

\[
i.e., D governed by an Arrhenius relationship \rightarrow temperature dependent
\]

Oxidation Modeling (cont.)

For shorter times:

\[
(t + \tau) \ll \frac{A^2}{4B} \Rightarrow X_{OX}(t) = \left( \frac{B}{A} \right) (t + \tau) \Rightarrow \text{oxide growth limited by reaction at the Si-SiO}_2 \text{ interface}
\]

Taylor expansion (first term after 1's cancel)

linear growth rate constant

For long oxidation times: oxide growth diffusion-limited

\[
(t + \tau) \gg \frac{A^2}{4B} \Rightarrow X_{OX}(t) = \sqrt{B(t + \tau)} \approx \sqrt{Bt}
\]

\[t \gg \tau\]

Parabolic rate constant
Oxidation Rate Constants

Table 6-2  Rate constants describing (111) silicon oxidation kinetics at 1 Atm total pressure. For the corresponding values for (100) silicon, all C values should be divided by 1.68.

<table>
<thead>
<tr>
<th>Ambient</th>
<th>B</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry O₂</td>
<td>C₁ = 7.72 x 10² μm² hr⁻¹</td>
<td>C₂ = 6.23 x 10⁶ μm hr⁻¹</td>
</tr>
<tr>
<td></td>
<td>E₁ = 1.23 eV</td>
<td>E₂ = 2.0 eV</td>
</tr>
<tr>
<td>Wet O₂</td>
<td>C₁ = 2.14 x 10² μm² hr⁻¹</td>
<td>C₂ = 8.95 x 10⁷ μm hr⁻¹</td>
</tr>
<tr>
<td></td>
<td>E₁ = 0.71 eV</td>
<td>E₂ = 2.05 eV</td>
</tr>
<tr>
<td>H₂O</td>
<td>C₁ = 3.86 x 10² μm² hr⁻¹</td>
<td>C₂ = 1.63 x 10⁸ μm hr⁻¹</td>
</tr>
<tr>
<td></td>
<td>E₁ = 0.78 eV</td>
<td>E₂ = 2.05 eV</td>
</tr>
</tbody>
</table>

* Above theory is great ... but usually, the equations are not used in practice, since measured data is available. Rather, oxidation growth charts are used.

Oxidation Growth Charts

Fig. 3.1

C 245: Introduction to MEMS Design  Lecture 3  C. Nguyen  9/4/07  15
Using the Oxidation Growth Charts

Example:
• <100> silicon
• Starting oxide thickness: \( X_i = 100 \text{nm} \)
• Want to do wet oxidation @ 1000°C to achieve \( X_{ox} = 230 \text{nm} \)
• What is the time \( t \) required for this?

Factors Affecting Oxidation

• In summary, oxide thickness is dependent upon:
  1. Time of oxidation
  2. Temperature of oxidation
  3. Partial pressure of oxidizing species (\( \propto N_o \))
• Also dependent on:
  4. Reactant type:
     - Dry \( O_2 \)
       Water vapor \( \Rightarrow \) faster oxidation, since water has a higher solubility (i.e., \( D \)) in \( SiO_2 \) than \( O_2 \)
  5. Crystal orientation:
     - \( <111> \) \( \leftarrow \) faster, because there are more bonds available at the Si-surface
     - \( <100> \) \( \leftarrow \) fewer interface traps; smaller \# of unsatisfied Si-bonds at the Si-SiO\(_2\) interface
Factors Affecting Oxidation

6. Impurity doping:
   P: increases linear rate const.
     no affect on parabolic rate constant
     faster initial growth \( \rightarrow \) surface reaction rate limited
   B: no effect on linear rate const.
     increases parabolic rate const.
     faster growth over an initial oxide \( \rightarrow \) diffusion faster

Thin Film Deposition
Thin Film Deposition

- Methods for film deposition:
  - Evaporation
  - Sputter deposition
  - Chemical vapor deposition (CVD)
  - Plasma enhanced chemical vapor deposition (PECVD)
  - Epitaxy
  - Electroplating
  - Atomic layer deposition (ALD)

Evaporation:
- Heat a metal (Al, Au) to the point of vaporization
- Evaporate to form a thin film covering the surface of the Si wafer
- Done under vacuum for better control of film composition

Evaporation

Filament Evaporation System:

1. Pump down to vacuum → reduces film contamination and allows better thickness control
2. Heat W filament → melt Al, wet filament
3. Raise temperature → evaporate Al

mean free path \( \lambda = \frac{kT}{\sqrt{2} \pi P d^2} \)

k = Boltzmann Constant
T = temperature
P = pressure
d = diameter of gas molecule
Evaporation (cont.)

- $\lambda$ can be ~60m for a 4Å particle at $10^{-4}$ Pa (-0.75 μTorr)
  - thus, at 0.75 μTorr, get straight line path from Al staple filament to wafer

  Problem: Shadowing & Step Coverage

Get an open line of sight deposition

Solns:
  i. Rotate water during evaporation
  ii. Etch more gradual sidewalls

Better Solution: forget evaporation $\rightarrow$ sputter deposit the film!

Sputter Deposition

- Use an energetic plasma to dislodge atoms from a material target, allowing the atoms to settle on the wafer surface

Not as low a vacuum as evaporation (~100 Pa) (750 mTorr)

Target (Al, SiO$_2$, Si$_2$N$_4$, ZnO, Ti, ...)

plasma

Vacuum Pump

wafer
Sputter Deposition Process

* **Step-by-step procedure:**

1. Pump down to vacuum
   \[ \text{(~100 Pa)} \rightarrow \text{1 Pa} = 9.8 \times 10^{-6} \text{ atm} \left( \frac{760 \text{ Torr}}{\text{atm}} \right) = 0.0075012 \text{ Torr} \]

2. Flow gas (e.g., Ar)
3. Fire up plasma (create Ar+ ions) \rightarrow apply dc-bias (or RF for non-conductive targets)
4. Ar+ ions bombard target (dislodge atoms)
5. Atoms make their way to the wafer in a more random fashion, since at this higher pressure, \( \lambda \approx 60 \mu \text{m} \) for a 4Å particle; plus, the target is much bigger

* **Result:** better step coverage!

Problems With Sputtering

1. Get some Ar in the film
2. Substrate can heat up
   \( \uparrow \) up to \(~350^\circ\text{C}\), causing nonuniformity across the wafer
   \( \downarrow \) but it still is more uniform than evaporation!
3. Stress can be controlled by changing parameters (e.g., flow rate, plasma power) from pass to pass, but repeatability is an issue

* **Solution:** use Chemical Vapor Deposition (CVD)
Chemical Vapor Deposition (CVD)

- Even better conformity than sputtering
- Form thin films on the surface of the substrate by thermal decomposition and/or reaction of gaseous compounds
  - Desired material is deposited directly from the gas phase onto the surface of the substrate
  - Can be performed at pressures for which \( \lambda \) (i.e., the mean free path) for gas molecules is small
  - This, combined with relatively high temperature leads to Excellent Conformal Step Coverage!

- Types of films: polysilicon, \( \text{SiO}_2 \), silicon nitride, SiGe, Tungsten (W), Molybdenum (M), Tantalum (Ta), Titanium (Ti), ...

The CVD Process

Reactant gas (i.e., catalyzing gases) are introduced into the reaction chamber.

- Energy required to drive reactions supplied by several methods: Thermal (i.e., heat), photons, electrons (i.e., plasma)
The CVD Process (cont.)

Step-by-Step CVD Sequence:

a) Reactant gases (+ inert diluting gases) are introduced into reaction chamber
b) Gas species move to the substrate
c) Reactants adsorbed onto the substrate
d) Atoms migrate and react chemically to form films
   This determines to a large extent whether or not a film is conformal (i.e. better step coverage)
e) Reaction by-products desorbed and removed from reaction chamber

Not Conformal
low T not enough adatom migration

Conformal
High T Plenty of adatom migration