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EE C247B - ME C218 Introduction to MEMS Design Spring 2014

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Lecture Module 3: Oxidation & Film Deposition

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Lecture Outline

- Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 3, 6
 - ↳ 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

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MEMS Fabrication

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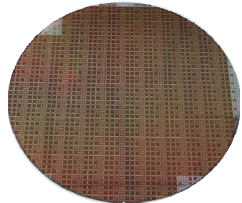
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Making Mechanical Devices

- 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

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Polysilicon Surface-Micromachining

- Uses IC fabrication instrumentation exclusively
- *Variations*: sacrificial layer thickness, fine- vs. large-grained polysilicon, *in situ* vs. $POCl_3$ -doping

300 kHz Folded-Beam Micromechanical Resonator

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Electroplating: Metal MEMS

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

RF Switch

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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

Micromechanical Vibrating Ring Gyroscope
1 mm
[Najafi, Michigan]

Microrotor (for a microengine)
[Pisano, UC Berkeley]

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Oxidation

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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:

High T (~900°C - 1200°C)
In dry O₂
or
Water vapor

56%
44%

Si Wafer

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Oxidation Modeling

(1) **Initially:** (no oxide @ surface)

gas stream
Si

↳ Growth rate determined by reaction rate @ the surface

(2) **As oxide builds up:**

gas stream
oxide
Si

↳ Reactant must diffuse to Si surface where the oxidation reaction takes place

↳ Growth rate governed more by rate of diffusion to the silicon-oxide interface

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Oxidation Modeling (cont.)

reactant concentration

N_0 = reactant conc. at oxide surface [in cm⁻²]
 N_i = reactant conc. at Si-SiO₂ interface

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

Diffusion coeff. [in μm/hr or m/s]

distance from surface

surface Si-SiO₂ interface

In the SiO₂: $J = D \frac{(N_0 - N_i)}{X_{ox}} = \text{constant}$ (1)

Assumption that the reactant does not accumulate in the oxide.

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Oxidation Modeling (cont.)

At the Si-SiO₂ interface:
Oxidation rate $\propto N_i \therefore J \propto N_i \Rightarrow J = k_s N_i$ (2)

Reaction rate constant @ Si-SiO₂ interface

Combining (1) and (2):

$$\left[N_i = \frac{J}{k_s} \right] \Rightarrow J = D \left(\frac{N_0 - J/k_s}{X_{ox}} \right)$$

$$J X_{ox} = D N_0 - \frac{D J}{k_s} \rightarrow J \left(X_{ox} + \frac{D}{k_s} \right) = D N_0$$

$\therefore J = \frac{D N_0}{X_{ox} + \frac{D}{k_s}} = \text{Flux of reactants}$

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Oxidation Modeling (cont.)

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

oxidizing flux

$$\left. \begin{array}{l} \text{Rate of change of oxide} \\ \text{layer thickness w/time} \end{array} \right\} = \frac{dX_{OX}}{dt} = \frac{J}{M} = \frac{DN_{O_2}/M}{X_{OX} + D/k_s} \quad (3)$$

of molecules of oxidizing species incorporated into a unit volume of oxide

$$\left. \begin{array}{l} = 2.2 \times 10^{22} \text{ cm}^{-3} \text{ for } O_2 \\ = 4.4 \times 10^{22} \text{ cm}^{-3} \text{ for } H_2O \end{array} \right\}$$

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

$$\frac{dX_{OX}}{dt} = \frac{DN_{O_2}/M}{X_{OX} + D/k_s} \Rightarrow \int_{X_i}^{X_{OX}} \left(X_{OX} + \frac{D}{k_s} \right) dX_{OX} = \int_0^t \frac{DN_{O_2}}{M} dt$$

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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]

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

where $A = \frac{2D}{k_s}$ $\tau = \frac{X_i^2}{B} + \frac{X_i}{(B/A)}$

$$B = \frac{2DN_{O_2}}{M} \quad D = D_0 \exp\left(-\frac{E_A}{kT}\right)$$

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

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Oxidation Modeling (cont.)

For shorter times:

$$\left[(t + \tau) \ll \frac{A^2}{4B} \right] \Rightarrow X_{OX}(t) = \left(\frac{B}{A} \right) (t + \tau) \Rightarrow$$

oxide growth limited by reaction at the Si-SiO₂ interface

Taylor expansion (first term after 1's cancel) linear growth rate constant

For long oxidation times: oxide growth diffusion-limited

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

$t \gg \tau$ Parabolic rate constant

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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_2 values should be divided by 1.68.

Ambient	B	B/A
Dry O ₂	$C_1 = 7.72 \times 10^2 \mu\text{m}^2 \text{ hr}^{-1}$	$C_2 = 6.23 \times 10^6 \mu\text{m hr}^{-1}$
	$E_1 = 1.23 \text{ eV}$	$E_2 = 2.0 \text{ eV}$
Wet O ₂	$C_1 = 2.14 \times 10^2 \mu\text{m}^2 \text{ hr}^{-1}$	$C_2 = 8.95 \times 10^7 \mu\text{m hr}^{-1}$
	$E_1 = 0.71 \text{ eV}$	$E_2 = 2.05 \text{ eV}$
H ₂ O	$C_1 = 3.86 \times 10^2 \mu\text{m}^2 \text{ hr}^{-1}$	$C_2 = 1.63 \times 10^8 \mu\text{m hr}^{-1}$
	$E_1 = 0.78 \text{ eV}$	$E_2 = 2.05 \text{ eV}$

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

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