



ME 141B: The MEMS Class

Introduction to MEMS and MEMS Design

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Outline today



- Introduction to thin films
- Oxidation
 - Deal-grove model
- CVD
- Epitaxy
- Electrodeposition



Creating thin (and thick) films



- Many techniques to choose from
- Differences:
 - Front or back end processes
 - Quality of resulting films (electrical properties, etch selectivity, defects, residual stress)
 - Conformality
 - Deposition rate, cost
- Physical techniques
 - Material is removed from a source, carried to the substrate, and dropped there
- Chemical Techniques
 - Reactants are transported to the substrate, a chemical reaction occurs, and the product deposit on the substrate to form the desired film



Taxonomy of deposition techniques



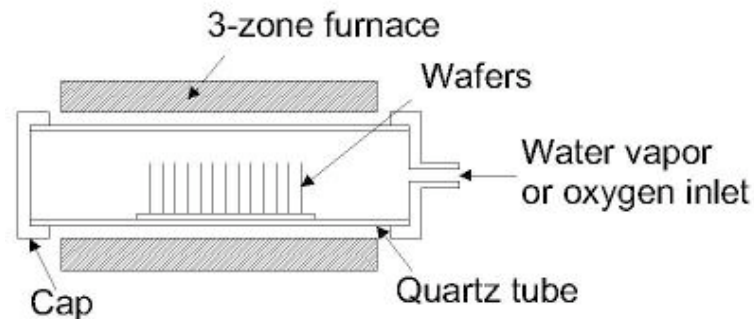
- Chemical
 - Thermal Oxidation
 - Chemical Vapor Deposition (CVD)
 - Low Pressure (LPCVD), Atmospheric pressure (APCVD), Plasma Enhanced (PECVD), Ultra High Vacuum CVD (UHCVD)
 - Epitaxy
 - Electrodeposition (Electroplating)
- Physical
 - Physical Vapor Deposition (PVD)
 - Evaporation
 - Sputtering
 - Spin-casting



Thermal Oxidation



- Most basic deposition technologies
- Oxidation of a substrate surface in an O_2 rich atmosphere
- Temperature is raised (800-1100C) to speed up process
- Only deposition technology which CONSUMES substrate
- Parabolic relationship between film thickness and oxidation time for films thicker than ~ 100 nm





why is oxidation so important?



- Oxides are vital in device structures:
 - gate oxide in MOS transistors
 - field oxide for device isolation
- SiO_2/Si has excellent electrical characteristics
- Other desirable characteristics: excellent adhesion, non-conductive, planar processing

****the ability to easily and reproducibly grow high-quality oxides on silicon is one of the principal reasons for the importance of silicon to semiconductor devices!***



When to use TO



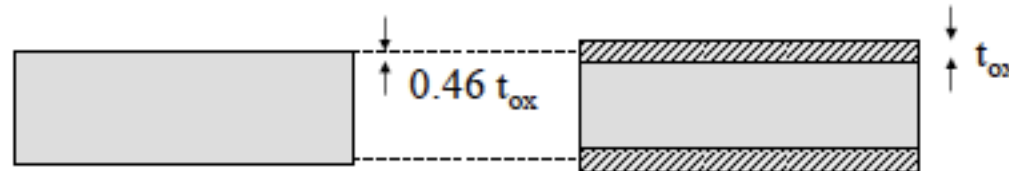
- Whenever you can!
- Best, highest quality oxide
- Unfortunately, high temperature makes it limited use
- Typically used to form films that are used for electrical insulation
- Also used as etch masks or etch stops for future processing steps



Oxidation I



- Silicon forms a high quality, stable oxide
 - How it works:
 - Oxygen diffuses through oxide to Si/oxide interface
 - $\text{Si} + \text{O}_2 + \text{high temperature } (\sim 1100) \text{ furnace} \rightarrow \text{SiO}_2$
 - Some Si is consumed



- Rate determined by diffusion of oxygen through oxide
- Diffusion limits practical oxide thickness to $< 2 \text{ } \mu\text{m}$
- A key front end process



Oxidation II



- Dry Oxidation (O_2)
 - High quality, slow oxidation rate, smaller maximum thickness (i.e. gate oxide)
- Wet Oxidation (steam)
 - H_2 to speed the diffusion
 - Lower quality, faster oxidation rate
- The Deal-Grove model describe the kinetics of oxidation quite well for oxides greater in thickness that about 30nm



oxidation reactions and oxide properties



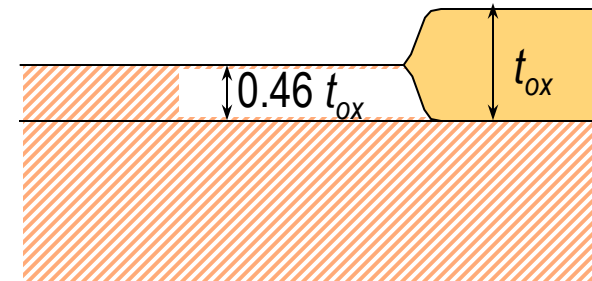
- Two common oxidation reactions:
 - Dry oxidation: $\text{Si (solid)} + \text{O}_2 \text{ (gas)} \longrightarrow \text{SiO}_2 \text{ (solid)}$
 - Wet oxidation: $\text{Si (solid)} + 2\text{H}_2\text{O (vapor)} \longrightarrow \text{SiO}_2 \text{ (solid)} + 2\text{H}_2$
- Crystal structure:
 - crystalline SiO_2 exists in >11 distinct forms
 - SiO_2 grown by thermal oxidation are amorphous
 - density of thermal SiO_2 (2.15 to 2.27 g cm⁻³) is less than crystalline SiO_2 (2.65 g cm⁻³) – the more “open” structure permits impurities (water, oxygen, sodium) to easily diffuse interstitially



oxide growth mechanism



- A film of growing SiO_2 of thickness t_{ox} will consume a layer of crystalline Si of about $0.46 t_{\text{ox}}$



- The oxide-Si interface is displaced from the original Si surface and is located deeper into the Si wafer
- With both O_2 and H_2O the oxidizing species moves through the oxide layer to react
- The displaced and deeper interface + inward migration of oxidizing species provides a clean, contaminant-free oxide-Si interface



The Deal-Grove Model



- Mathematically describes the growth of an oxide layer on the surface of a material
- Used to analyze thermal oxidation of silicon
- Physical assumptions
 - Oxygen diffuses from the bulk to the ambient gas to the surface
 - It diffuses through the existing oxide layer to the oxide-substrate interface
 - It then reacts with the substrate
- Model:
 - Henry's law
 - Fick's law of diffusion
 - First-order reaction
- Also assume steady state conditions



The Deal-Grove Model



For oxides greater than about 30 nm thick:

$$x_{final} = 0.5 \left[A_{DG} \left[\sqrt{1 + \frac{4 B_{DG}}{A_{DG}^2} (t + \tau_{DG})} - 1 \right] \right]$$

where

$$\tau_{DG} = \frac{x_i^2}{B_{DG}} + \frac{x_i}{B_{DG} / A_{DG}}$$

(Constants are given in the text; beware units of B_{DG} , $\mu\text{m}^2/\text{hour}$)

Growth goes approximately as t for short times, and approximately as \sqrt{t} for long times.



Deal Grove constants



Temperature	A_{DG}	B_{DG}
920	0.05	0.203
1000	0.226	0.287
1100	0.11	0.510

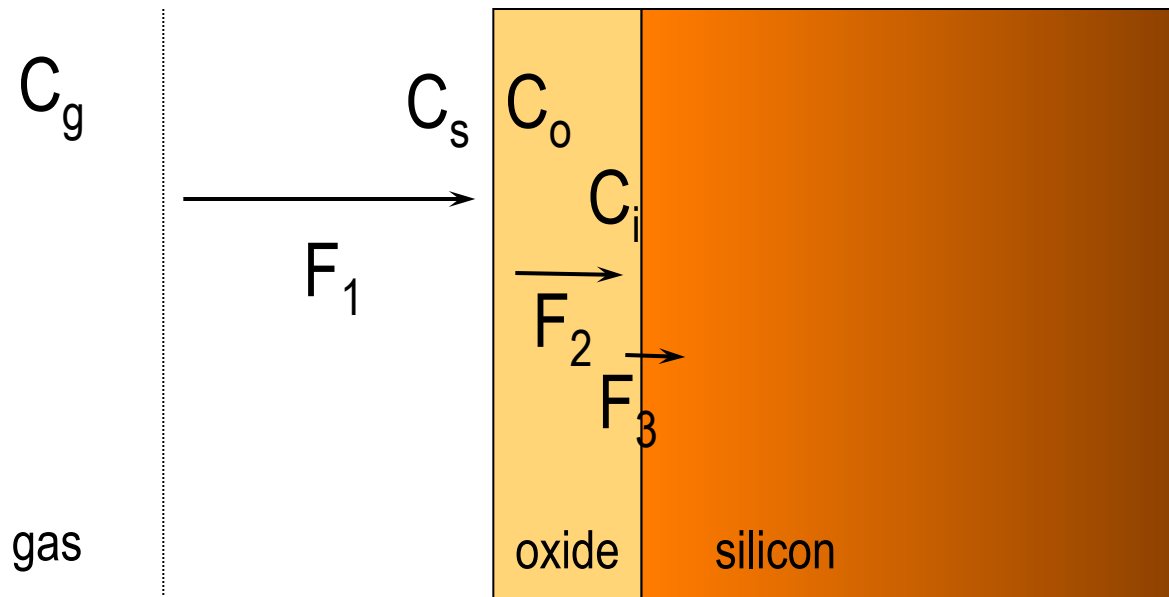
Determine how long it takes to grow 1um of oxide on a bare silicon wafer at 1000C under both wet and dry conditions

$$t = x_f^2 / B_{DG}$$

47 minutes under wet conditions and 14.1 hours under dry conditions



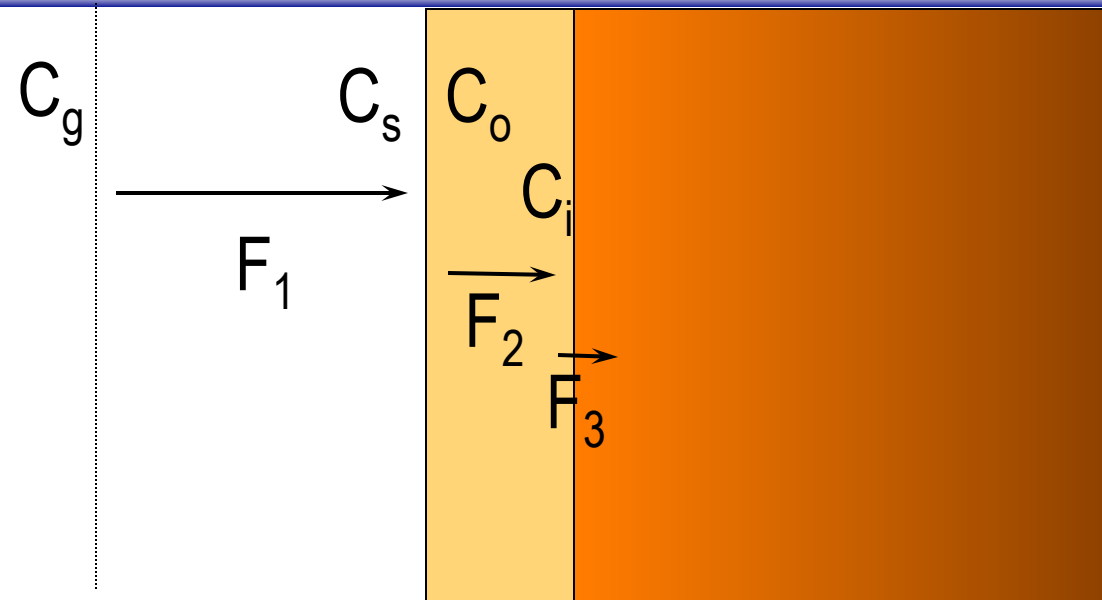
The Deal-Grove model



assumption: oxide growth occurs by diffusion of oxygen to the silicon interface, where the reaction $\text{Si} + \text{O}_2 \rightarrow \text{SiO}_2$ occurs



The Deal-Grove model



Fluxes:

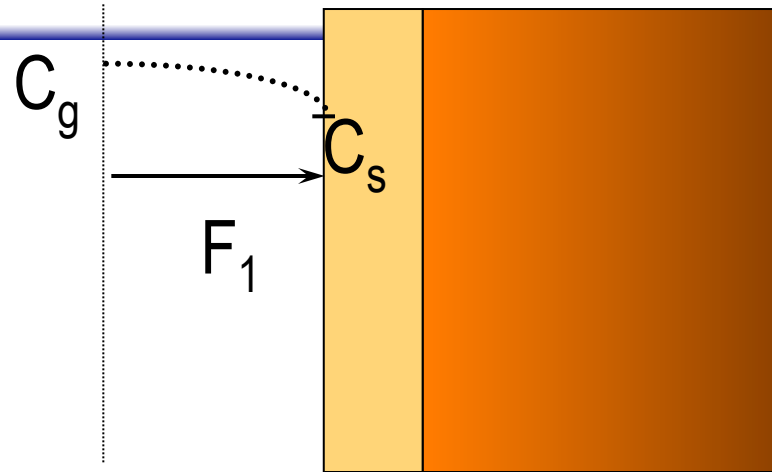
- F_1 -- oxygen flux to the surface
- F_2 -- oxygen flux through the oxide
- F_3 -- oxygen flux reacting with the silicon substrate

Concentrations:

- C_g -- gas-phase concentration
- C_s -- oxygen conc. at surface
- C_o -- conc. inside oxide surface
- C_i -- conc. at Si/SiO₂ interface



F_1 -- Gas-phase diffusion flux



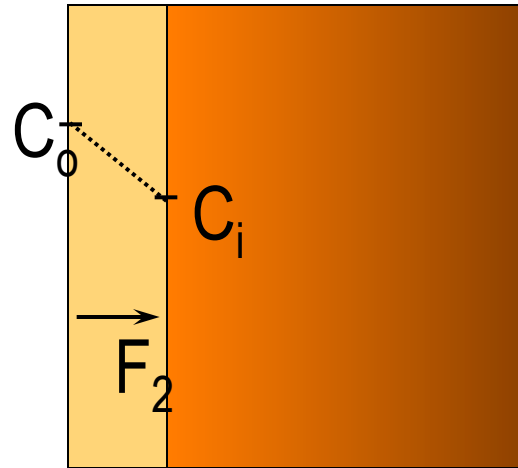
- Oxygen must diffuse across a stagnant boundary layer to the surface:

$$F_1 = D_{O_2} \frac{C_g - C_s}{t_{sl}}$$
$$= h_g (C_g - C_s)$$

where h_g is the mass transport coefficient



F_2 -- Oxide diffusion flux



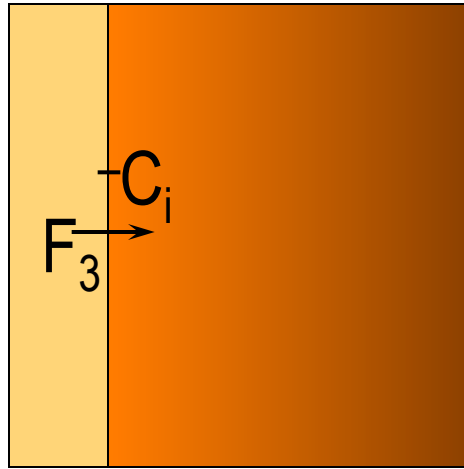
- Oxygen must diffuse through the oxide to the silicon interface:

$$F_2 = D_{O_2} \frac{C_o - C_i}{t_{ox}}$$

(note: the diffusivity is for oxygen in the oxide)



F_3 -- Oxide reaction flux



- The oxygen at the Si/SiO₂ interface reacts to form the oxide:

$$F_3 = k_s C_i$$

where k_s is the chemical rate constant for the oxidation reaction



Solution to the Deal-Grove model (1)



- at steady state (**not equilibrium!**) the fluxes will be equal:

$$F_1 = F_2 = F_3 \equiv F$$

- note that the oxygen concentration at the oxide surface (C_o) is proportional to the gas pressure (Henry's Law)

$$C_o = HP_G = HkT C_G$$

since $C_G = n/V = P_G/kT$ (ideal gas law)

- “After some algebra...” one obtains:

$$C_i = \frac{HP_G}{1 + \frac{k_s}{h_G} + \frac{k_s t_{ox}}{D}}$$



Solution to the Deal-Grove model (2)



$$C_i = \frac{HP_G}{1 + \frac{k_s}{h_G} + \frac{k_s t_{ox}}{D}}$$

as H , P_G and $h_g \uparrow$,

$C_i \uparrow$

as $k_s \uparrow$, $C_i \downarrow$

also: $F = F_3 = k_s C_i$

- The oxide growth rate will be given by:
(flux at interface) ÷ (number of O_2 molecules per unit vol. of SiO_2)

- The resultant oxide growth rate is

$$R = \frac{F}{N_1} = \frac{dt_{ox}}{dt} = \frac{Hk_s P_G}{N_1 \left[1 + \frac{k_s}{h_G} + \frac{k_s t_{ox}}{D} \right]}$$

$cm^{-2} sec^{-1}$ → F
cm^{-3} → N_1



Solution to the Deal-Grove model (3)



$$R = \frac{F}{N_1} = \frac{dt_{ox}}{dt} = \frac{Hk_s P_G}{N_1 \left[1 + \frac{k_s}{h_G} + \frac{k_s t_{ox}}{D} \right]}$$

The solution to this differential equation is:

$$t_{ox}^2 + At_{ox} = B(t + \tau)$$

where

$$A = 2D \left(\frac{1}{k_s} + \frac{1}{h_G} \right) \quad B = \frac{2DHP_G}{N_1} \quad \tau = \frac{t_o^2 + At_o}{B}$$



Evaluation of the Deal-Grove model



$$t_{\text{ox}}^2 + At_{\text{ox}} = B(t + \tau)$$

where

$$A = 2D \left(\frac{1}{k_s} + \frac{1}{h_G} \right)$$

$$B = \frac{2DHP_G}{N_1}$$

$$\tau = \frac{t_o^2 + At_o}{B}$$

1. In most cases, oxidation is performed at atmospheric pressure where $h_G \gg k_s$ and $A \approx 2D/k_s$ (units: cm)
2. $C_o = HP_G$ so $B = 2DC_o/N_1$ (units: $\text{cm}^2 \text{sec}^{-1}$)
3. t_o is the oxide thickness at $t = 0$



Short times and thin oxides



$$t_{\text{ox}}^2 + At_{\text{ox}} = B(t + \tau) \quad \longrightarrow \quad t \approx 0 \text{ and } t_{\text{ox}}^2 \Rightarrow 0$$

$$\text{or: } t_{\text{ox}} = \frac{B}{A}(t + \tau)$$

- Early in the oxidation process the oxide thickness is **linearly proportional** to the oxidation time
- The ratio B/A is often called the “linear rate constant”
- B/A is equal to $C_o k_s / N_1$ and has units of $\text{cm sec}^{-1} \rightarrow$ **independent** of D
- τ arises from the boundary condition at $t = 0$ -- either the oxide thickness at $t = 0$ is t_o , or the thickness is zero at time $-\tau$



Long times and thick oxides



$$t_{\text{ox}}^2 + At_{\text{ox}} = B(t + \tau) \longrightarrow t_{\text{ox}}^2 \gg t_{\text{ox}} \text{ and } t \gg \tau$$

or: $t_{\text{ox}}^2 = Bt$

- B depends on the product of D and $C_o \rightarrow$ a function of reactant concentration within the oxide and its ability to diffuse through the oxide
- B is often called the “parabolic rate constant” since a plot of the square of the thickness versus time would look like a parabola
- Systems that exhibit parabolic growth kinetics typically are ***diffusion controlled***



The two limiting regimes



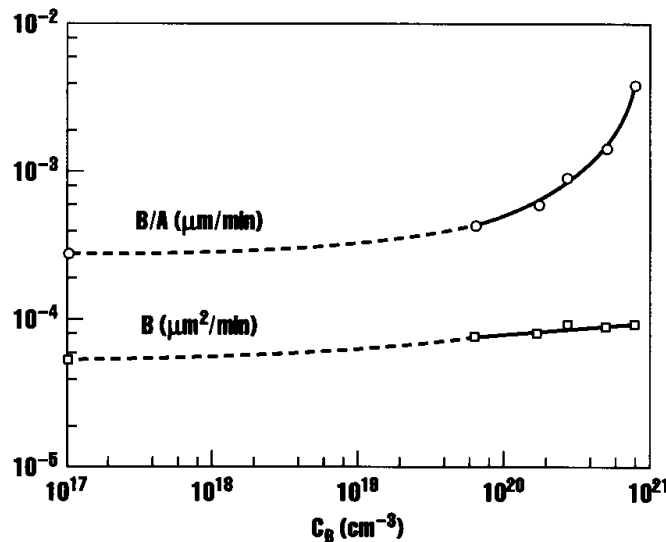
- **Linear regime** → the growth rate is constant in time and is independent of the amount of gas and substrate that are consumed
- **Parabolic regime** → a thermally-activated diffusion process is controlling the growth rate
- In general, the Deal-Grove model does an excellent job of describing the oxidation process under a wide variety of conditions



Observations on the linear regime



- Since the linear rate depends on the surface reaction rate, it can be sensitive to the properties of the substrate
 - the linear rate constant for growth on the (111) Si surface is 1.7× greater than for growth on the (100) surface (*reason: larger number of available bonds on the (111) surface*)
 - heavy doping of the silicon substrate can increase the linear rate constant by a factor of 10 -- doping enhanced oxidation, or DEO (*reason: doping alters the interstitial and vacancy concentrations*)



note: no effect on the parabolic rate constant (more to come on doping effects in oxidation...)



Initial rapid growth rate



- Deviations from the Deal -Grove linear-parabolic oxidation theory for very thin oxide layers (short-time growth) -- growth *faster* than expected
- Possible causes included: space-charge effects (field-assisted diffusion); structural defects in the oxide; stress effects leading to increased diffusivity; increased solubility of the oxidant in the thin oxide; and diffusion of silicon to the oxide surface

- Modify the Deal-Grove expression:

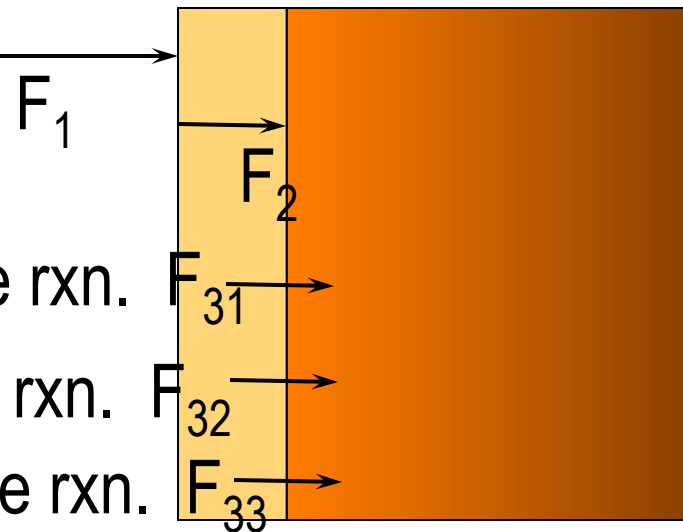
$$\frac{dt_{\text{ox}}}{dt} = \frac{B}{2t_{\text{ox}} + A} + Ce^{-t_{\text{ox}}/L}$$

modifications
to basic Deal-
Grove model

linear-parabolic surface rxn.

thin-regime surface rxn.

vacancy-assisted surface rxn.





Observations on the parabolic regime



- The parabolic rate constant is sensitive to factors that alter the ability of the oxidizing species to diffuse through the oxide
 - H₂O is a smaller molecule than O₂ and thus will have a larger diffusion coefficient
 - The oxide formed by **wet oxidation** is more porous and less dense than that formed without water (**dry oxidation**) and permits higher diffusivities at lower temperatures

ppm H ₂ O	B/A (Å min ⁻¹)	B (Å ² min ⁻¹)
<1	2.2	4350
1000	2.9	8400

- Increasing the oxygen pressure will also increase B and decrease the time needed to grow a thick oxide



A sample calculation



A silicon wafer is initially covered by an SiO₂ film 0.3 μm thick. What is the time required to increase the thickness to 0.5 μm?

$$t_{\text{ox}}^2 + At_{\text{ox}} = B(t + \tau) \approx Bt \quad (\text{ignore } \tau \text{ for thick oxide})$$

For a wet oxidation at 1200°C, $A = 0.05 \mu\text{m}$ and $B = 0.720 \mu\text{m}^2/\text{hr}$, so:

$$(0.2)^2 + (0.05)(.2) = (0.720)t \text{ or } t = 0.069 \text{ hours or } \sim 4.2 \text{ minutes}$$

If a dry oxidation at is performed at 1200°C, $A = 0.04 \mu\text{m}$ and $B = 0.045 \mu\text{m}^2/\text{hr}$, so:

$$(0.2)^2 + (0.04)(.2) = (0.045)t \text{ or } t = 1.067 \text{ hours or } \sim 64 \text{ minutes}$$



Interference measurement of oxide thickness



By measuring the intensity of reflected light as a function of wavelength, the oxide thickness can be determined from:

$$t_{\text{ox}} = \frac{\Delta\lambda}{2n_{\text{ox}}} \left. \vphantom{\frac{\Delta\lambda}{2n_{\text{ox}}}} \right\} \text{ strictly true only at normal incidence}$$

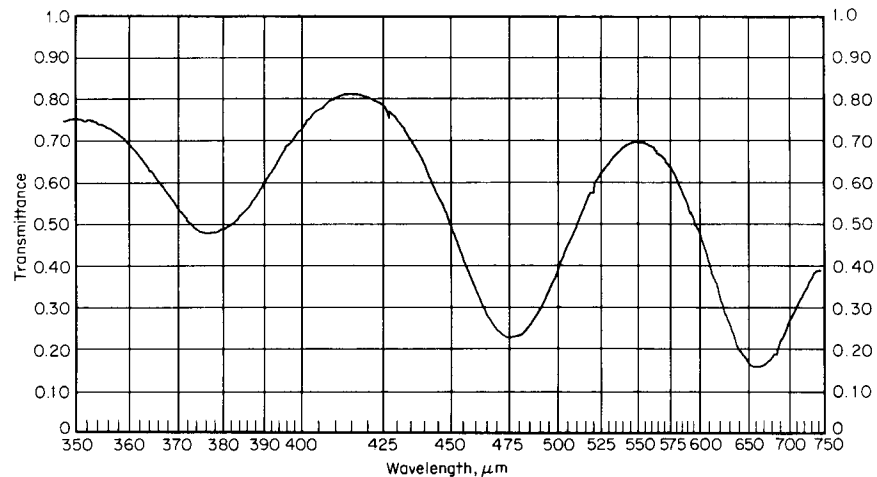
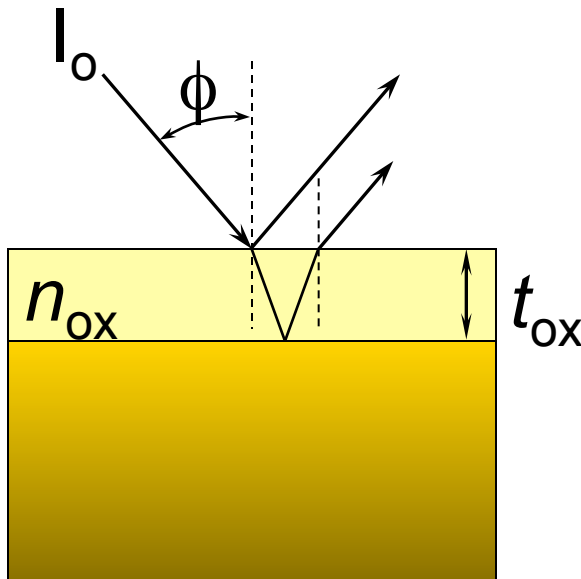


Fig. 6.12. Reflected intensity of an SiO_2 layer on a Si substrate.



- Interference effects can give a thin transparent layer a characteristic color
- Color depends on:
 - film thickness
 - index of refraction
 - spectral distribution of the viewing light
- Experienced viewers can estimate the thickness of a film to about 100Å

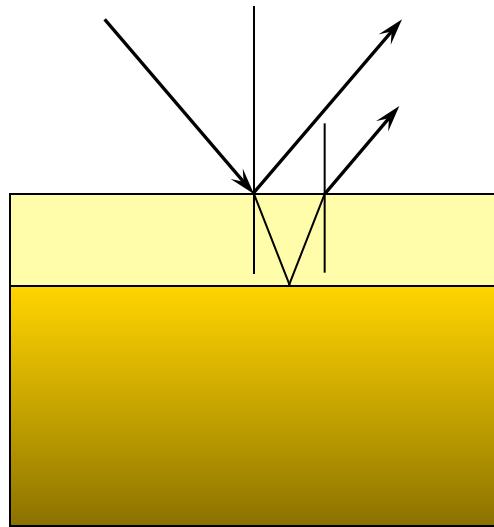
Table 6.6. Color Chart for Thermally Grown SiO₂ Films Observed Perpendicularly under Daylight Fluorescent Lighting

Film thickness, μm	Color and comments	Film thickness, μm	Color and comments
0.05	Tan	0.63	Violet-red
0.07	Brown	0.68	“Bluish” (Not blue but borderline between violet and blue-green. It appears more like a mixture between violet-red and blue-green and looks grayish)
0.10	Dark violet to red-violet	0.72	Blue-green to green (quite broad)
0.12	Royal blue	0.77	“Yellowish”
0.15	Light blue to metallic blue	0.80	Orange (rather broad for orange)
0.17	Metallic to very light yellow-green	0.82	Salmon
0.20	Light gold or yellow—slightly metallic	0.85	Dull, light red-violet
0.22	Gold with slight yellow-orange	0.86	Violet
0.25	Orange to melon	0.87	Blue-violet
0.27	Red-violet	0.89	Blue
0.30	Blue to violet-blue	0.92	Blue-green
0.31	Blue	0.95	Dull yellow-green
0.32	Blue to blue-green	0.97	Yellow to “yellowish”
0.34	Light green	0.99	Orange
0.35	Green to yellow-green	1.00	Carnation pink
0.36	Yellow-green	1.02	Violet-red
0.37	Green-yellow	1.05	Red-violet
0.39	Yellow	1.06	Violet
0.41	Light orange	1.07	Blue-violet
0.42	Carnation pink	1.10	Green
0.44	Violet-red	1.11	Yellow-green
0.46	Red-violet	1.12	Green
0.47	Violet	1.18	Violet
0.48	Blue-violet	1.19	Red-violet
0.49	Blue	1.21	Violet-red
0.50	Blue-green	1.24	Carnation pink to salmon
0.52	Green (broad)	1.25	Orange
0.54	Yellow-green	1.28	“Yellowish”
0.56	Green-yellow	1.32	Sky blue to green-blue
0.57	Yellow to “yellowish” (not yellow but is in the position where yellow is to be expected. At times it appears to be light creamy gray or metallic)	1.40	Orange
		1.45	Violet
		1.46	Blue-violet
0.58	Light orange or yellow to pink borderline	1.50	Blue
0.60	Carnation pink	1.54	Dull yellow-green

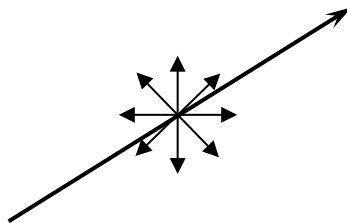
After Pliskin and Conrad.⁵⁷



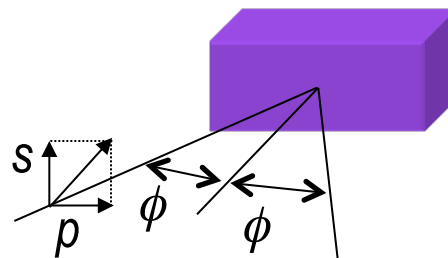
Physical characterization of oxides -- ellipsometry



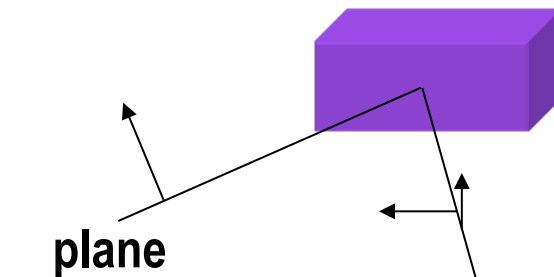
- As light is reflected from a surface, it is normally reduced in amplitude and shifted in phase
- If there are multiple reflecting layers, the various beams will interact further with each other



unpolarized



plane polarized into components p and s



plane polarized

elliptically polarized components differ in phase & amplitude



Ellipsometry for oxide thickness measurement

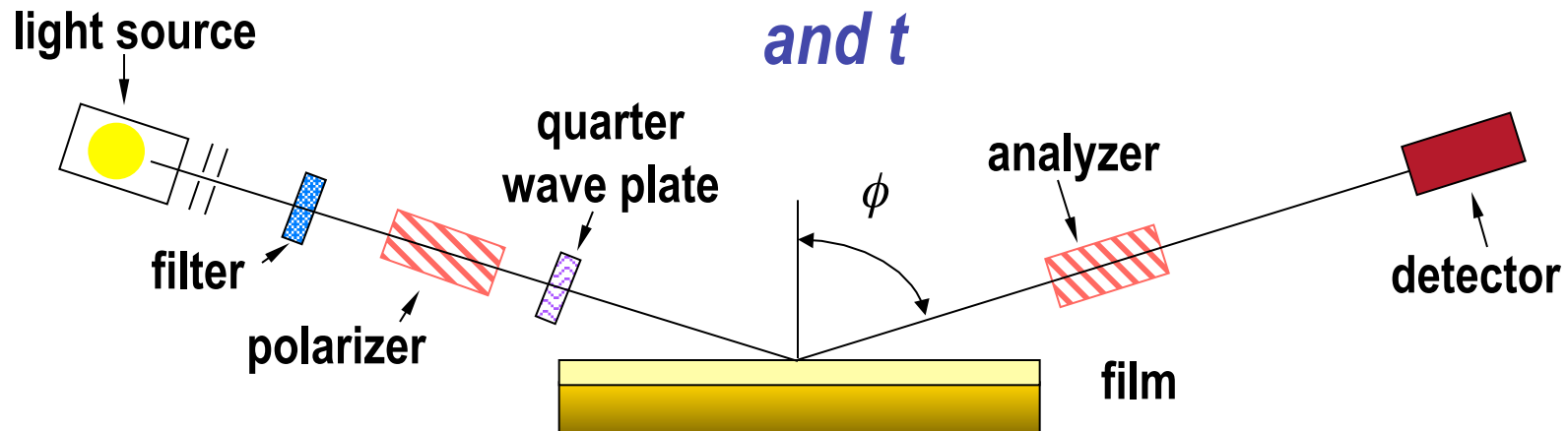


Most useful for studying thin ($< 1\lambda$) layers on thick substrates

Δ = differential phase change = $\Delta_p - \Delta_s$

$$\Psi = \tan^{-1}\left(\frac{R_p}{R_s}\right) \left. \vphantom{\frac{R_p}{R_s}} \right\} \begin{array}{l} R_p \text{ and } R_s \text{ are the reflection} \\ \text{coefficients for the } p \text{ and } s \\ \text{components} \end{array}$$

Δ and Ψ can be directly related to n and t





Validity of Model



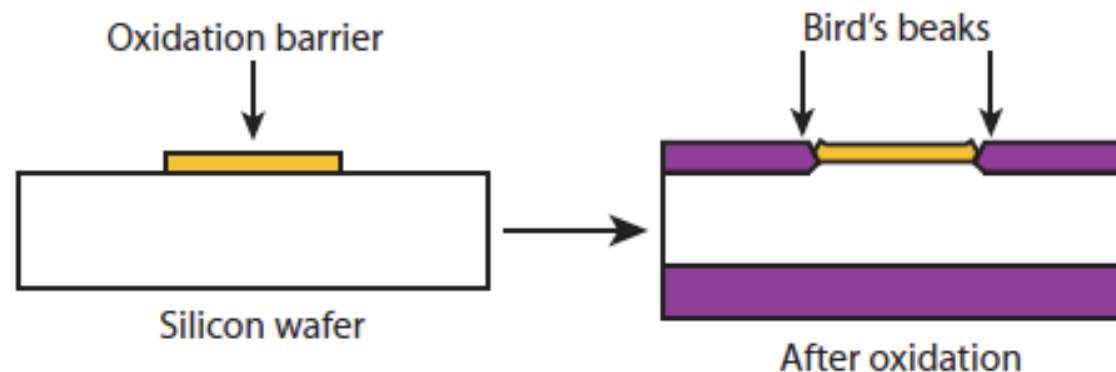
- Works well for single-crystal silicon
- Thin oxides grow more quickly in O_2
- Fails for polycrystalline silicon
 - Random orientation of the crystal grains makes it difficult to choose value for linear rate constant
 - Oxidant molecules diffuse rapidly along grain boundaries – oxidizes more rapidly
- Dopants strain silicon lattice – making it easier for oxygen to enter – oxidizes faster



Local Oxidation



- Oxidation can be masked locally by an oxidation barrier, such as silicon nitride
- Oxide undercuts edge of mask layer to form a “bird’s beak”
- Oxidation followed by an oxide etch can also be used to sharpen silicon features



Senturia, Microsystem Design.



CVD



- CVD is a chemical process used to produce high-purity, high-performance solid materials
- Typical CVD process
 - Wafer exposed to one or more volatile precursors
 - These react and/or decompose on surface
 - This produces desired deposit
- Can deposit in various forms
 - Monocrystalline
 - Polycrystalline
 - Amorphous
 - Epitaxial
- Materials include silicon, carbon fiber, carbon nanofibers, filaments, carbon nanotubes, SiO_2 , silicon-germanium, tungsten, silicon carbide, silicon nitride, etc...



Chemical Vapor Deposition (CVD)



- How CVD works:
 - Gaseous reactants, often at low pressure
 - Long mean free path; reactants reach substrate
 - Reactants react and deposit products on the substrate
 - Unlike Oxidation, does not consume substrate material
- Energy sources facilitate CVD reactions:
 - High temperature, plasma, laser
- Processing temperatures vary widely
- Commonly deposited films: Oxide, silicon nitride, polysilicon
- CVD results depend on pressures, gas flows, temperature
 - Film composition, uniformity, deposition rate, and electrical and mechanical characteristics can vary



Types of CVD



- Atmospheric pressure CVD (SPCVD) – CVD processes at atmospheric pressure
- Low Pressure CVD (LPCVD)- CVD processes at subatmospheric pressures.
 - Reduced pressures tend to reduce unwanted gas-phase reaction and improve uniformity across the wafer
 - Most modern CVD processes are LPCVD or UHCVD
- Ultrahigh vacuum CVD (UHCVD) – CVD process at a very low pressure, $\sim 10^{-8}$ torr
- Plasma-enhanced CVD (PECVD) – CVD process that utilize a plasma to enhance chemical reaction rates of the precursors
 - Allows low temperatures

10/6/10 • Other types, MPCVD, ALCVD, MOCVD



Some reasons to use CVD



- Oxide formation:
 - To get a thicker layer than thermal oxidation can provide
 - To create oxide on a wafer that can't withstand high temperatures (for example because of metal features)
 - To create oxide on top of a material that is not silicon
- For film formation in general
 - To tailor the film properties (like form stress) by adjusting pressures, flow rates, external energy supply, ratios of different precursor gases (to adjust proportions of different materials in the final product)
 - Conformailty : (more or less) even coating on all surfaces
- Drawbacks:
 - Films deposited at low temperature are often lower quality than high temp versions, and have less predictable properties
 - Flammable, toxic or corrosive source gases



Thick Film Formation



- CVD is a common MEMS tool for creating thick films on the wafer surface
 - In practice, film stress limits thickness (film delamination or cracking, or curvature of underlying structures)
 - Can deposit thick oxides; nitrides are still typically submicron
 - Must anneal deposited oxides for some applications – lose low stress property on anneal



Commonly Deposited Substances



- Polysilicon
 - Deposited from silane (SiH_4) ($\text{SiH}_4 \rightarrow \text{Si} + 2\text{H}_2$)
 - Usually performed in LPCVD systems
 - Growth rate 10-20 nm per minute
- Silicon dioxide
 - Source gases include silane and oxygen, dichlorosilane, nitrous oxide, or TEOS (tetraethylorthosilicate)
 - Choice of source depends on thermal stability of substrates
 - ie. aluminum is sensitive to high temperature
 - TEOS is the best, but needs 650-700C, silane is lower quality. Thermal oxidation is best
 - Ozone may deposit TEOS at lower temperatures – being explored



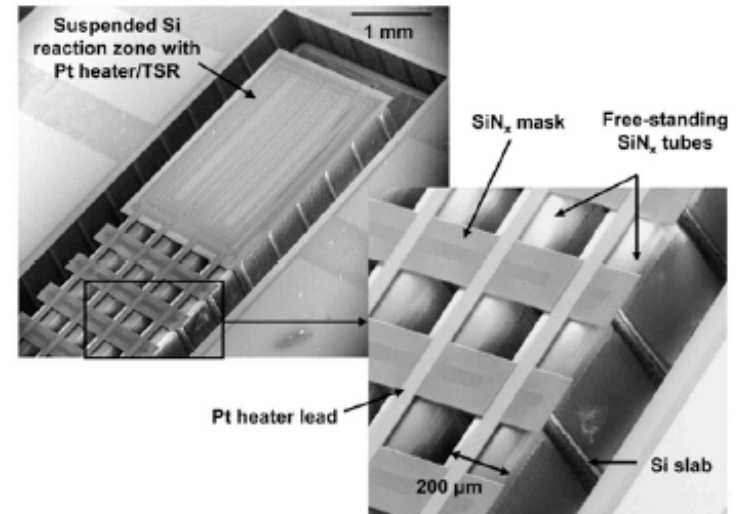
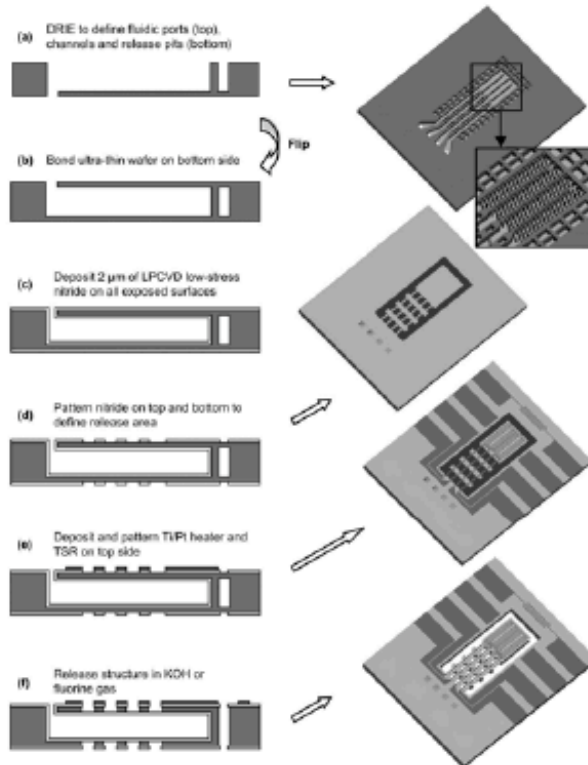
Commonly Deposited Substrates



- Silicon Nitride
 - LPCVD generally used here
- Metals
 - Molybdenum, tantalum, titanium, nickel and tungsten
 - Deposited by LPCVD



CVD enables conformal coating



MEMS-based fuel processor.



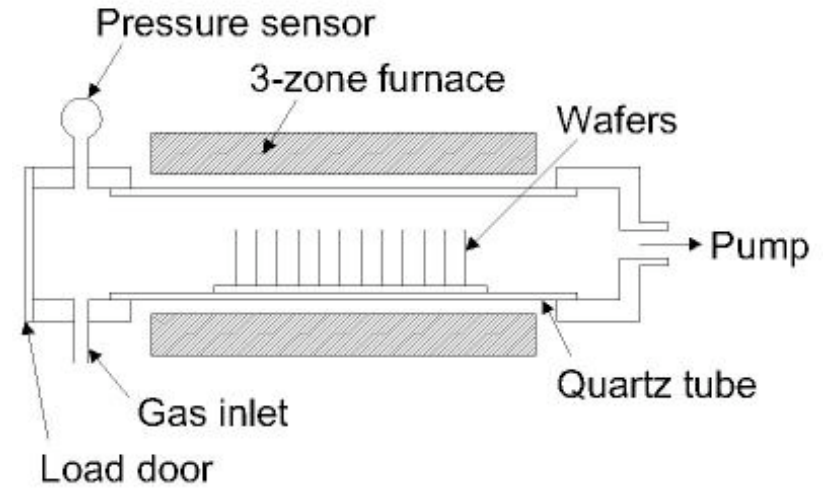
LPCVD Polysilicon



- Amorphous at lower deposition temperatures and high deposition rates
 - Typical temperature: ~590 C
- Polycrystalline at higher deposition temperatures and lower deposition rates
 - Typical temperature: ~625 C
- Grain size and structure depend on detailed deposition conditions
 - E.g. thicker films → larger grains
- Structure, electrical properties, and mechanical properties also vary with post-deposition thermal processing
 - Grain growth
 - Dpoant activation or diffusion



CVD Machine





Epitaxy



- CVD deposition process in which atoms move to lattice sites, continuing the substrate's crystal structure
 - Homoepitaxy: same material, i.e. Si on Si
 - Heteroepitaxy: different materials, i.e. AlGaAs, on GaAs
- How it happens
 - Slow deposition rate (enough time to find a lattice site)
 - High Temperature (enough energy to move a lattice site)
- Selective epitaxy is possible through masking
- Can grow a doped Si layer of known thickness



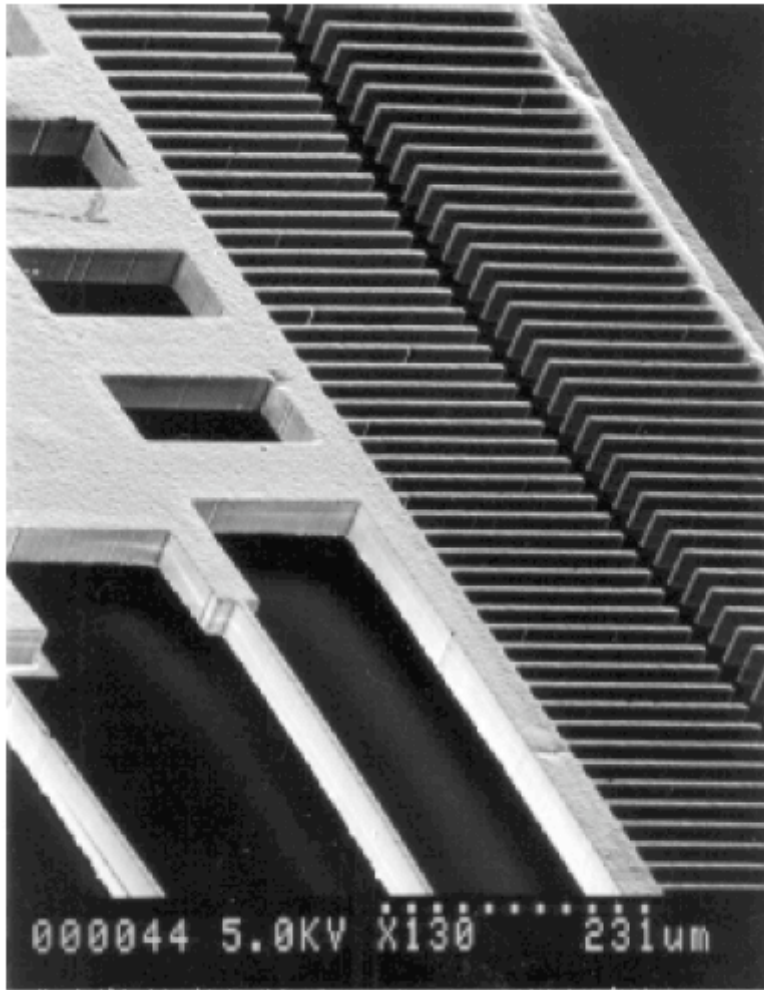
Electroplating: basics



- Pass a current through an aqueous metal solution
 - Anode is made of the meta that you want to deposit
 - Cathode is the conductive seed material on your wafer
 - Positive metal ions travel to the negatively charged cathode on your wafer and deposit there
- Preparing your wafer
 - If you want to plate metal in some places and not in others, you will need a patterned metal seed layer (and typically a “sticky” metal adhesion layer under that)
 - For very short features, just plate onto the seed layer
 - For taller features, need to plate into a mold
 - Molds can be photoresist, silicon, SU-8, et.. Depending on the needs of your device



Electroplating

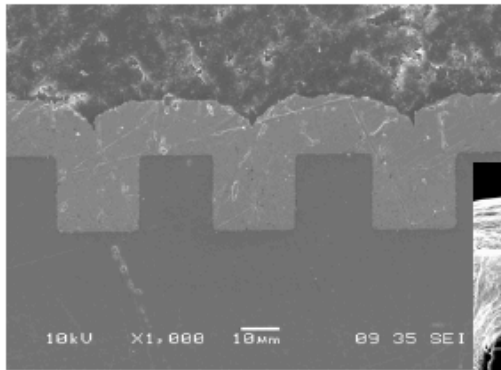


Electroplating for LIGA

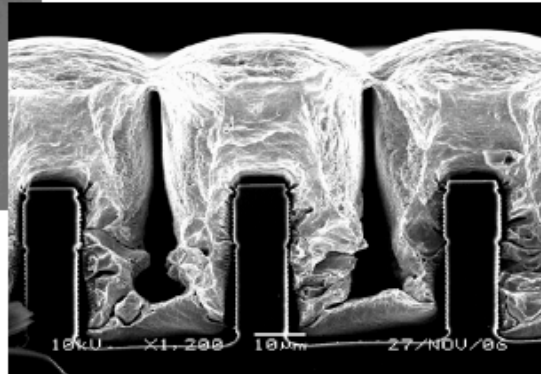
40 μm thick films of nickel fabricated by electroplating into a mold



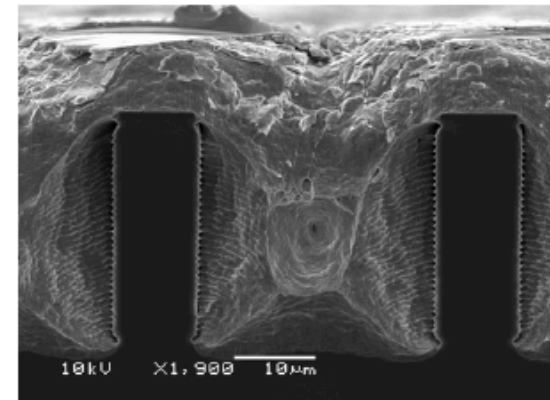
Electroplating realities



Test run w/ bump plating - perfect



Real device forms keyholes – different loading pattern



Solution: Cu damascene fill, with additives/agitation to promote fill at bottom

Courtesy of Dariusz Golda. Used with permission.

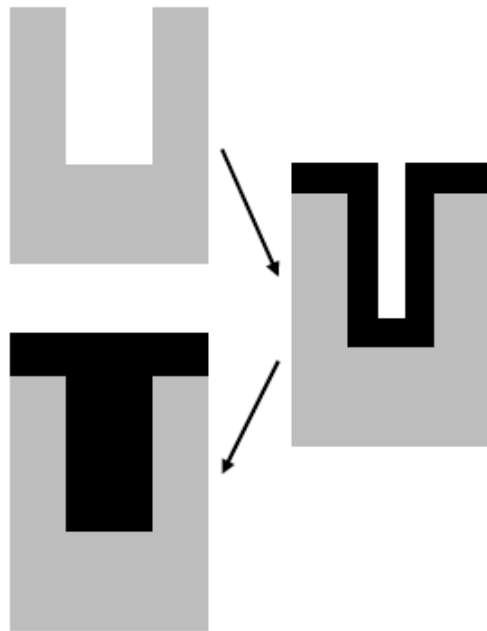


Conformality and keyholes



- To lowest order, conformal films coat sidewalls and horizontal surfaces at the same rate
- But high aspect ratio trenches are prone to keyholes (CVD, electroplating, etc..)

What you want:



What you get:

