ME 141B: The MEMS Class

Introduction to MEMS and MEMS Design

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Outline today

- Introduction to thin films
- CVD
- Epitaxy
- Electrodeposition

Taxonomy of deposition techniques

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

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 precursers
  - These react and/or decompose on surface
  - This produces desired deposit
- Can deposit in various forms
  - Monocrystaline
  - 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, ~10^{-8} torr
- Plasma-enhanced CVD (PECVD) – CVD process that utilize a plasma to enhance chemical reaction rates of the precursors
  - Allows low temperatures
- 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 of 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

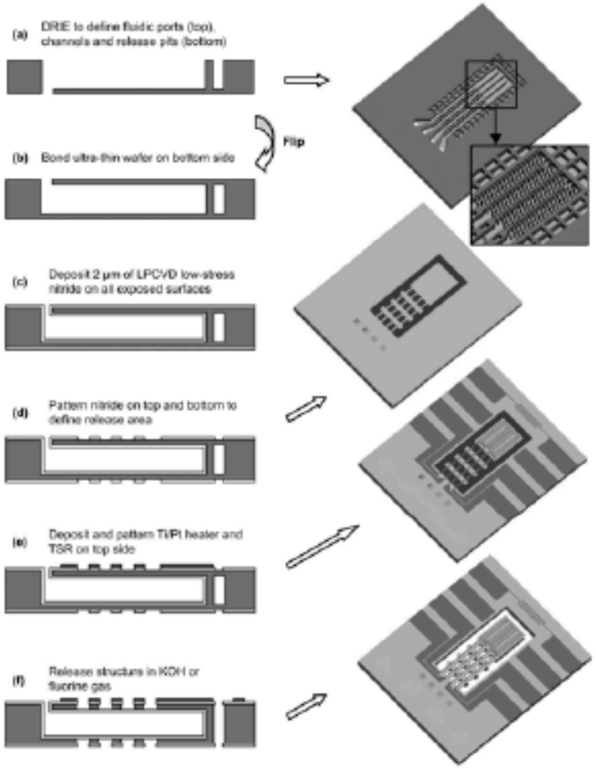
Commonly Deposited Substances

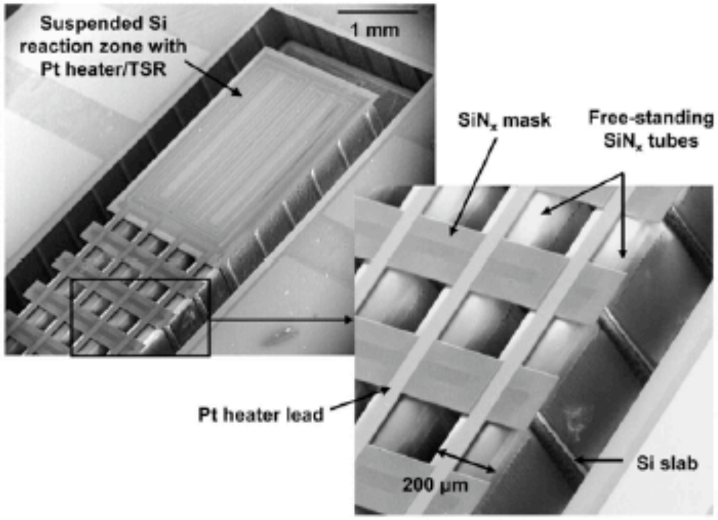
- Polysilicon
  - ➢ Deposited from silane (SH_4) ($SiH_4 \rightarrow Si + 2H_2$)
  - ➢ Usually preformed in LPCVD systems
  - ➢ Growth rate 10-20 nm per minute
- Silicon dioxide
  - ➢ Source gases include silane and oxygen, dichlorosilane, nitrous oxide, or TEOS (tetraethlyorthosilicate)
  - ➢ Choice 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, tatalum, titatnium, nickel and tungsten
  - Deposited by LPCVD

CVD enables conformal coating



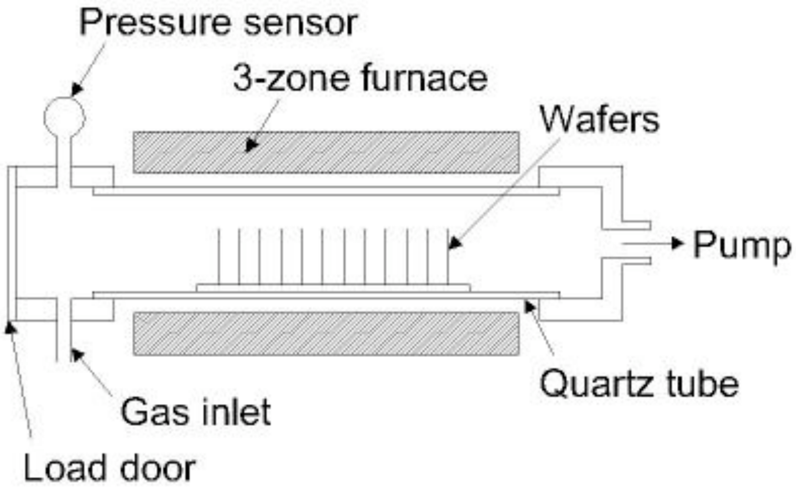


MEMS-based fuel processor.

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


Pressure sensor
3-zone furnace
Wafers
Pump
Quartz tube
Gas inlet
Load door

Epitaxy

- CVD deposition process in which atoms move to lattice sites, continuing the substrate's crystal structure
- Deposits monocrystalline film on a monocyrstalline substrate
  - ➢ Deposited film = epitaxial film or epitaxial layer
- Epi = "above" , "taxis" = "in ordered manner"
- May be grown from gaseous or liquid precursoers.
  - ➢ Since it acts on a seed crystal, film takes on lattice structure and orientation identical to those on substrate
  - ➢ Different from CVD or thermal oxide!!

Types of Epitaxy

- Homoepitaxy: only one material, i.e. Si on Si
  - A crystalline film is grown on the a substrate or film of the same material
  - Used for growing a more purified film than the substrate
  - Also known as “epi”
- Heteroepitaxy: different materials, i.e. AlGaAs, on GaAs
  - Cystalline film grows on a substrate or film of another material
  - Often applied growing films of materials of which single crystals cannot be obtained
- Heterotoepitaxy – similar to Heteroepitaxy but the thin film growth is not limited to two dimensional growth

Epitaxy applications

- Used in nanotechnology and semiconductor fabrication
- Only affordable method of high crystalline quality growth for silicon-germanium, gallium nitride, gallium arsenide, indium phosphide
- Used to grow pre-doped silicon
  - ➢ Common in pacemakers, vending machines, etc…
- 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

Epitaxy methods

- VPE, LPE, SPE, MBE
- Vapor Phase Epitaxy – silicon is deposited from silicon tetrachloride at approximately 1200C

$$SiCl_{4(g)} + 2H_{2(g)} \leftarrow\rightarrow Si_{(s)} + 4HCl_{(g)}$$

  - Reaction is reversible, growth rate depends strongly upon proportion of source gases
  - Growth rates above 2um per minute produce polycrystalline silicon
  - Etching occurs if too much HCl byprodcut is present
- May also use silane, dichlorosilane, and trichlorosilane source gases at lower temperatures
  - Not as clean, always polycrystalline, may have SiO_2 contamination

Epitaxial methods

- LPE – liquid phase epitaxy
  - Method to grow semiconductor crystal layers from the melt on solid substrates
  - Tempertaures well below melting temp of deposited semiconductor → the semiconductor is dissolved in the melt of another materials
  - At conditions between dissolution and deposition, the deposition is slow and uniform -> monocyrstalline films deposit abour 0.1-1 um/min
  - Conitions depend on temperature and concetration of dissolved semiconductor in the melt
  - Growth can be controlled by cooling
  - Can add dopants
- Mainly use for compound semiconductors

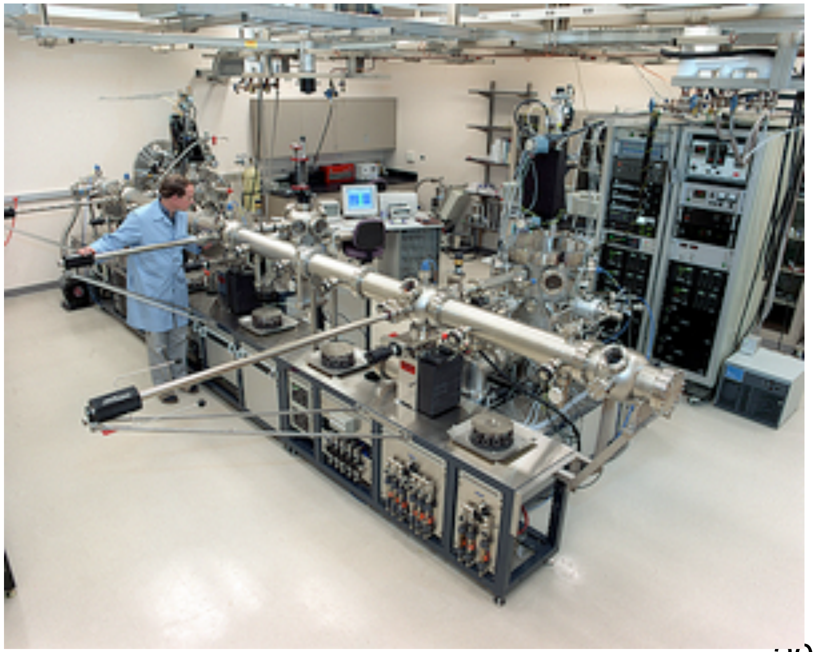
Epitaxial methods (con't)

- Solid-phase Epitaxy
  - Done by first depositing a film of amorphous material on a crystalline material
  - Heated to crystallize the film
  - Single crystal substrate serves as a template for crystal growth
- Not very widely used
- Annealing step used to recrystallize Silicon layers amorphized during ion implantation is considered a type of SPE

Molecular Beam Epitaxy

- MBE very common at UCSB (Herb Krommer, Art Gossard)
- A source material is heated to produce an evaporated beam of particles – these particles travel through a very high vauum to the substrate, where they condense
- High quality, low throughput
- Grows selectively on exposed

Monocystalline surfaces



Electrochemical Deposition

- A plating process that uses electrical current to reduce cations of a desired material from a solution and coat a conductive object with a thin layer of the desired material, such as a metal
- Electro deposition is like a galvanic cell acting in reverse
- Plating processes use the reduction of metal ions in solution to form solid metal
  - ➢ Many metals – Au, Ag, Cu, Hg, Ni, Pt, Permalloy, [NiFe], etc…
- Electroplating uses electrical current to drive reduction
- Electroless plating uses reducing agents to drive metal deposition

Electroplating: basics

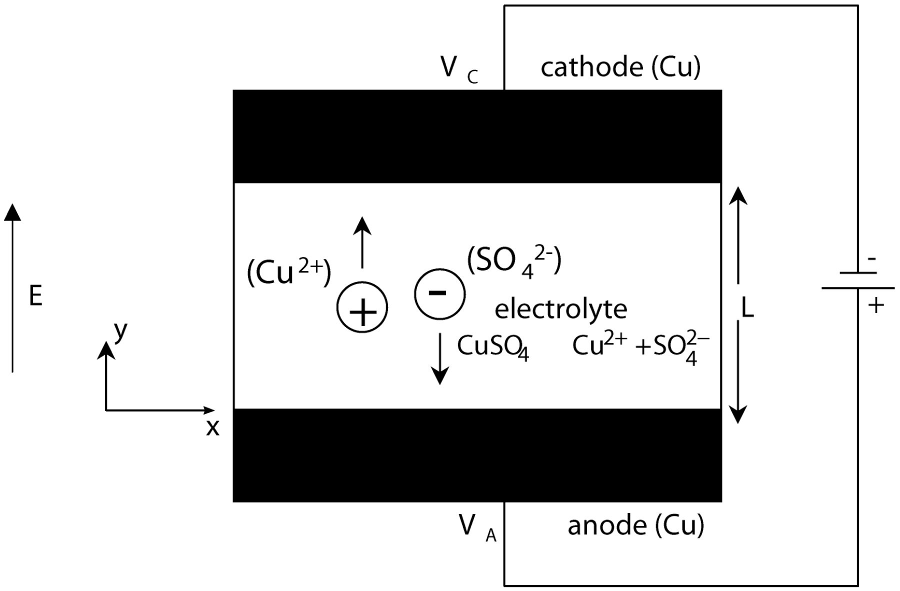
- Pass a current through an aqueous metal solution
  - Anode is made of the metal that you want to deposit
  - Cathode is the conductive seed material on your wafer
  - Positive metal ions travel to the negatively charged cathode on your wafer and deposit there
- Preparing your wafer
  - If you want 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

- Pulsing the electroplating current allows to replenish reactants (stress control, control over morphology, etc… possible)
- Under diffusion-limited conditions, amorphous metal layers can be plated (very high surfaces, e.g. "platinum black"
- Process parameters: overpotential, electrolyte composition, additives, pH, stirring, temperature
- Control parameters: film structure, impurity content, resistivity

Electroplating

ELECTROCHEMICAL CELL



Long-Range Diffusion

Cu^{2+} concentration decreases

H^+ concentration decreases

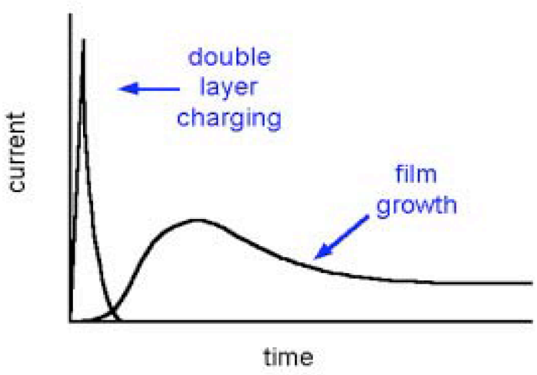
charge neutrality maintained

Cu is the electron donor and Cu^{2+} is the electron acceptor

(Some H+ reacts to form H* to combine to form H_2(g) but only 0 to 10% of the current is 'spent' on this, depending on the additive. The corresponding current efficiency would be 90 to 100%

Electrodeposition can be diffusion limited or interface limited.

Electroplating Details



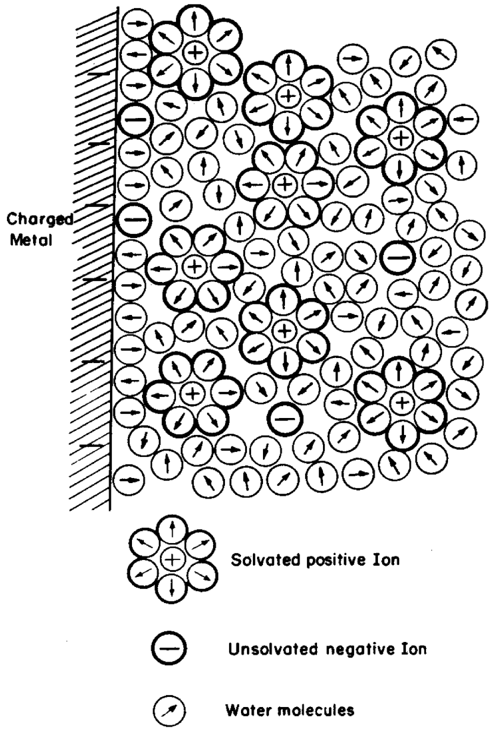


Fig. 7.7. A schematic representation of the structure of an electrified interface. The small, positive ions tend to be solvated, while the larger, negative ions are usually unsolvated (*cf.* Section 2.3.7).

Dendritic Growth

In Electrodeposition, Field Intensification at Perturbations
Leads to Dendritic Growth

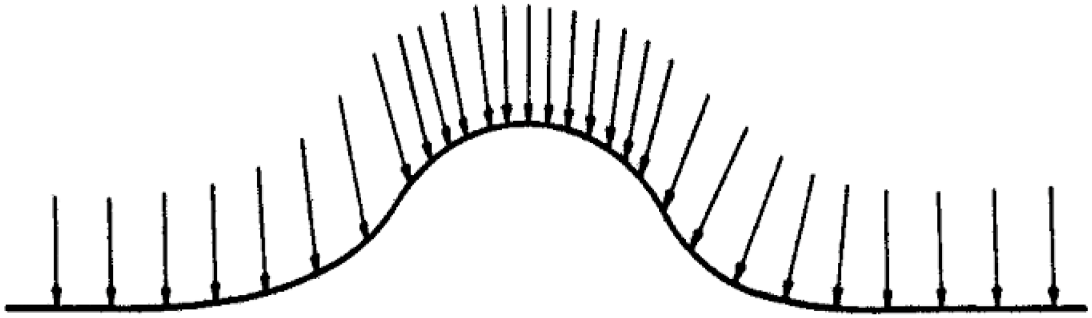


Fig. 10.55. A representation of the concentrated electric field, at a projection, producing a faster growth than at the flat surface.

Dendritic Growth

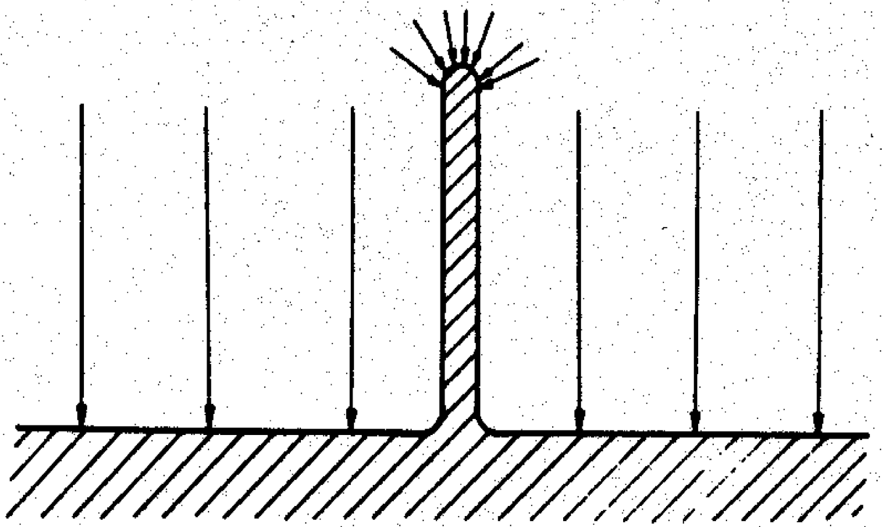
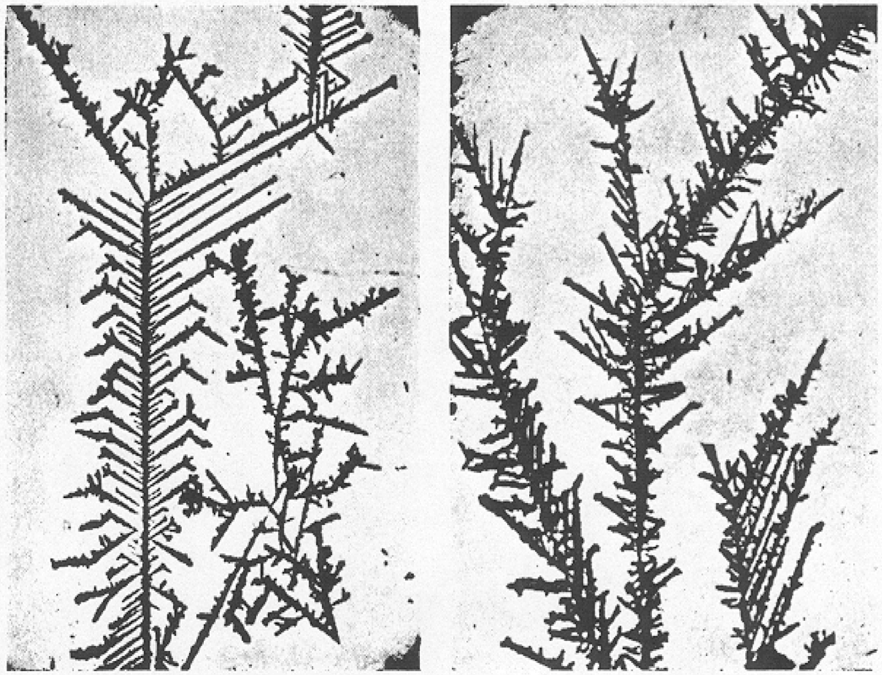


Fig. 10.57. The elementary dendrite theory in which the tip of a macrospiral has a radius of curvature $r \gg \delta$ and hence the growth rate is much greater at the tip than at a flat surface.

Dendritic Growth



(a) (b)

Fig. 10.58. (a) Two-dimensional (left) and three-dimensional (right) silver dendrites (after Wranglen); (b) three-dimensional cadmium dendrites (after Wranglen).

Electroplating

Perturbations lead to field intensification which leads to more rapid growth => interface is inherently unstable

⇒ with no additives, dendritic growth

Additives:

preferential surface adsorption at high field locations, suppresses growth of perturbations (levelers?)

suppress surface diffusion to cause more nucleation and smaller grain size; smaller than size of stable perturbations (brighteners?)

Levelers and brighteners are proprietary, and their actual mechanistic function is usually unknown.

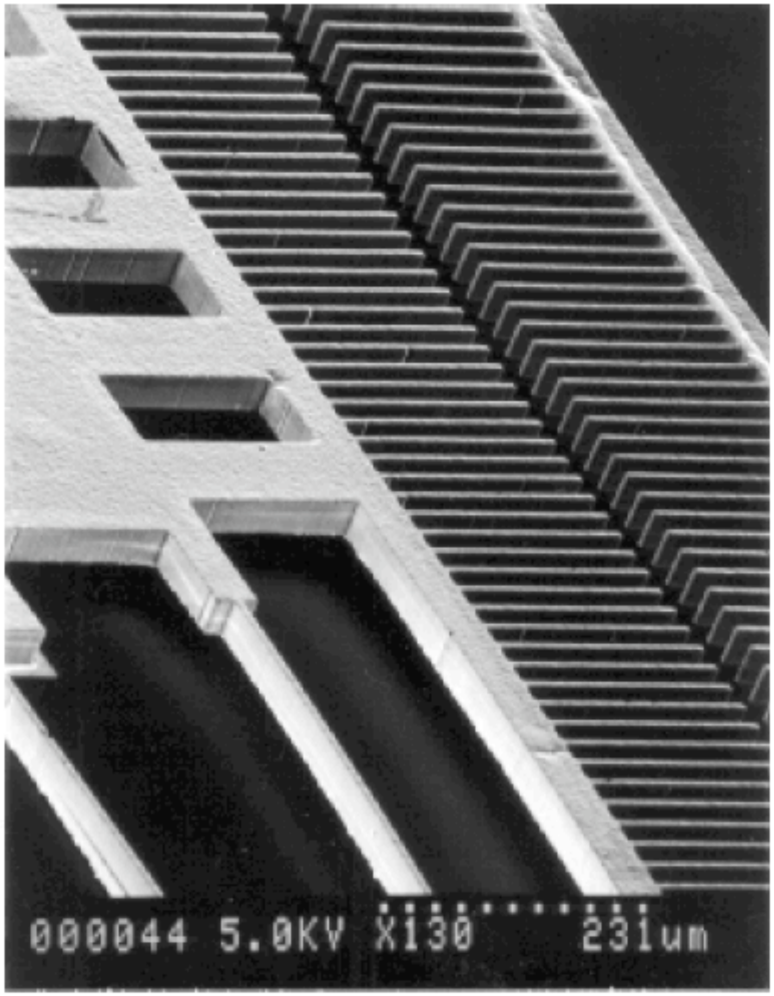
Both slow growth.

Electroplating

Grain Structures of Polycrystalline Thin Films

Cross-Sectional Microgr aph of Electrodeposited Cu Film

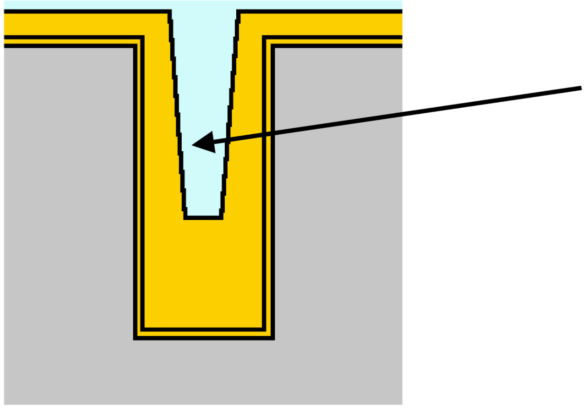
Electroplating



Electroplating for LIGA

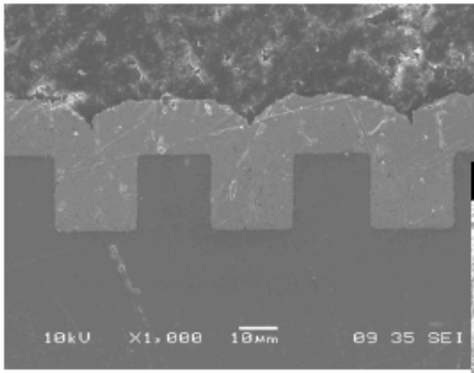
40 μm thick films of nickel fabricated by electroplating into a mold

Keyholing

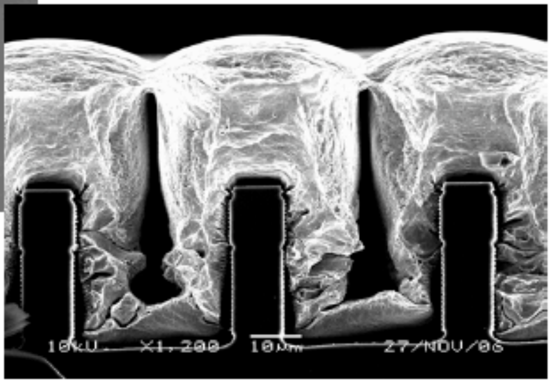


Electroplating solution becomes depleted of additives (diffusion-limited) => growth rate increases => trenches fill faster!

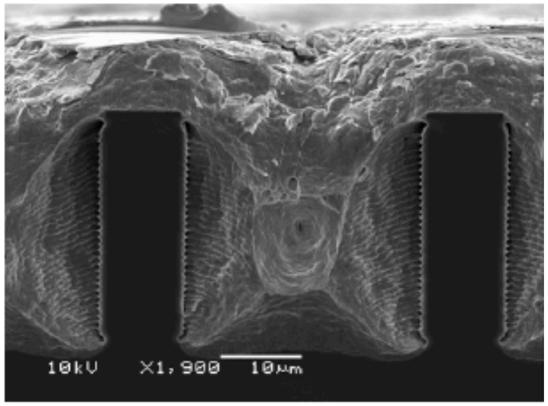
Electroplating realities



Test run w/ bump plating - perfect



Real device forms keyholes – different loading pattern



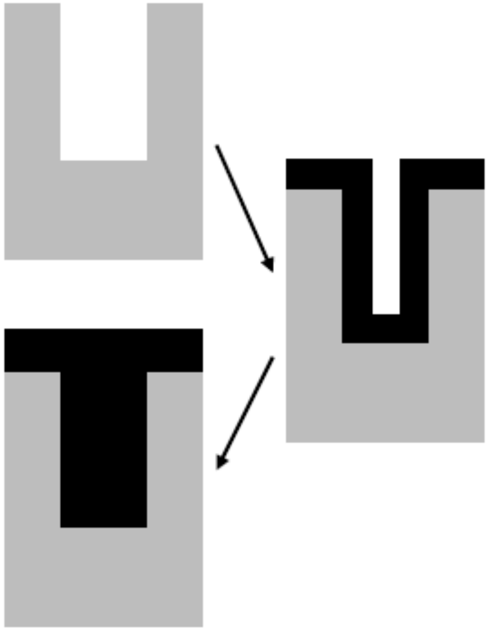
Solution: Cu damascene fill, with additives/agitation to promote fill at bottom

Courtesy of Dariusz Golda. Used with permission.

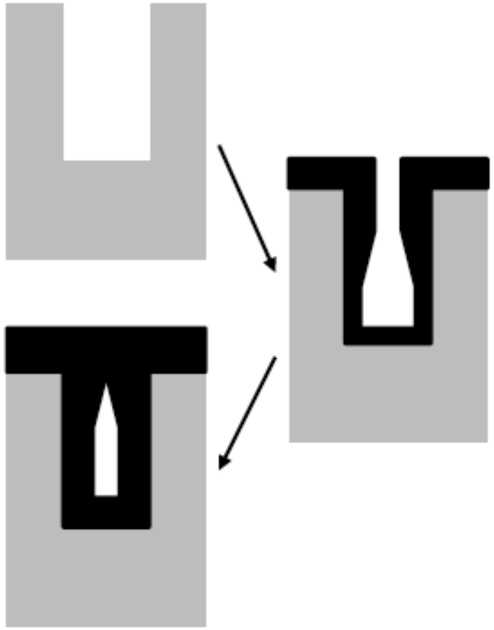
Conformality and keyholes

- 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:



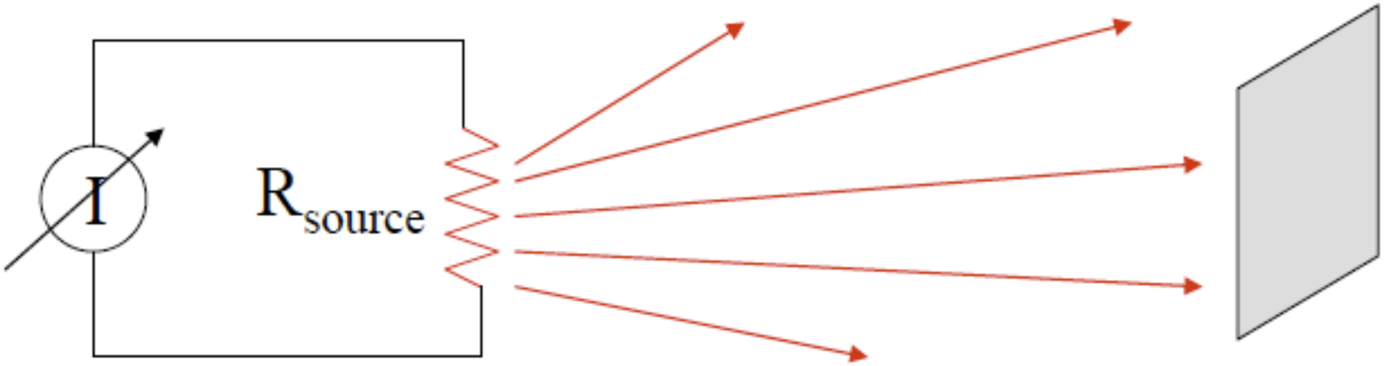
What you get:



Physical Vapor Deposition

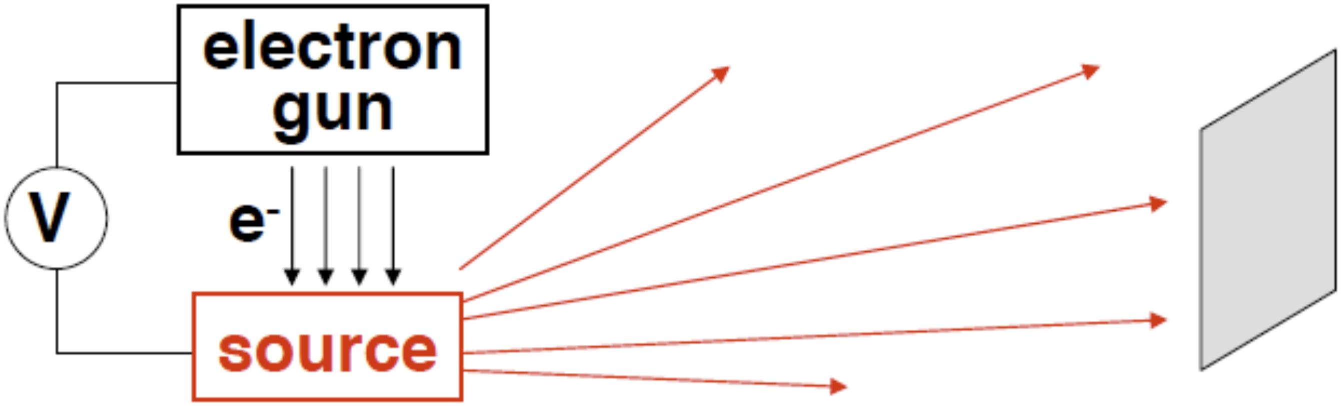
- Remove materials from a solid source
- Transport material to substrate
- Deposit material on substrate
- Differences among PVD techniques
  - How material is removed from source
  - Directionality when it arrives at substrate
  - Cleanliness of deposition
- A family of quick, low temperature processes

Thermal Evaporation



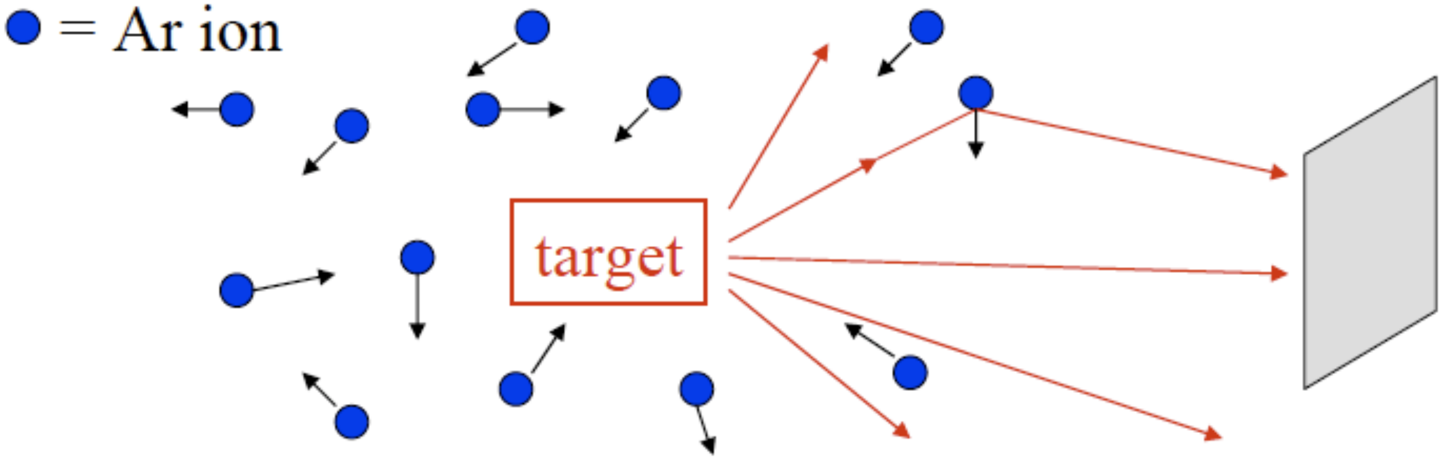
- Source is resistively heated in high vacuum
  - Typical source: metal
- Hot source atoms are emitted in all directions and stick where they land
- Substrate receives a directional flux of source material
  - Good for liftoff processes, otherwise poor conformality
- Possible contamination from generalized heating

E-beam Evaporation



- Electron beam heats source in high vacuum
  - Typical source: metal
- Hot source atoms are emitted in all directions and stick where they land
- Substrate receives a directional flux of source material
  - Good for liftoff processes, otherwise poor conformality
- Heating is less generalized → less contamination

Sputtering



- Unreactive ions (i.e. Ar) knock material off a target by momentum transfer
- Targets: metals, dielectrics, piezoelectrics, etc..
- Different methods of obtaining energetic ions
  - Magnetron, plasma
- Low pressure, but not high vacuum
- Less directional and faster than evaporation

Sputter Deposition

- Use a DC or RF plasma in a parallel plate arrangement
- Put target on the cathode (-) and the substrate on the anode
- Introduce a sputtering gas that will ionize positively (typicaly Ar).
- Ar ionized, is accelerated to the target, and sputters **neutral** target atoms
- Sputtered target atoms travel to the substrate (at low Ar pressure sputtered atoms have fewer collisions with Ar atoms).
- Sputtered atoms arrive at substrate and implant, bounce or diffuse around a bit, or simply stick, depending on their kinetic energies

Advantages of Sputter Deposition

- More conformal than evaporation (ED)
- Better thickness uniformity and compatible with batch processing (vs. ED)
- Easier stoichiometry control than ED or CVD
- Can be done with almost any material (unlike CVD)
- Arriving atoms have higher energies
  - Higher effective surface diffusivity
  - But can create subsurface defects
- Disadvantages
  - Subsurface defects can be generated
  - Sputtering and impurity gases are more likely to be incorporated (must have very pure and/or gettered sputtering gas)
- NOT good for epitaxial films, good for polycrystalline and amorphous films

Process Parameters

- Substrate Bias
  - Grounded, positive, negative or floating (affects energy of depositing atoms)
- DC voltage (affects rate)
- Sputtering gas pressure (affects rate and energy
  - A few hundred mtorr
- Reactive gas pressure, if any
  - E.g. N_2 for reactive sputter deposition of TiN from a Ti target
- Background pressure and sputtering gas purity (Affects film purity)
- Substrate temperature (affects film structure and stress)
  - Hot, cold, or uncontrolled (modestly heated)

Doping

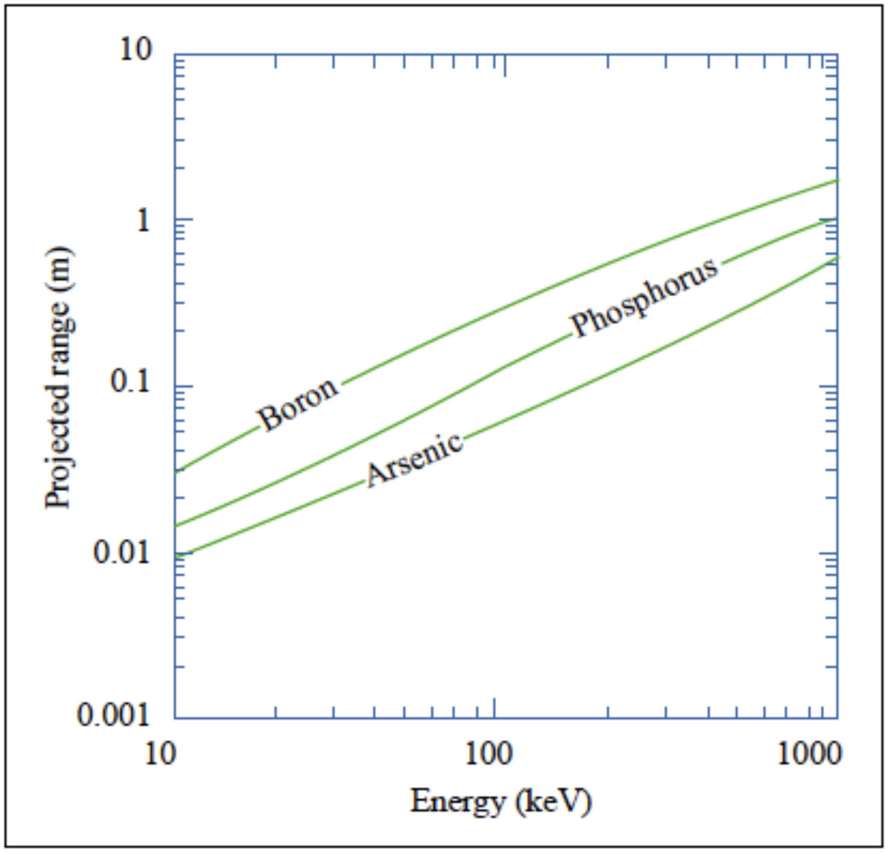
- Doping is the introduction of a controlled amount of impurities to change the conductivity type and degree of a semiconductor
- In silicon, boron is a p-type dopant (creating holes), while phosphorus, arsenic, and antimony are n-type dopants (creating conduction electrons)
- Some doping incorporated in initial silicon melt
- All modern thin film doping is done with ion implantation
- Doping doesn’t add a new thin film, but it modified the properties of a thin film at the surface of an existing material

Ion Implantation

- A high-voltage accelerator is used to shoot ions at the wafer
- The beam must be rastered and the wafer must be rotated to achieve uniform dose
- Usually a thin protective layer, such as oxide, is used to prevent sputtering of the surface and to reduce channeling
- The depth of the implant dose depends on energy
- Activation anneal after implantation allows dopants to reach proper positions in crystal

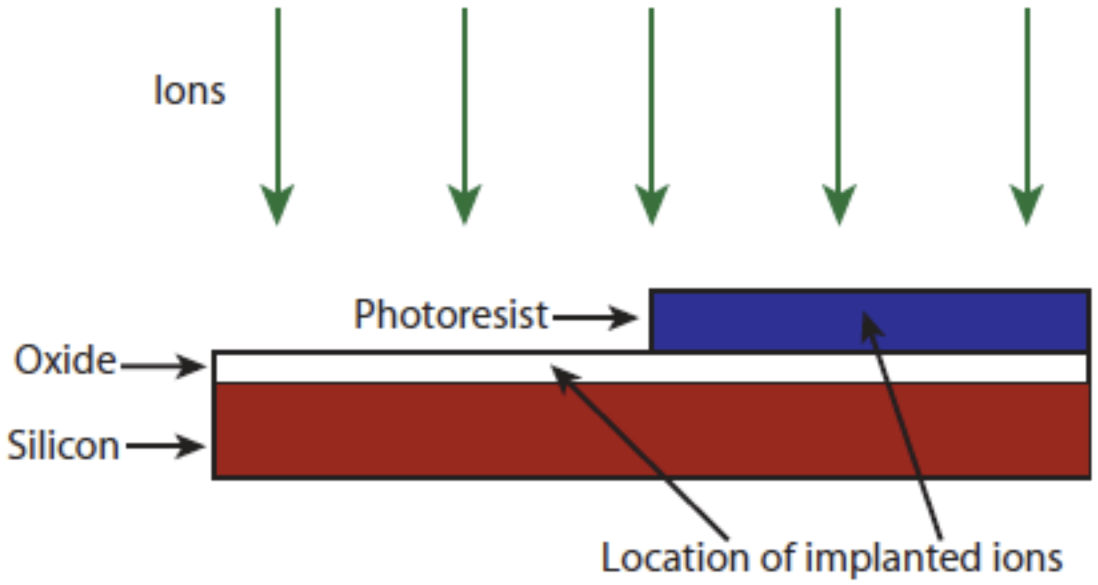
Effective Range

- The effective range measures the location of the peak concentration of an implanted species



Masking of implants

- Control of which regions of a wafer receive the implant is achieved with masking layers

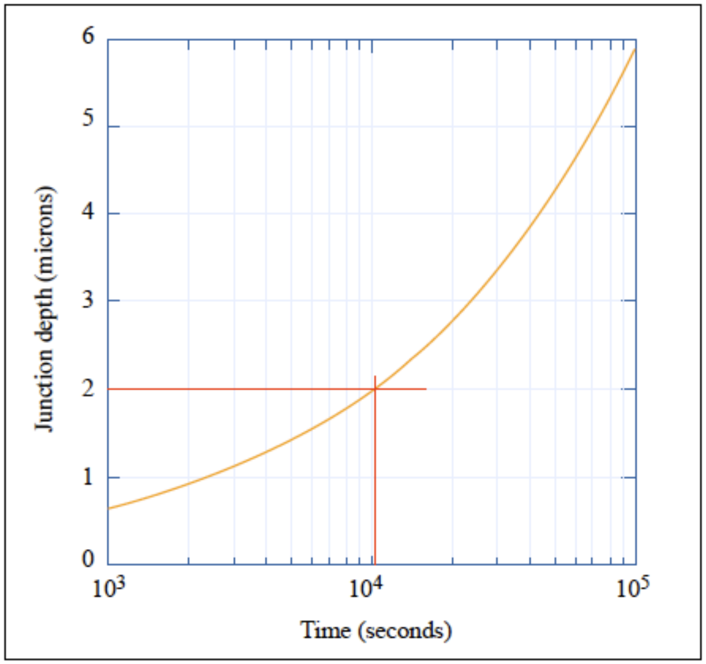


Diffusion

- After implantation, ions are driven deeper into the substrate by diffusion, a high-temperature process
- The junction depth is the point at which the implanted ion concentration is equal (but of opposite type) to the substrate doping

$$x_j = \sqrt{(4Dt)\ln\left(\frac{\overset{\text{Implant dose}}{\overset{\downarrow}{Q}}}{\underset{\substack{\uparrow\\ \text{Background doping}\\ \text{concentration}}}{N_D}\sqrt{\pi Dt}}\right)}$$

Image by MIT OpenCourseWare.



Etching, liftoff, and adhesion layers

- Films are patterned differently depending on whether the material in question tends to react with other materials
- Materials that react (for example, aluminum):
  - ➢ Deposit a blanket film (sputtering good for better conformality), do photolithography, and etch it into desired shape
- Materials that don't react readily (for example, noble metals):
  - ➢ Hard to etch: typically use liftoff instead
  - ➢ Pattern resist, then deposit metal on top with a directional deposition tool
  - ➢ Not very sticky: typically need an aehesion layer to stick the noble metal to what lies beneath
  - ➢ Example: use a few hundred A thick layer of Cr or Ti to adhere Au to an underlying oxide (deposited without breaking vacuum between layers)

Is that all you can do with deposited films?

- No!
- Spin-casting: put the stuff that you want to deposit in a liquid, spin it onto the surface like resist, and bake out the solvent (spin on glass, PZT piezoelectrics)
- Other forms of vapor deposition designed for a particular purpose (depositing the inert polymer parylene by vapor deposition followed by polymerization)
- Lamination of free-standing resist films onto surfaces
- Self assembled monolayers
- …