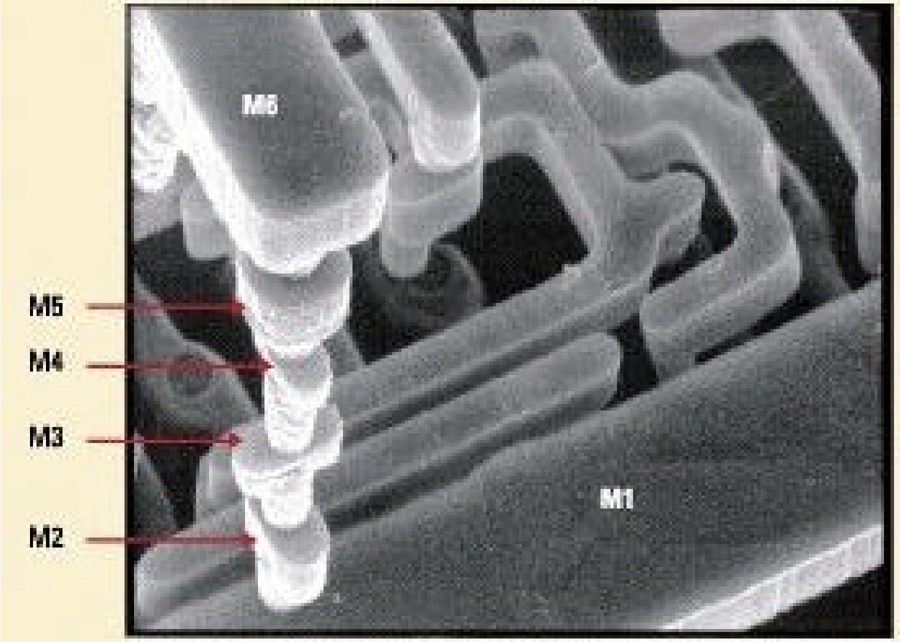
Metallization – deposition and etching

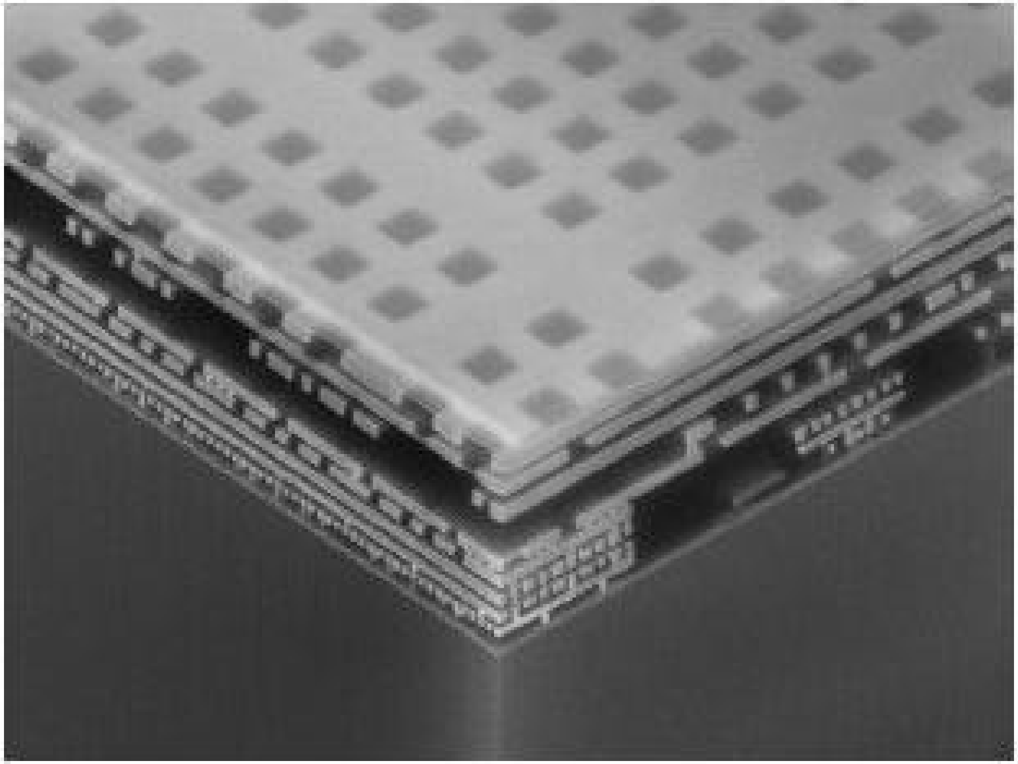
Material mainly taken from Campbell, UCCS

Application

- Metallization is back-end processing
- Metals used are aluminum and copper
- Mainly involves deposition and etching, also planarization
- Similar (but typically less complicated) process flows as in front-end processing



6 metal level copper dual damascene process crossection at 0.18µm node (R. DeJule, “Dual-damascene: overcoming process issues”, Semiconductor International, pp. 94, June 2000)



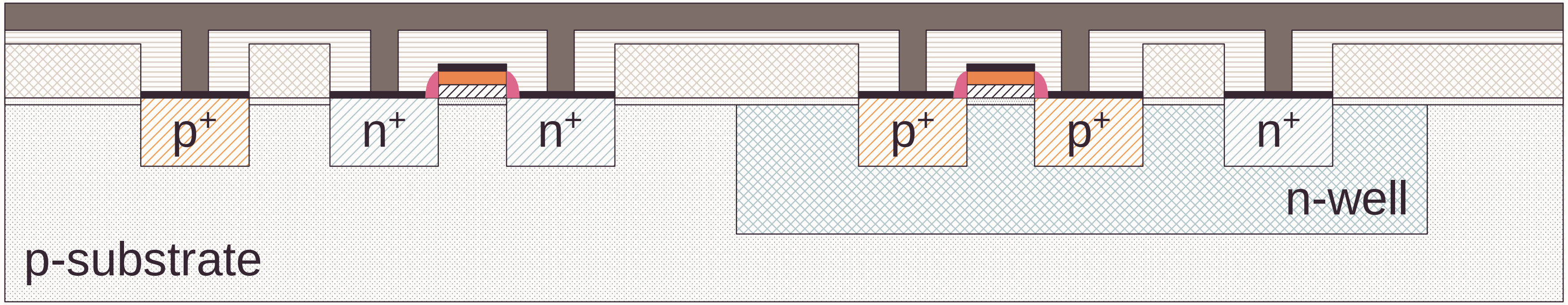
3D SEM of 9 metal level Cu process (H. Ruelke, C. Streck, M. -Van. Ngo, L. You, S. Weiher-Telford, O. Chretien, J. Matusche, D. Dugiarto, J. Sabharwal, “Manufacturing implementation of low-k dielectrics for copper damascene technology”, Advanced Semiconductor Manufacturing Conference, pp. 356–9, 2002.)

CMOS/Process steps

– Process step: Metal interconnect 1 (1)

- Deposit layer of metal over the entire wafer

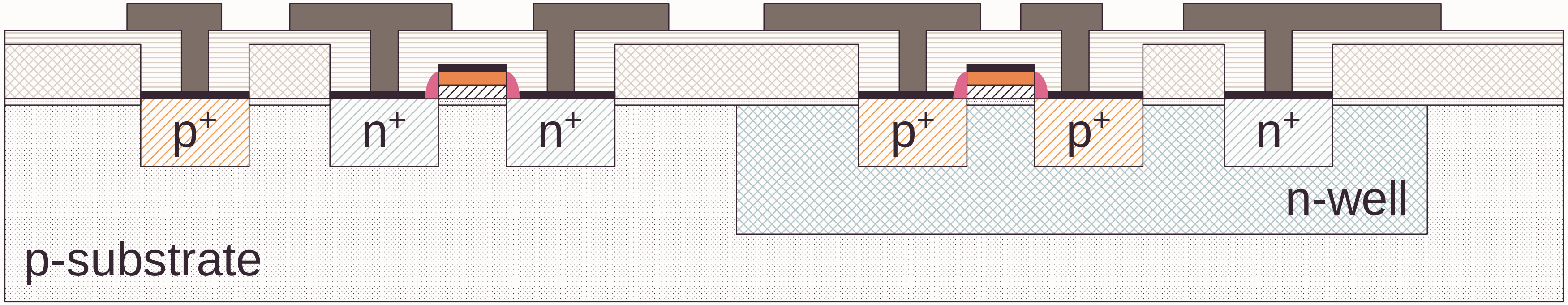
  Common metals: Aluminium or copper



CMOS/Process steps

– Process step: Metal interconnect 1 (2)

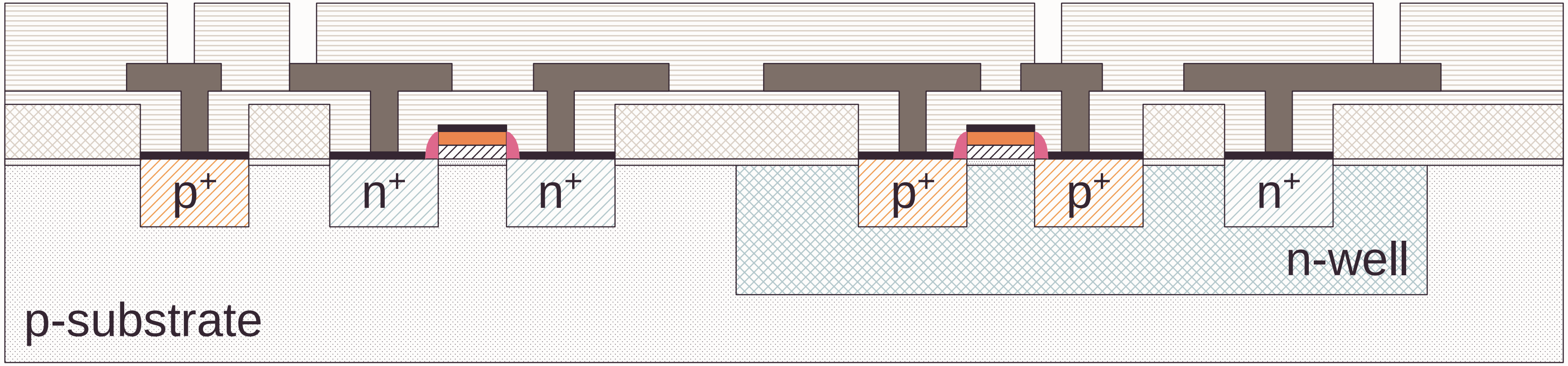
- Photolithography sequence using “Metal 1 mask”
- Metal selectively etched



CMOS/Process steps

– Process step: Via windows

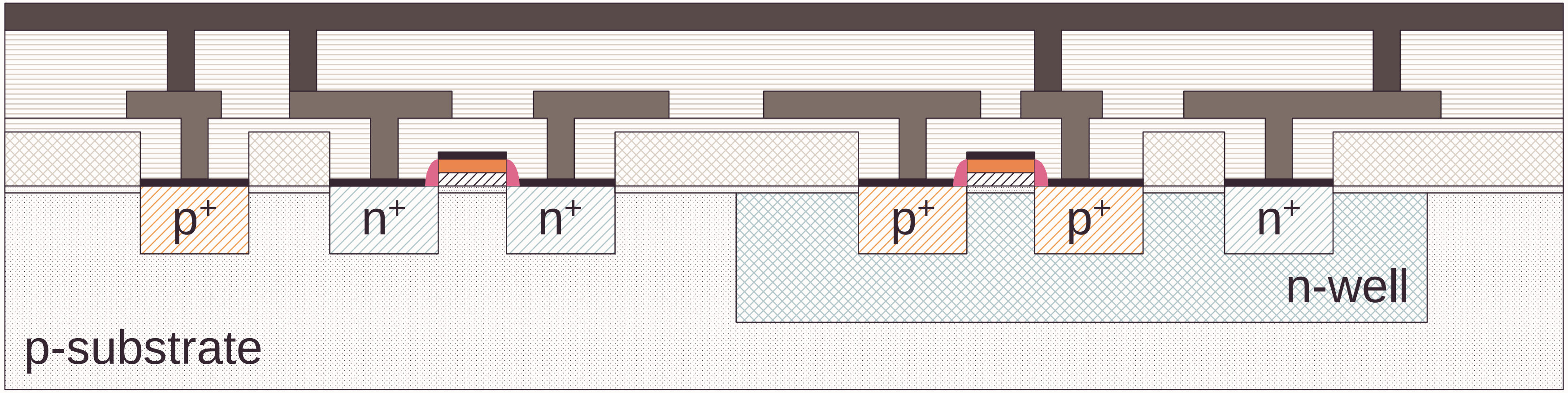
- Cover wafer with a layer of SiN_3
- Lithography using the “via mask”
- Plasma etching



CMOS/Process steps

– Process step: Metal interconnect 2 (1)

- Deposit layer of metal over the entire wafer



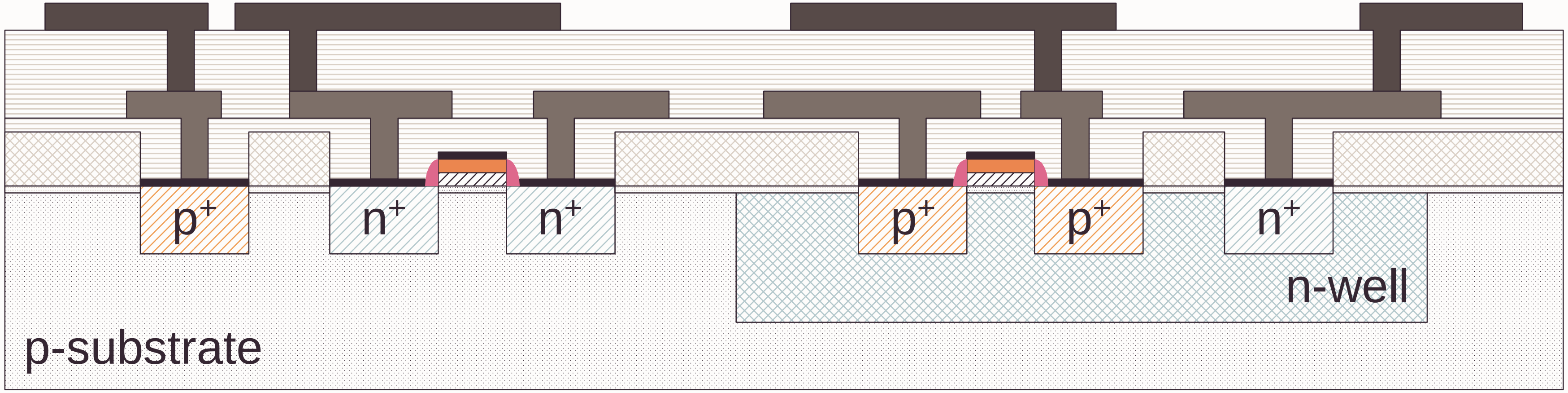
CMOS/Process steps

– Process step: Metal interconnect 2 (2)

- Photolithography sequence using “Metal 2 mask”
- Metal selectively etched

– Metal interconnect layers:

- Two masks required for each additional metal layer: “via *n* mask” and “metal *n* mask”
- Reliability: Dimensions of contacts/vias cannot be changed by layout designer (to avoid “contact spiking”). If a large contact area is required, many small contacts/vias are used in parallel.



Deposition

- Depositions that happen because of a **chemical** reaction:
  - **C**hemical **V**apor **D**eposition (CVD)
  - Electrodeposition
  - Epitaxy
  - Thermal oxidation

- Depositions that happen because of a **physical** reaction:
  - **P**hysical **V**apor **D**eposition (PVD)
    - Evaporation
    - Sputtering
  - Casting

- Chemical deposition techniques exploit the creation of solid materials directly from chemical reactions in gas and/or liquid compositions or with the substrate material. The solid material is usually not the only product formed by the reaction. Byproducts can include gases, liquids and even other solids.

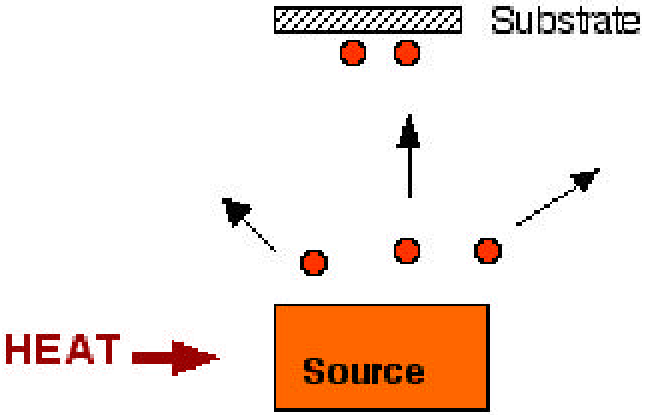
- In physical deposition processes, the material deposited is physically moved on to the substrate. There is no chemical reaction which forms the material on the substrate.

Physical Vapor Deposition

- The two main processes are evaporation and sputtering
- Widely used for metals because it is cheap and less complex than CVD
- Step coverage of films is poor
- Quality of deposited film is inferior compared to CVD (higher resistivity metals and insulators with more defects and traps)

Evaporation

- Metal is melted in vacuum and transported to the sample through vacuum
- Very common in III-V semiconductors, becoming less common
- Deposition rate depends on pressure, temperature and atomic mass of species
- Actual amount of material deposited on wafer will depend on the solid angle subtended by the wafer

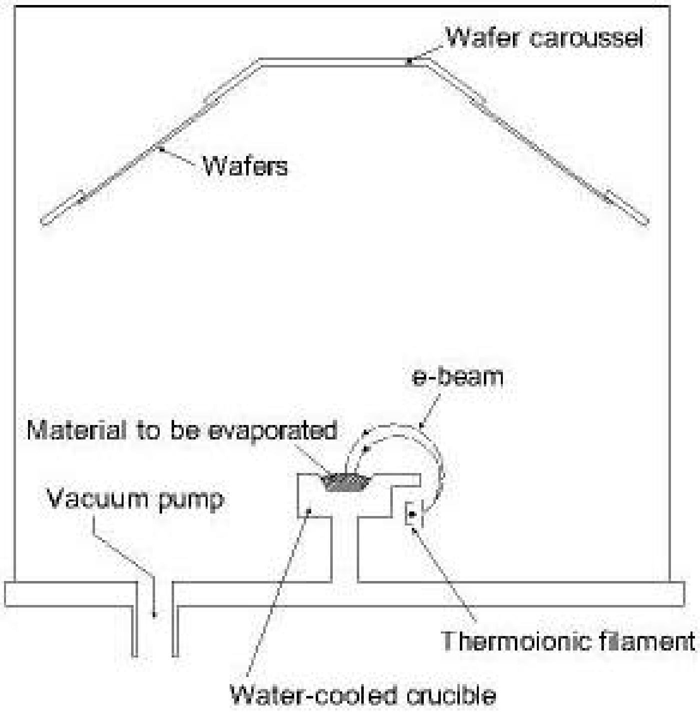


Evaporation

- Wafers placed in hemispherical cage for uniform deposition
- Step coverage is bad in evaporation -vertical etched surfaces in the wafer will not have any metal deposited on them
- To minimize these problems, rotating planetaries, substrate heating and elimination of true steps are used.
- Two types of evaporation – thermal evaporation (heating by resistive elements or inductive heating) and E-beam evaporation

E-beam Evaporation

- In e-beam evaporation, an electron beam is aimed at the source material causing local heating and evaporation.
- Choice of evaporation method typically relates to the phase transition properties of that material (for example, aluminum is quite difficult to evaporate using resistive heating).
- Multicomponent films are usually generated by sequential deposition using separate sources.

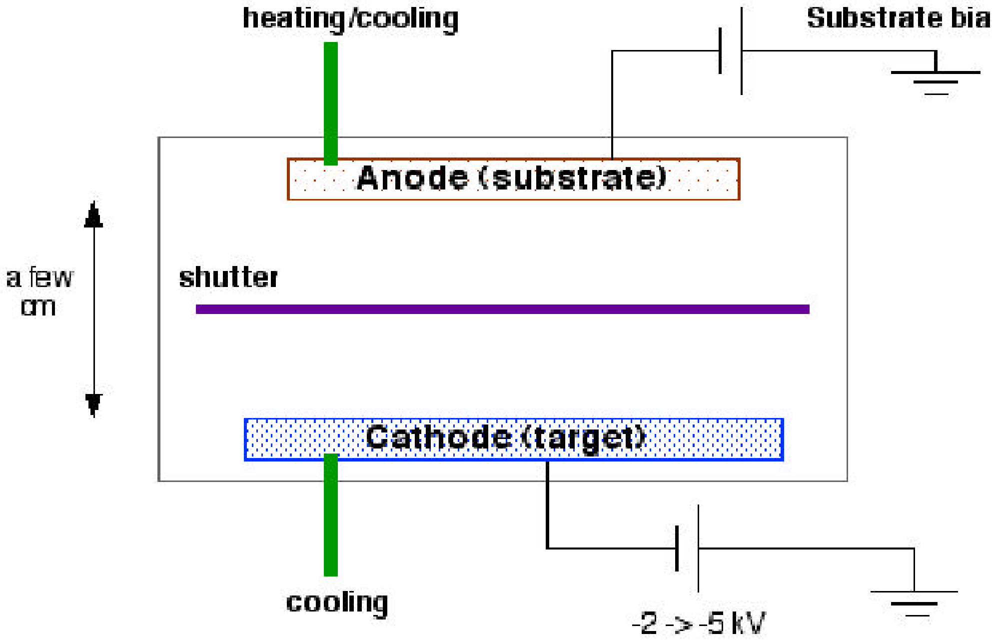


Sputtering

- It is the primary alternative to evaporation
- It provides better step coverage than evaporation
- There is less radiation damage than in e-beam evaporation
- Stoichiometry control is better for multicomponent systems
- Material is released from the source at much lower temperature than evaporation

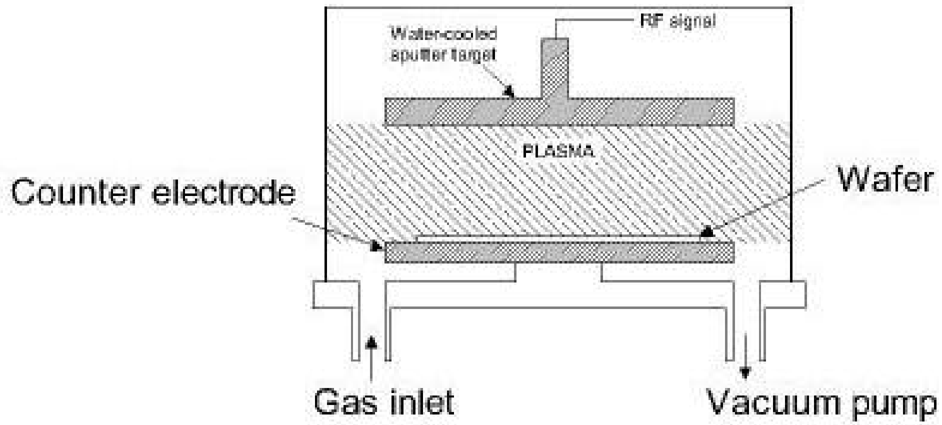
DC Sputtering

- The substrate is placed in a vacuum chamber with the source material (target), and an inert gas (such as argon) is introduced at low pressure.
- A gas plasma is struck using a DC power source, causing the gas to become ionized. The ions are accelerated towards the surface of the target, causing atoms of the source material to break off from the target in vapor form and condense on all surfaces including the substrate.



RF Sputtering

- Similar to DC sputtering, different method of creating ions
- Sputter deposition occurs when target electrode is negative
- In DC systems, positive charge builds up on cathode (target), and very high voltages are required to deposit insulators
- RF sputtering avoids charge build-up by alternating potential
- Substrate and chamber make for a very large electrode, so not too much sputtering of substrate occurs



Sputtering

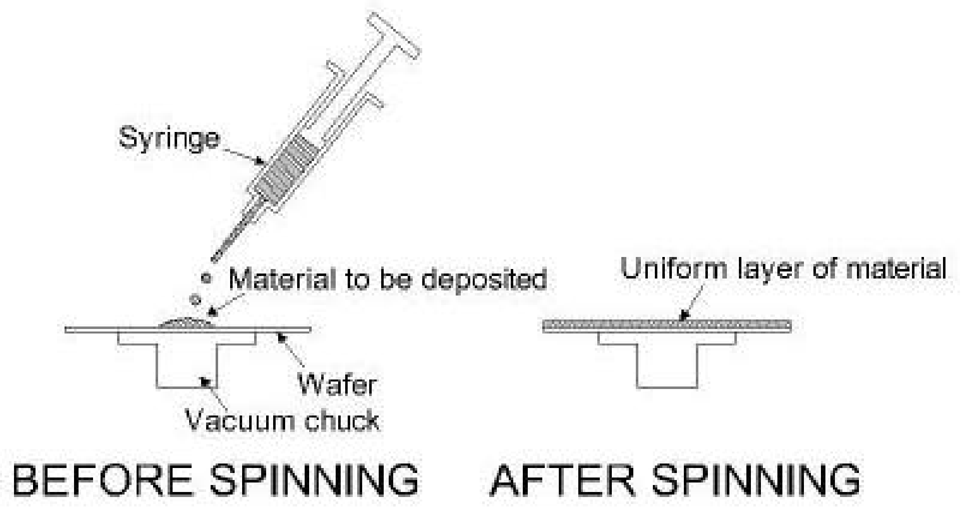
- Wafer and target are kept close together to maximize collection of sputtered material
- Pressure is of the order of 0.1 Torr (mean free path of the order of 1 mm). This increases step coverage.
- Energy spread of depositing material is of the order of 10-50 eV
- Compromise between increasing the number of Ar ions, and increasing scattering of Ar ions with neutral Ar atoms. If you can increase the number of ions without increasing the number of neutrals, you can operate at lower pressures
- Particle energy and deposition rate depend strongly on sputter voltage, substrate bias and pressure

Sputtering

- At frequencies less than 50 kHz, electrons and ions in plasma are mobile, and both follow the switching of the anode and cathode. This is equivalent to DC sputtering of both surfaces.
- At frequencies above 50 kHz, ions (heavy) can no longer follow the switching electrons, this neutralizes positive charge build up
- Other variants of sputtering:
  - Magnetron sputtering (magnetic and electric field, put magnets behind target, higher deposition rate because electrons strike Ar atoms more frequently)
  - Ion deposited sputtering (bombard surface with different ions, requires low voltage, change in film properties because of local rearrangement of atoms)
  - Reactive sputtering (add reactive gas such as oxygen or nitrogen to chamber during deposition, good stoichiometry control, can poison target if chemical reaction rate is faster than sputter rate)
- Sputtering compared to evaporation – smaller grain size, many grain orientations, better adhesion of film

Casting

- Material is dissolved in liquid form in solvent, and applied to substrate by spraying or spinning.
- Used for polymers (photoresist) using the spin-coating method, also used for spin-on glasses.
- Thickness of film ranges from single monolayer (for adhesion promotion) to tens of microns.

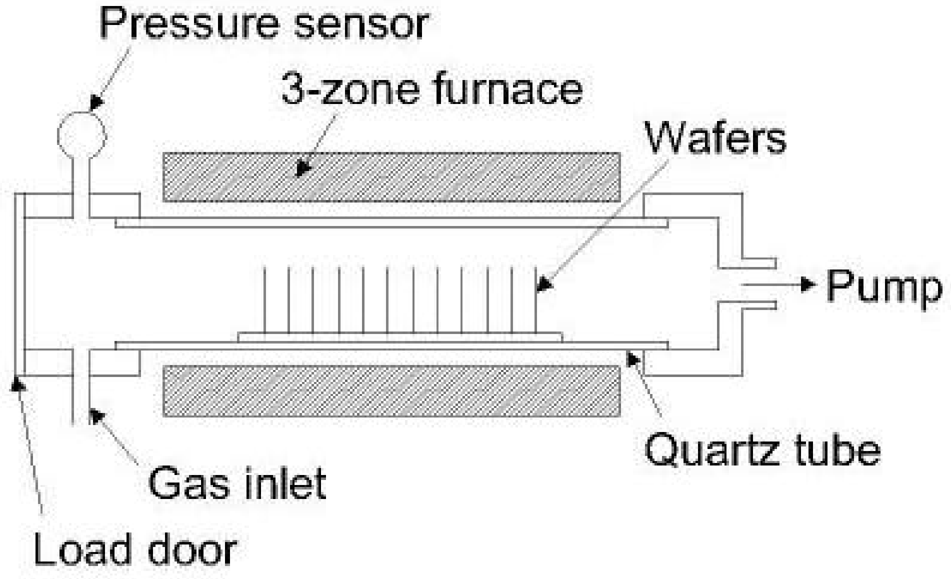


Chemical Vapor Deposition

- Substrate placed in chamber and number of gases supplied
- Reaction takes place between the source gases, product is a solid that condenses on all surfaces in the reaction chamber
- Used for many different materials (SiO2, Si3N4, polysilicon, tungsten, copper, etc.)
- Can have atmospheric pressure CVD or low pressure CVD (much more common), another variant is plasma enhanced CVD.

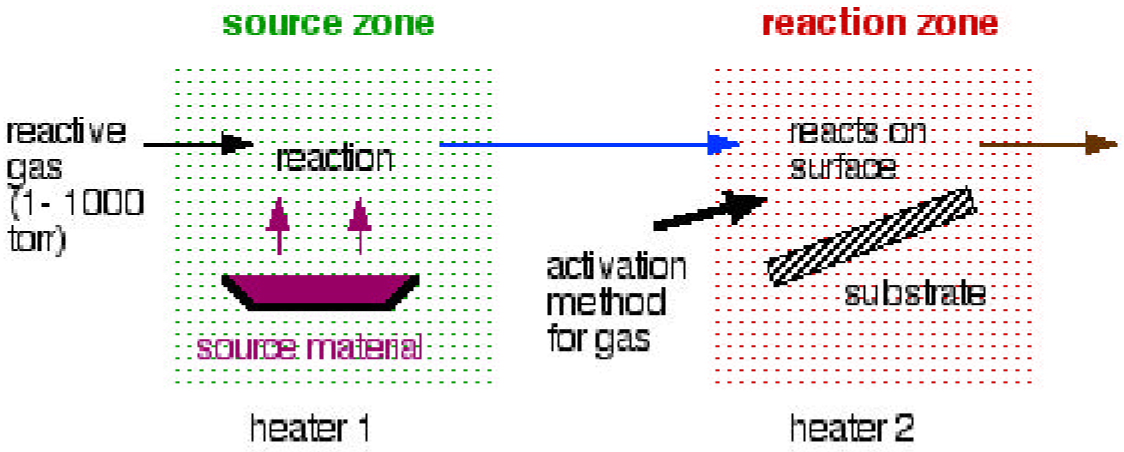
LPCVD

- Excellent uniformity of thickness and material characteristics
- High deposition temperatures (>600C) and relatively slow deposition rate
- Byproducts (gaseous) formed during processing
- LPCVD can be used to deposit films on both sides of at least 25 wafers at a time.



PECVD

- Lower temperature process (200-400C)
- Extra energy is supplied to the gas molecules by the plasma in the reactor
- Quality of films is typically inferior to LPCVD films
- PECVD systems can only deposit films on one side of up to 4 wafers at a time.

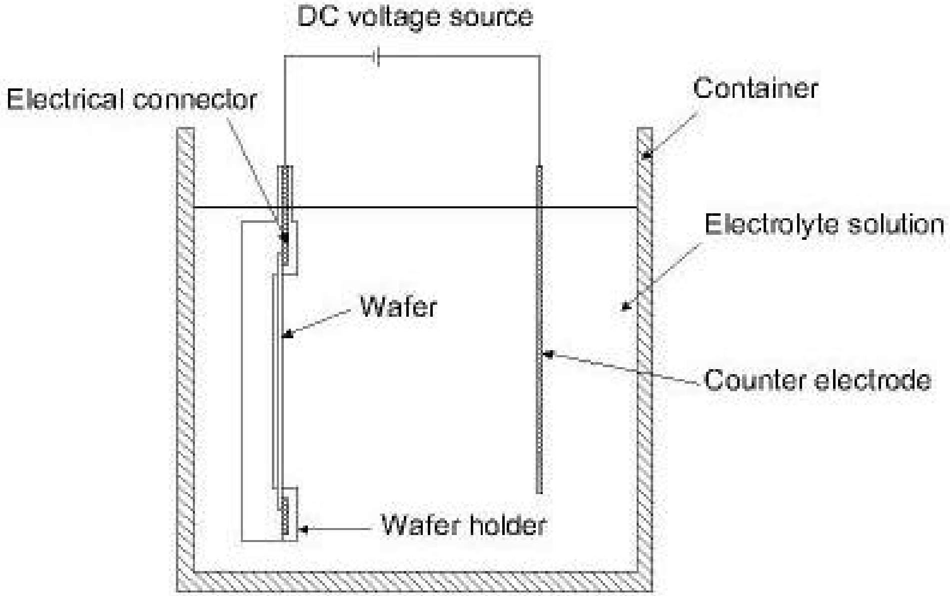


Electrochemical Deposition

- Used for metals such as copper, gold and nickel
- Film thickness can be varied easily (<1micron, >100 microns)
- Control of deposition achieved by using external electric potential, it requires electrical contact to the substrate while immersed in a liquid bath
- The surface of the substrate must have an electrically conducting coating (seed layer) before deposition can be done using this method

Electrochemical Deposition

- Two methods – electroplating and electroless plating
- In the electroplating process the substrate is placed in a liquid solution (electrolyte).
- When an electrical potential is applied between a conducting area on the substrate and a counter electrode (usually platinum) in the liquid, a chemical redox process takes place resulting
- in the formation of a layer of material on the substrate and usually some gas generation at the counter electrode.



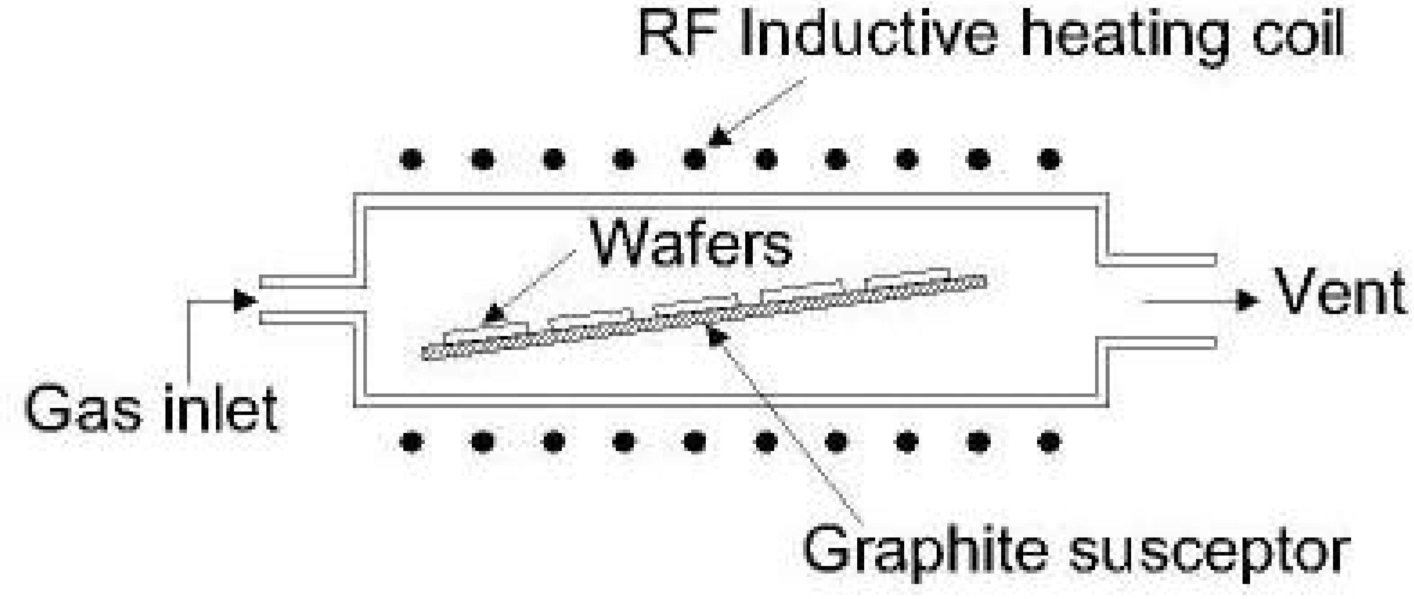
Electrochemical Deposition

- In the electroless plating process a more complex chemical solution is used
- Deposition happens spontaneously on any surface which forms a sufficiently high electrochemical potential with the solution.
- It does not require any external electrical potential and contact to the substrate during processing.
- It is more difficult to control with regards to film thickness and uniformity.

Epitaxy

- Similar to basic CVD process
- Epitaxy is the growth of a film with a crystallographic relationship between film and substrate (same material – homoepitaxy, different materials – heteroepitaxy)
- If the substrate is a single crystal oriented in a specific direction, the film will orient the same way. A similar principle holds for amorphous and polycrystalline films.
- In vapor phase epitaxy, a number of gases are introduced into an induction heated reactor in which only the substrate is heated (to >50% of melting point of material being deposited)
- Epitaxy generally results in relatively high growth rates

Epitaxy


RF Inductive heating coil
Wafers
Vent
Gas inlet
Graphite susceptor

Molecular Beam Epitaxy

- Needs independently controlled thermal and/or electron beam sources for all materials and dopants.
- Evaporation at very low deposition rates
- Typically in ultra-high vacuum
- Very well controlled
- Grow films with good crystal structure
- Expensive
- Often use multiple sources to grow alloy films
- Deposition rate is so low that substrate temperature does not need to be as high