NANYANG TECHNOLOGICAL UNIVERSITY

Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Deposition - Physical Vapour Deposition

Learning Objectives

At the end of this lesson on deposition, you should be able to:

- Describe the properties of a high-quality thin film.
- Explain the fundamental concepts in Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD).
- Explain the advantages and possible limitations of PVD and CVD techniques, and ways to improve them.

Standard Process Iteration

There are three main categories in semiconductor fabrication process:

Lithography

Patterning of substrate
(Silicon wafer)

Etching

Removal of materials
from the substrate

Deposition

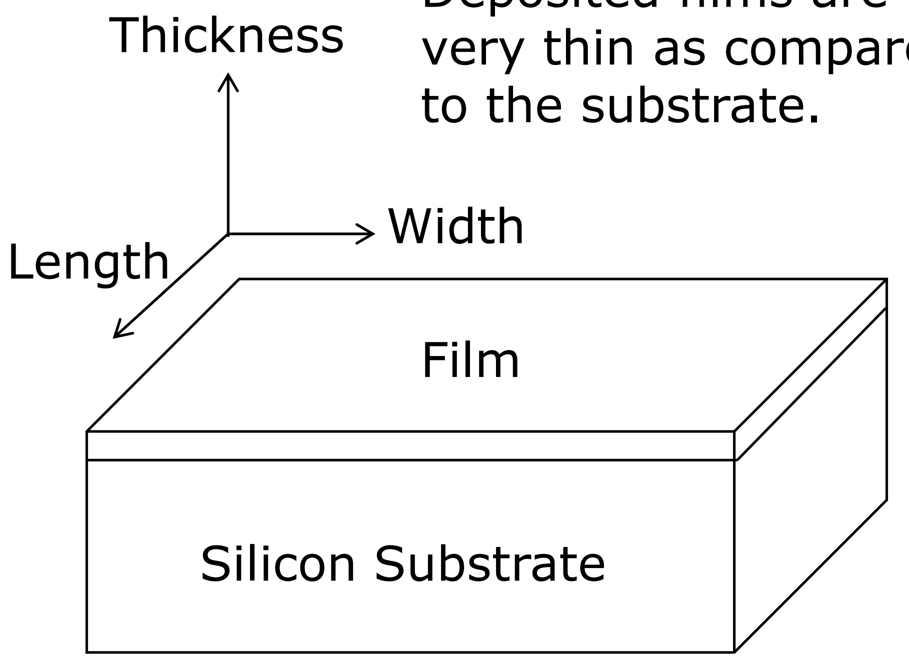
Deposit materials
(metal/ non-metal)
on the substrate

Thin Film Deposition

Thin film: Thickness typically < 1000 nm

Special properties of thin films: Different from bulk materials

- Not fully dense
- Under stress
- Different defect structures from bulk materials
- Strongly influenced by surface and interface effects

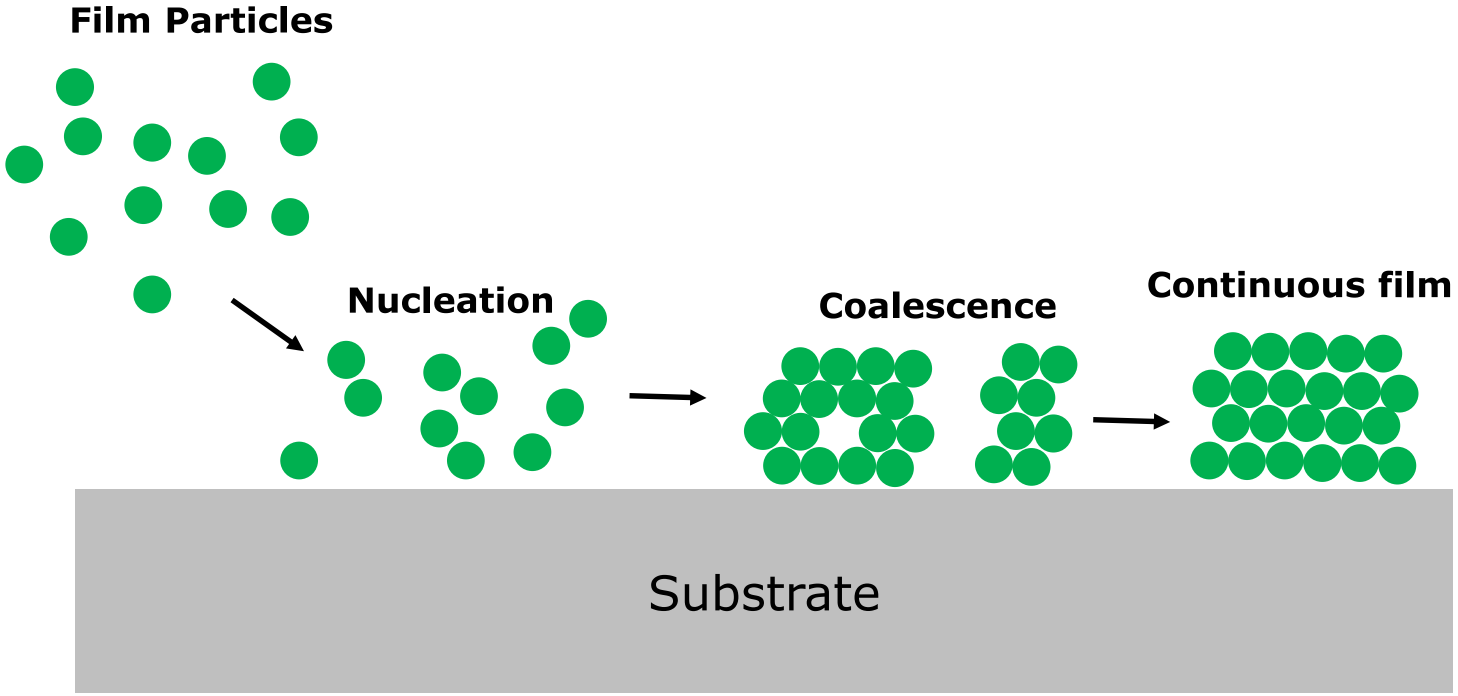


Deposited films are very thin as compared to the substrate.

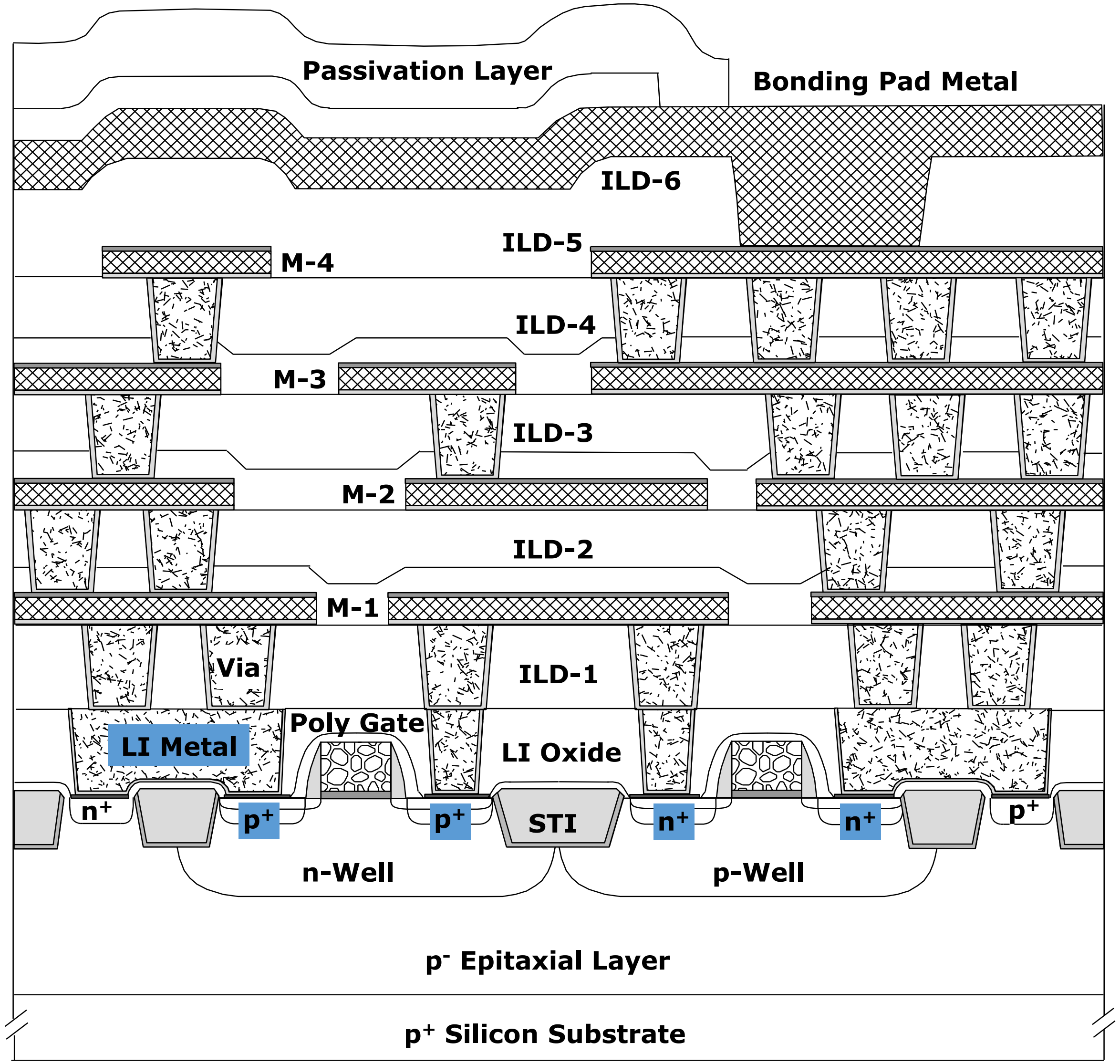
Mechanism in Thin Film Deposition

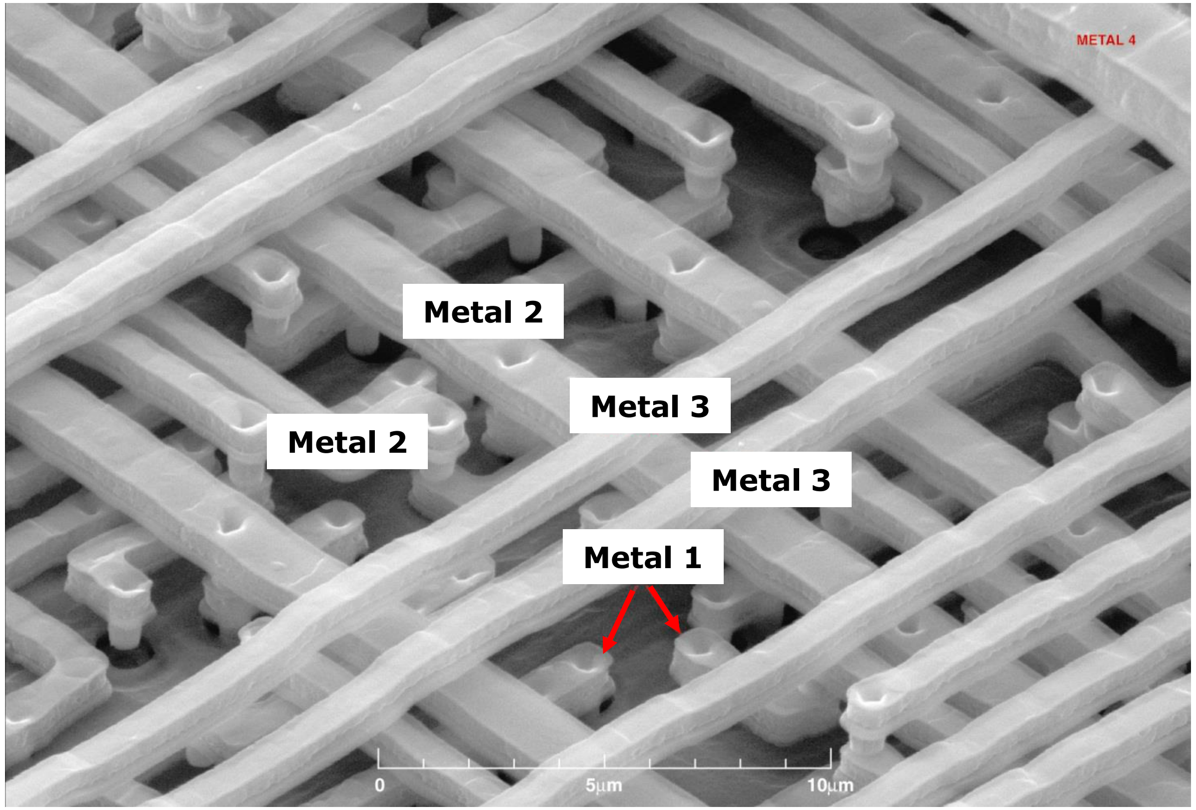
Here are the **typical steps** to deposit thin films:

1. Emission of particles from source (heating, high voltage, etc.)
2. Transport of particles to substrate
3. Condensation of particles on substrate



Multilevel Metallisation on a Wafer





Deposition of the high-quality thin film is needed for multilevel metallisation.

Thin Film Deposition Methods

Two main deposition methods used today:

- **Physical Vapour Deposition (PVD)** (no chemical reaction involved)
  The vapour of thin film materials is created inside the chamber, and condensation occurs on wafer surface leading to the deposition of a solid thin film.
  E.g. Evaporation and sputter deposition are most commonly used for metals.

- **Chemical Vapour Deposition (CVD)** (involves chemical reaction)
  Reactant gases are introduced into the chamber, and chemical reactions occur on wafer surface leading to the deposition of a solid thin film.
  E.g. APCVD, LPCVD, and PECVD, which are most commonly used for dielectrics and Si.

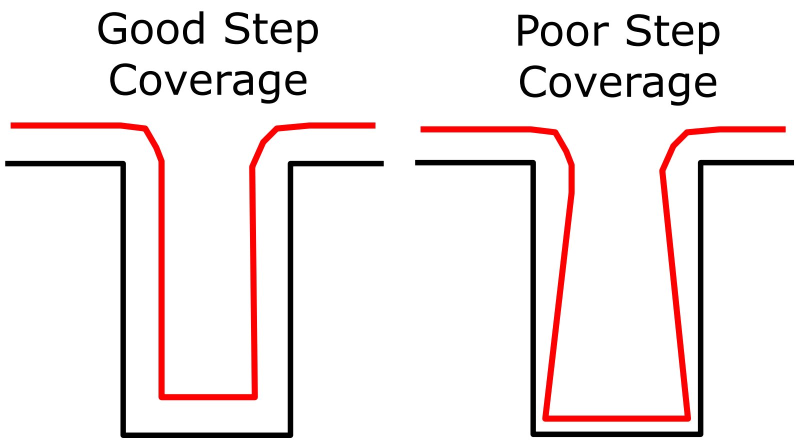
General Characteristics of Thin Film Deposition

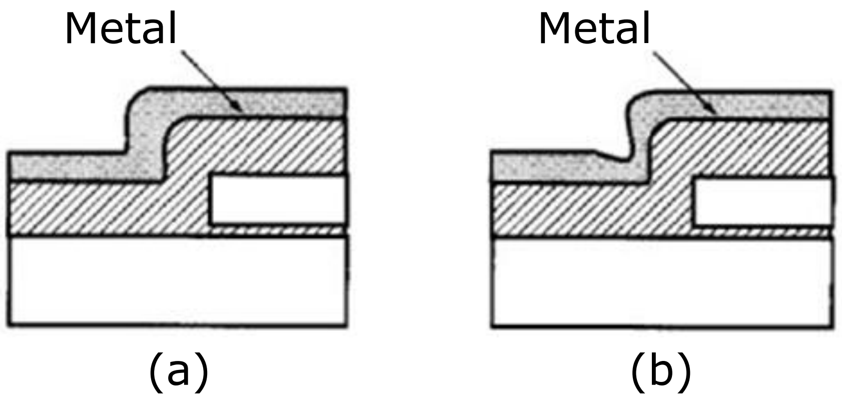
Quality of Film:

- Physical and chemical properties
- Electrical property: Breakdown voltage
- Mechanical properties: Film stress and substrate adhesion
- Optical properties: Transparency and refractive index
- Composition
- Film density and defect (pinhole) density
- Texture
- Impurity level and doping
- Conformality (step coverage)
- Trench/ hole filling

Will be further discussed in this lesson

Step Coverage

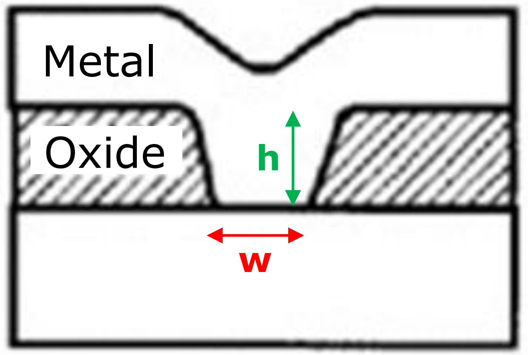




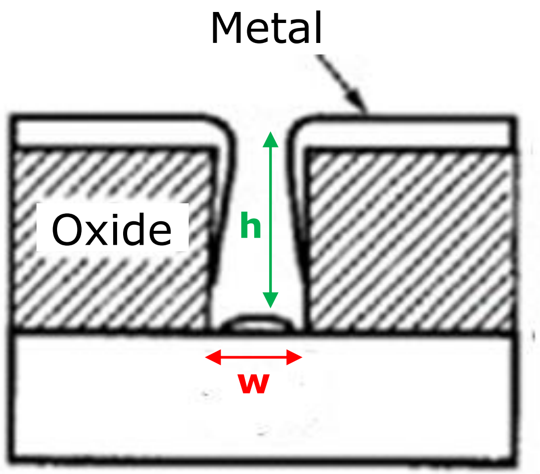
The step coverage of a deposition is its conformality in filling a hole/ trench. Good step coverage film is needed for electrical connection.

For example, in depositing metal in non-planar topography:

- Figure (a): Conformal step coverage, with a constant thickness on horizontal and vertical surfaces
- Figure (b): Non-conformal step coverage, thinner for vertical surfaces



Low Aspect Ratio Trench



High Aspect Ratio Trench

Aspect ratio (AR):

AR = height/width

AR = h/w

It is generally more difficult to fill higher aspect ratio trenches, as the filling may have poor step coverage due to poor conformality.

Hence, it is important to understand the thin film deposition techniques to produce high-quality thin films.

Thin Film Deposition Methods: Physical Vapour Deposition (Evaporation)

Physical Vapour Deposition (PVD): Evaporation and Sputtering

In PVD, chemical reactions are not involved. There are **two types of PVD**:

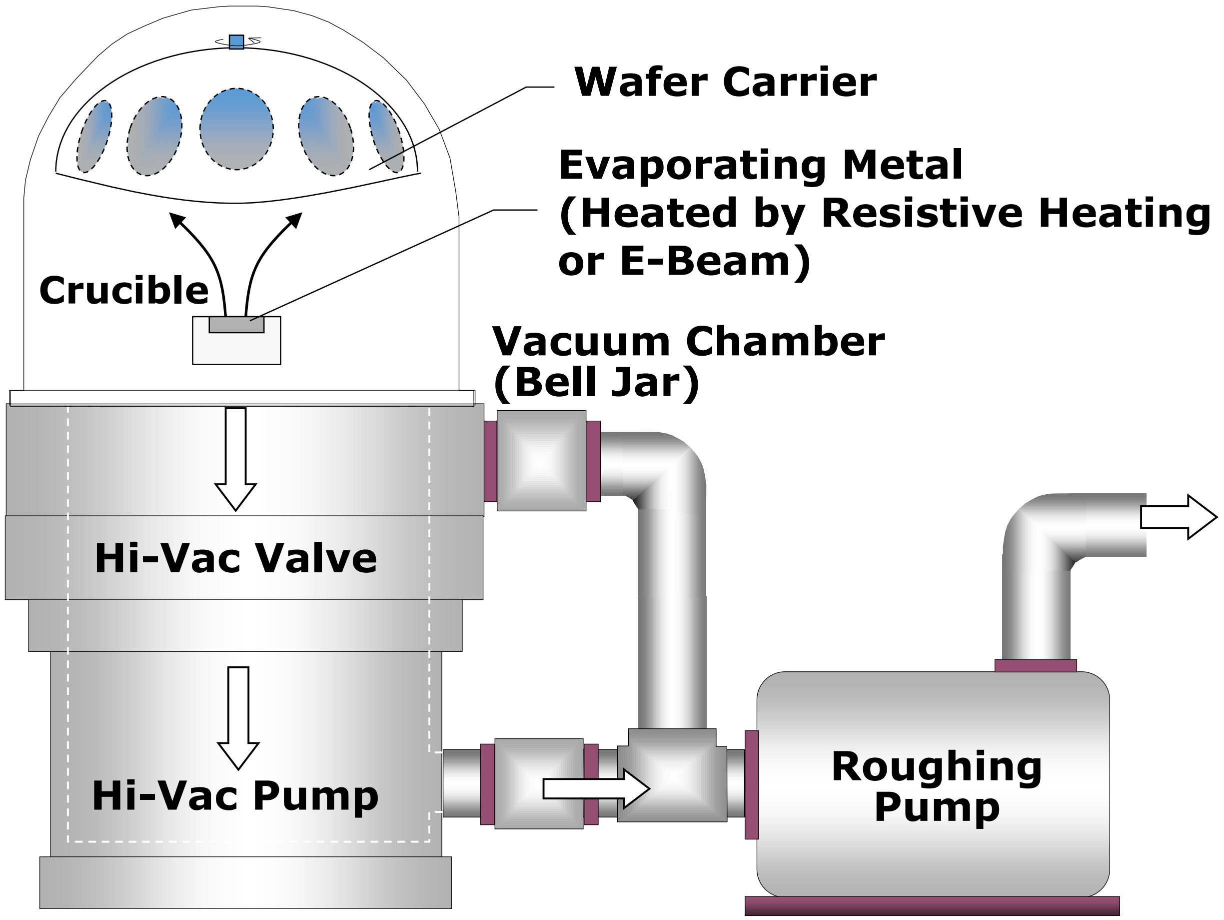
Evaporation:

- Material source is heated to high temperature in a vacuum either by thermal or e-beam methods.
- Material is vapour transported to target in a vacuum.
- Film quality (density) is often not as good as sputtered film.
- The film thickness can be monitored precisely using a quartz balance.

Sputter deposition: *(There is also sputter etching as discussed earlier)*

- Material is removed from the target by momentum transfer.
- Gas particles (often Argon) are ionised by plasma, ions strike the target and remove (sputter away) the atoms in the target.
- Sputtered atoms are condensed on the substrate.
- It involves energetic bombardment of ions.
- The as-deposited film is denser due to higher energy of the sputtered atoms.

Evaporation (Also Called Vacuum Deposition)



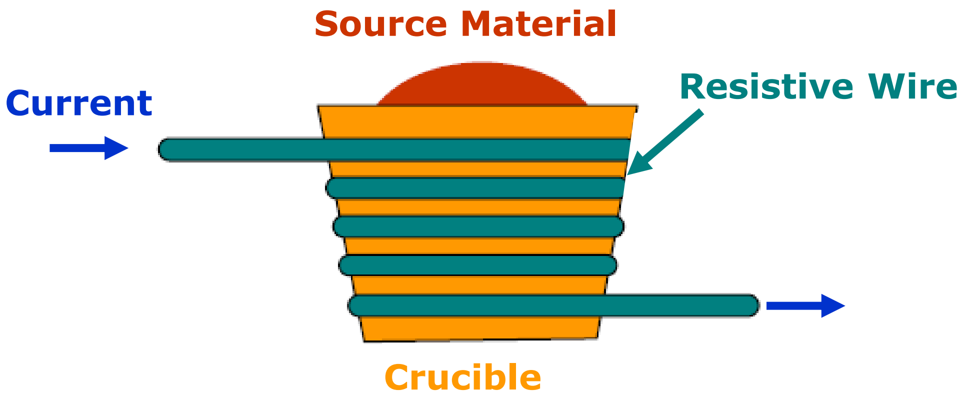
- In evaporation, the source material is heated in a high vacuum chamber (P < 10^{-5} Torr), hence, the name vacuum deposition.
- High vacuum is required to minimise collisions of source atoms with air molecules.
- Heating is done by resistive or e-beam sources.
- Surface interactions are physical and can be very fast (> 1 μm/min is possible, but film quality may suffer. For R&D, it is typically 0.1 ~ 1nm/sec).
- It has poor conformal coverage.

Types of Evaporation According to Heating Method

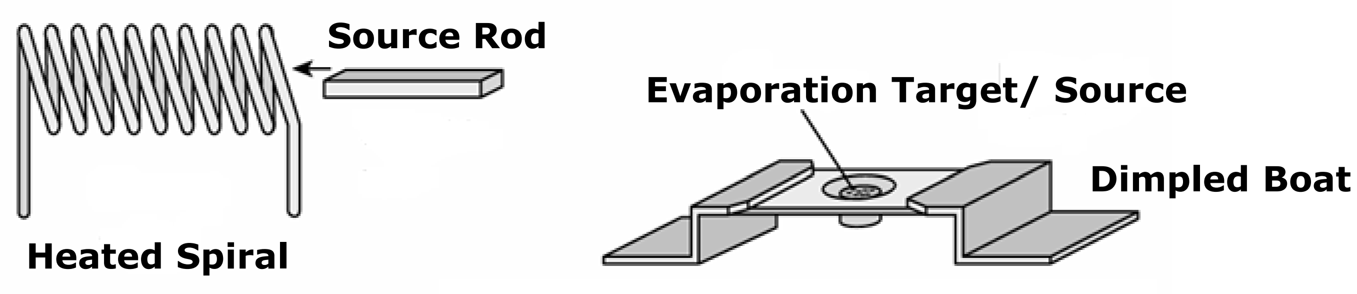
Two types of evaporation:

1. **Thermal evaporator:**
    - Resistive heating
    - A relatively old deposition technique
2. **Electron beam evaporator:**
    - Heated by electron beam
    - Most popular technique
    - More expensive than the thermal evaporator

Thermal Evaporation



- Widespread use for materials whose vapour pressure can be reasonable at 1,600^{o}C or below
- Common evaporant materials:
  Au, Ag, Al, Sn, Cr, Sb, Ge, In, Mg, and Ga

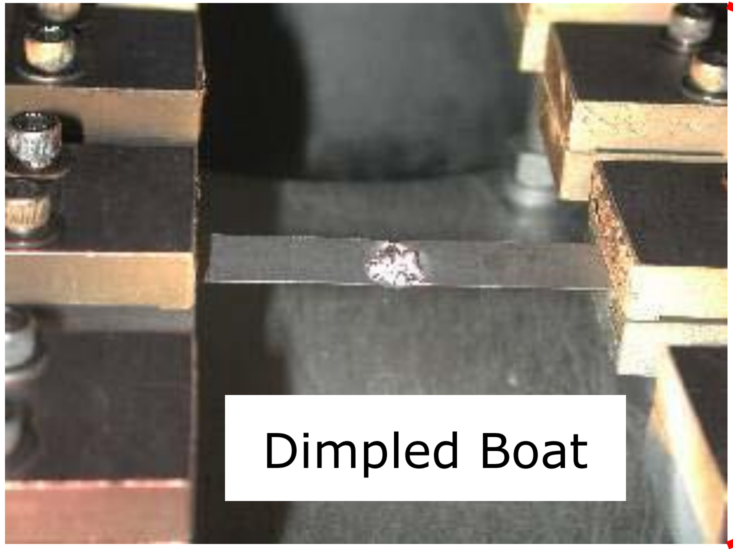


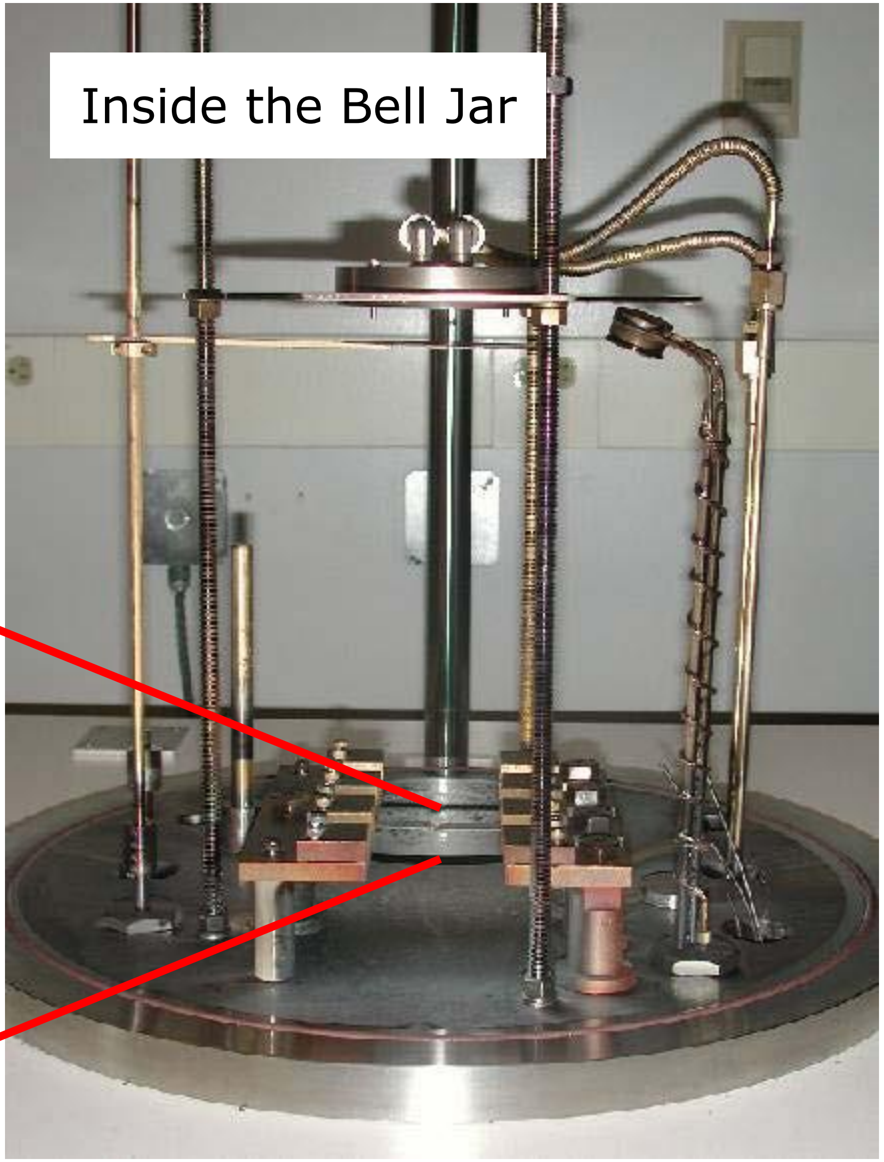
(A) (B)

A. Heating the source rod using heated spiral
B. Heating the source material using a dimpled boat

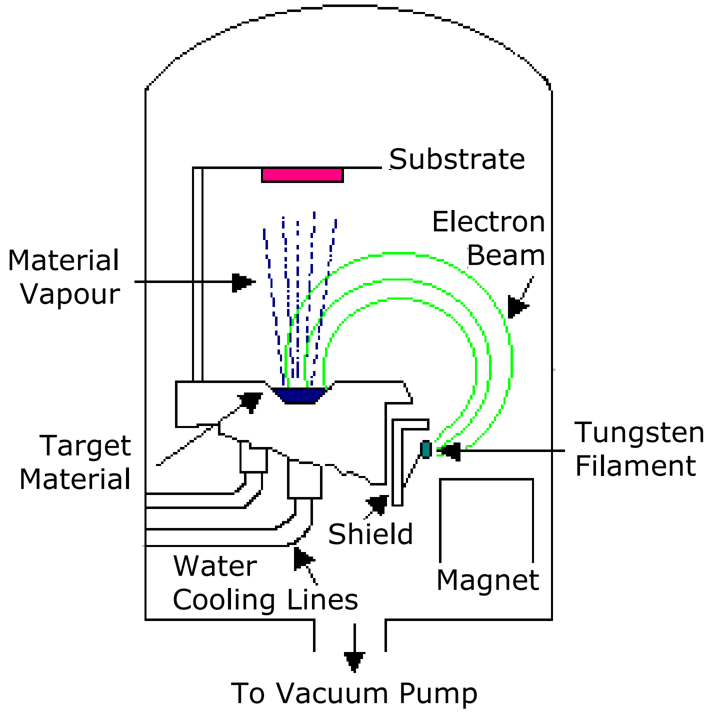
Photos of Thermal Evaporator

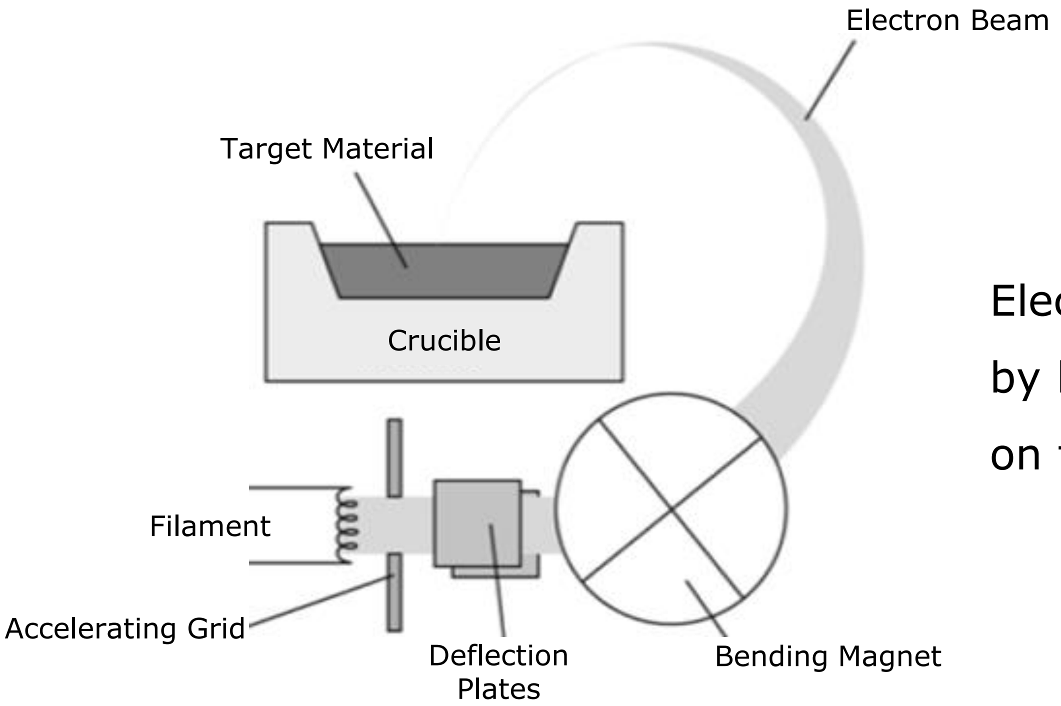
Bell Jar





Electron Beam Evaporation

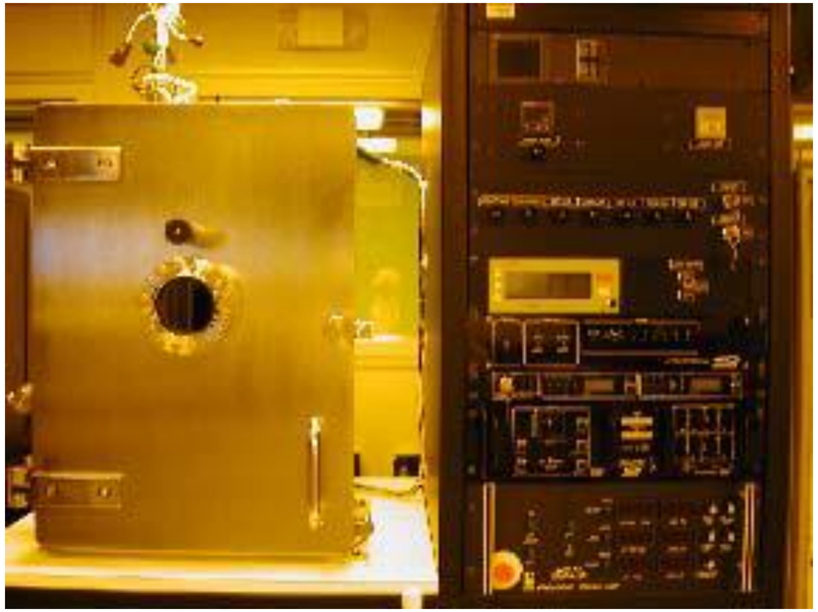




Electron beam deflected by bending magnet to hit on the target material

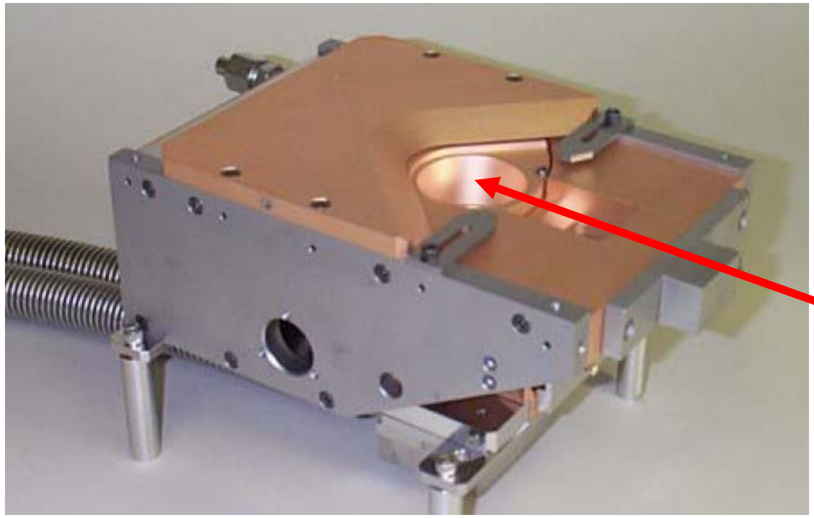
- A focused electron beam is used to heat and evaporate metals. Electrons are accelerated by DC 10kV, with a current of 10s-100s of mA, the target material temperature can be very high.
- It is suitable for high melting point metals like W, Ta, etc.
- Evaporation occurs at a highly localised point near the beam bombardment spot on the source surface, so little contamination from the crucible.

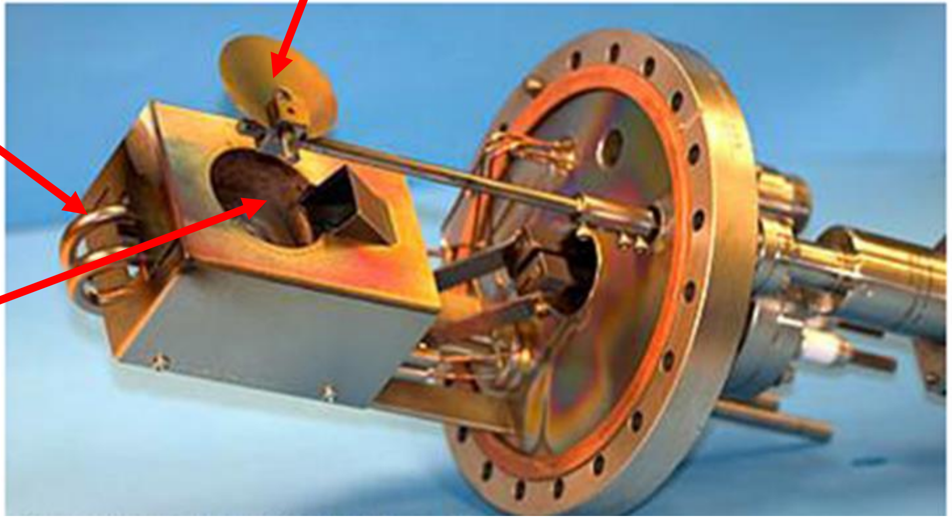
Photos of e-Beam Evaporator



Mechanical shutter:

- Evaporation is initiated by heating of target by e-beam collision, but the heating of target cannot be terminated instantly.
- A shutter is needed to terminate the deposition instantly.





Typical Boat/ Crucible Material

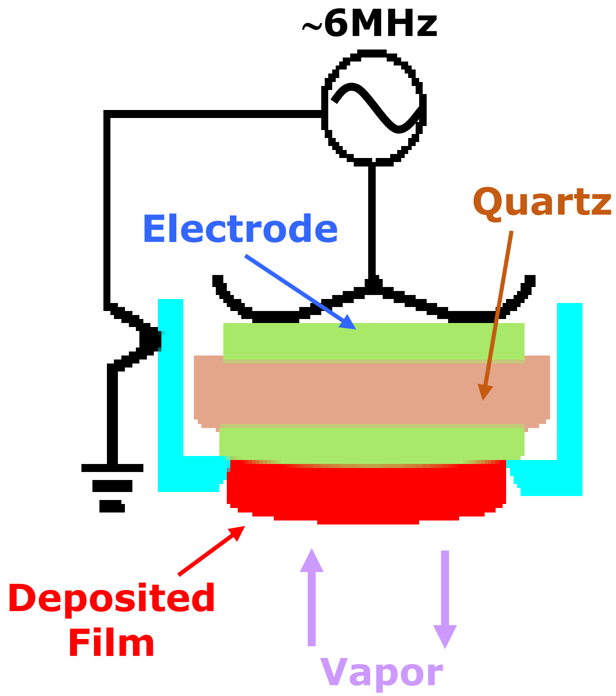
Refractory Metals	
Material	Melting Point (°C)
Tungsten (W)	3,380
Tantalum (Ta)	3,000
Molybdenum (Mo)	2,620
Refractory Ceramics	
Graphite (C)	3,799
Alumina (Al_2O_3)	2,030
Boron Nitride (BN)	2,500

Considerations: Thermal conductivity, thermal expansion, electrical conductivity, and reactivity

Graphite: Most popular, but avoid cracking the crucible due to stress/ temperature gradients

Aluminum: Tungsten dissolves in aluminum, so not quite compatible

How to Monitor Film Thickness during Evaporation?



Quartz Crystal Micro-Balance (QCM):

- QCM can monitor the thickness deposited on the wafer by measuring the shift of resonance frequency when the film is deposited on its surface.
- It can measure film thickness with a sub-Å accuracy.

Advantages and Limitations of Electron Beam Evaporation

Advantages:

- Films can be deposited at high rates (up to ~100 Å/s)
- Low energy atoms (~0.1 eV) leave little surface damage
- Little residual gas and impurity incorporation due to high vacuum conditions
- Very little substrate heating

Limitations:

- Difficult to achieve accurately controlled alloy compounds
- Poor step coverage
- X-ray damage

Comparison of Thermal and e-Beam Evaporation

	Thermal	E-Beam
Material	Metal of low melting point materials	Both metal and dielectrics
Typical Evaporating Materials	Au, Ag, Al, Cr, Sn, Sb, Ge, In, Mg, Ga	Everything in 'Thermal' plus Ni, Pt, Ir, Rh, Ti, V, Zc, W, Ta, Mo, Al_2O_3, SiO, SiO_2, SnO_2, TiO_2, ZrO_2
Impurity	High	Low
Deposition rate	1 ~ 20 Å/s	10 ~ 100 Å/s
Temperature Range	~ 1,800°C	~ 3,000°C
Cost	Low	High

Thermal evaporation:
- Simple, robust, and in widespread use
- Use W, Ta, or Mo filaments to heat evaporation source
- Typical filament currents are 200-300 Amperes
- Exposes substrates to visible and IR radiation
- Contamination from heated boat/ crucible

Electron beam evaporation:
- More complex, but extremely versatile, virtually any material
- Less contamination, less heating to wafer (as only small source area heated to very high temperature)
- Exposes substrates to secondary electron radiation, where high voltage electron beam can generate X-rays
- Since x-rays will damage substrate and dielectrics (leads to trapped charge), e-beam evaporators cannot be used in MOSFET

Thin Film Deposition Methods:
Physical Vapour Deposition (Sputter Deposition)

NANYANG TECHNOLOGICAL UNIVERSITY

Now, let us look at sputter deposition:

Evaporation:

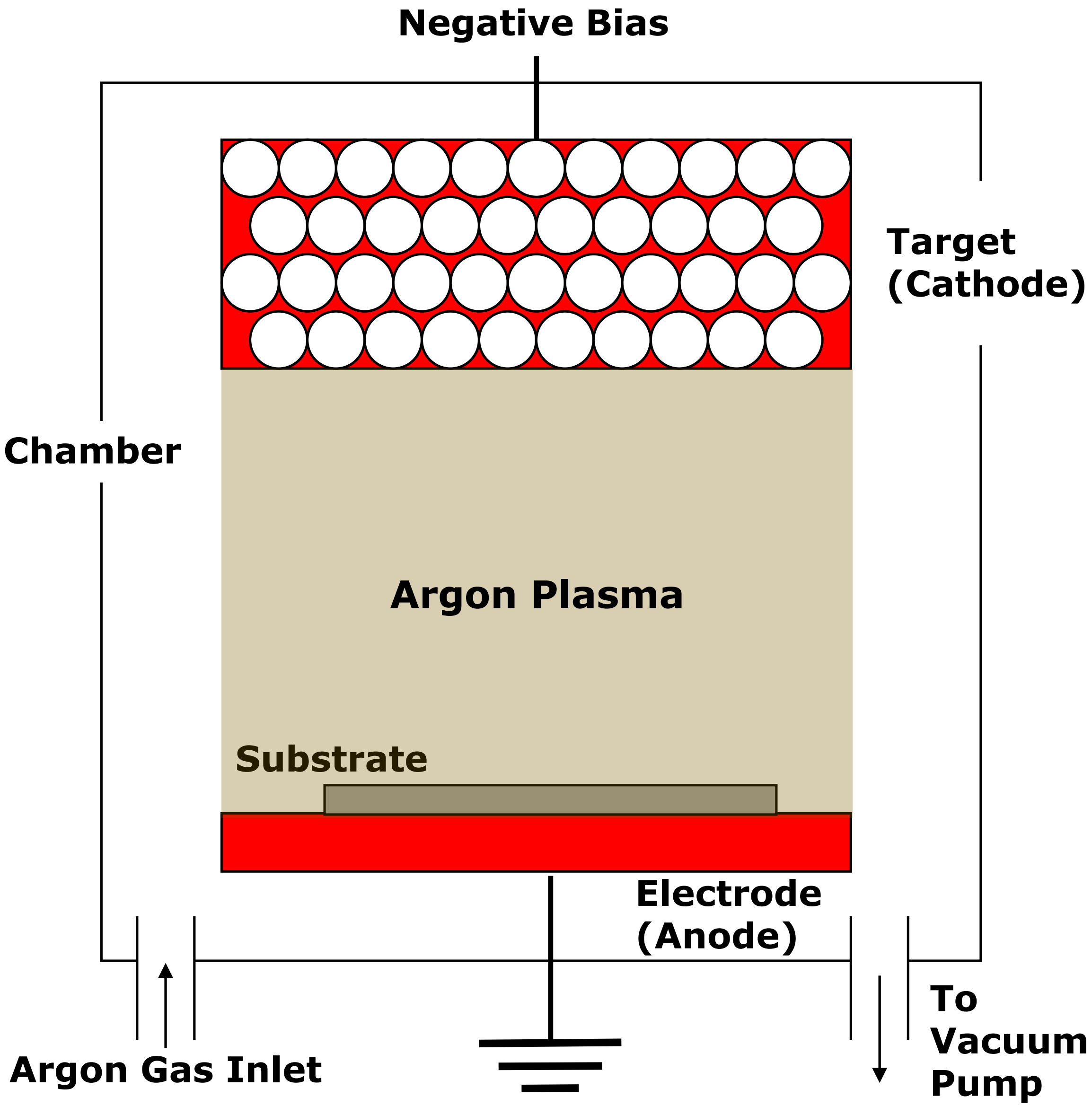
- Material source is heated to high temperature in a vacuum either by thermal or e-beam methods.
- Material is vapour transported to target in a vacuum.
- Film quality (density) is often not as good as sputtered film.
- The film thickness can be monitored precisely using a quartz balance.

Sputter deposition: *(There is also sputter etching as discussed earlier)*

- Material is removed from the target by momentum transfer.
- Gas particles (often Argon) are ionised by plasma, ions strike the target and remove (sputter away) the atoms in the target.
- Sputtered atoms are condensed on the substrate.
- It involves energetic bombardment of ions.
- The as-deposited film is denser due to higher energy of the sputtered atoms.

Schematic Diagram of Sputtering System

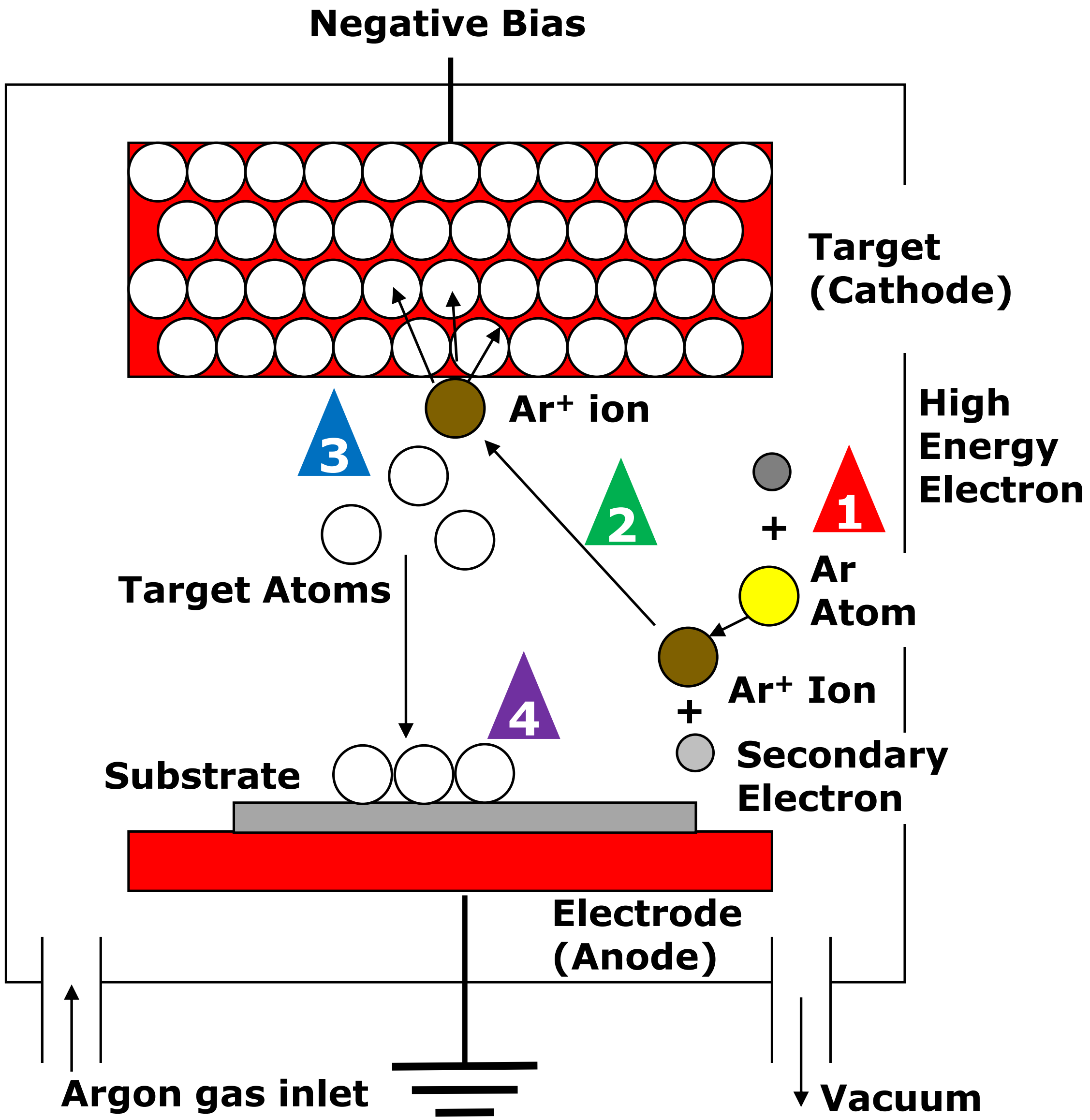
- The material to be sputtered (sputtering target) is placed in the cathode of an electrical circuit and is supplied with a high negative voltage.
- The substrate is placed on an electrically grounded anode.
- Gas is introduced into the chamber. The electrical field accelerates electrons and turn the gas into plasma.



Sputtering Process: Overview

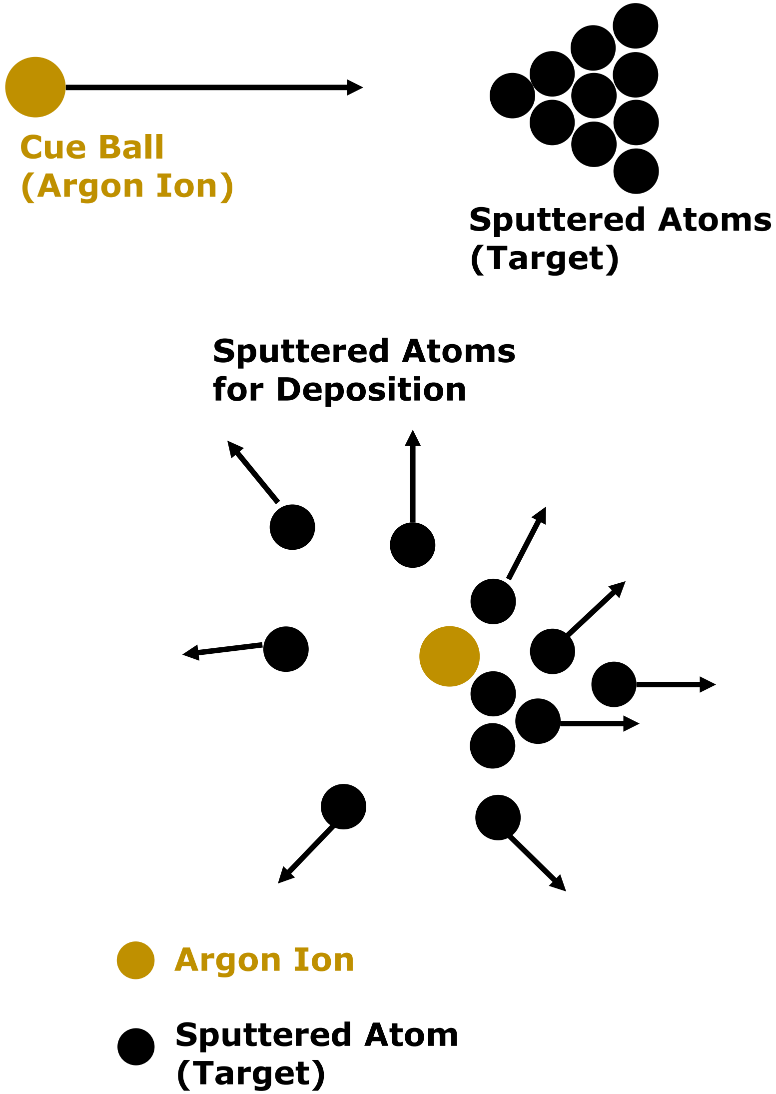
- Basically, sputtering is similar to sputter etching, where heavy and neutral ions are used to remove atoms from the target surface.
- Heavy, chemically inert ions – argon ions are usually used.
- The overall process of sputtering deposition can be summarised as such. Potential is applied between cathode and anode to form an argon plasma.

1. High energy electrons from the plasma collide with argon atoms to form Ar+ ions and secondary electrons.
2. The Ar+ ions will then be accelerated towards the sputtering target through negative bias applied to the target.
3. When high energetic Ar^+ ions strike the target surface, the momentum of the argon transfers to the target material to dislodge one or more atoms. This is referred to momentum transfer.
4. The ejected (sputtered) atoms move through the plasma, land on the substrate (on the anode), condense and form a thin film.



Sputtering Process: Overview (Cont'd)

Targets for
Sputter Deposition



- Major process parameters include operation pressure (~1-100mTorr), power (few 100W), voltage (-2 to -5kV for DC sputtering), and substrate bias is sometimes added.
- In addition to the semiconductor industry, a wide range of industrial products use sputtering. For example: LCD, computer hard drives, hard coatings for tools, and metals on plastics.
- It can be analogically described as the cue ball (Ar+) striking the billiard balls (target atoms).

General Properties of Sputtering Deposition

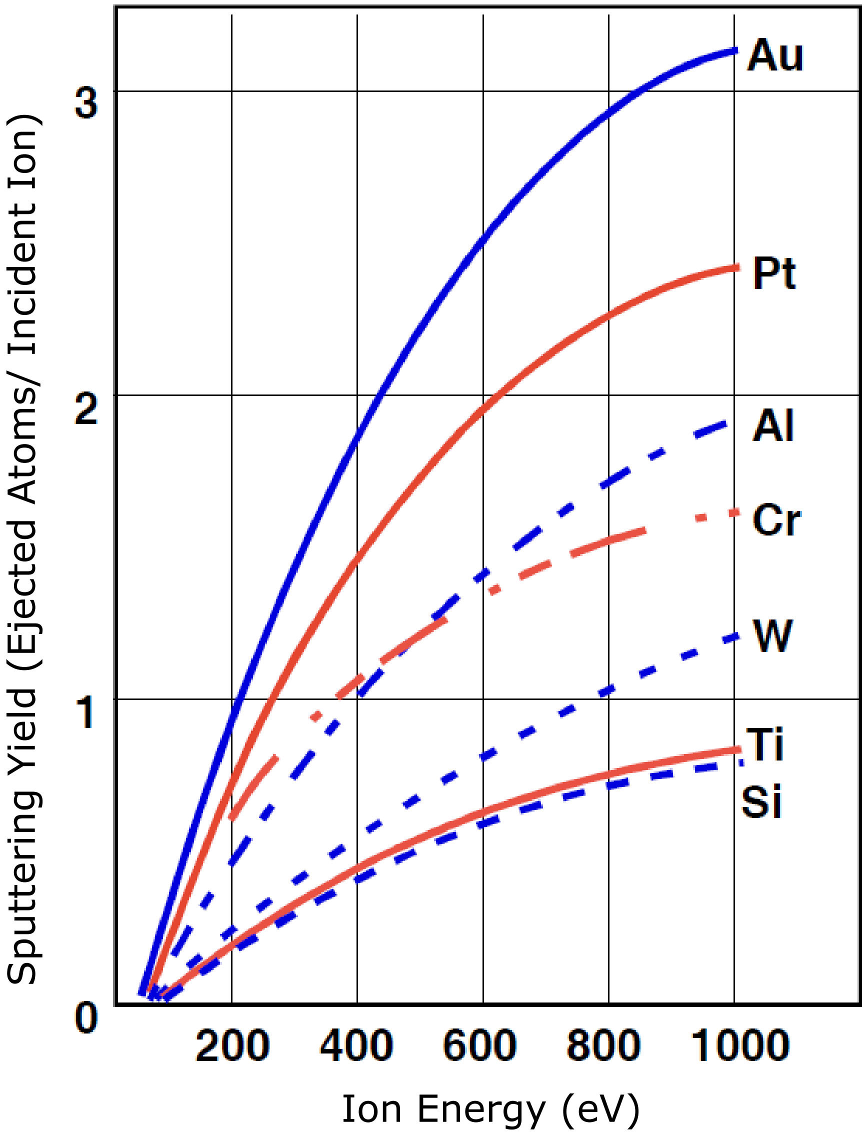
- The energy of each bombarding ion is 500-1000eV. The energy of sputtered atoms is 3-10eV. Thus, the sputtering process is very inefficient from the energy point of view as **95% of the incoming energy goes to target heating and secondary electron**.
- High rate sputter processes need **efficient cooling techniques to avoid target damage** from overheating which can cause a serious problem.
- The sputtered species, in general, are predominantly **neutral or not charged particles**.
- The energies of the atoms or molecules sputtered at a given rate are about one order of magnitude higher than those thermally evaporated at the same rate, which often leads to **better film quality**.
- However, since sputtering yields are low and the ion currents are limited, **sputter-deposition rates are invariably one to two orders of magnitude lower** compared to thermal evaporation rates under normal conditions. **Sputter yield is dependant on various factors**.

Sputter Yield

- Sputter yield is the number of sputtered atoms per bombarding (impinging) ion. The higher the yield, the higher sputter deposition rate
- The yield is rather insensitive to the target temperature except at very high temperatures where it shows an apparent rapid increase due to the accompanying thermal evaporation
- The sputter yield depends on:
    - **a) Ion energy**
    - **b) Ion incident angle**
    - **c) Ion mass**

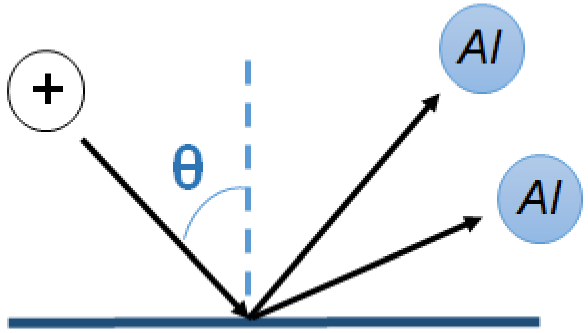
Dependence of Sputter Yield on Ion Energy

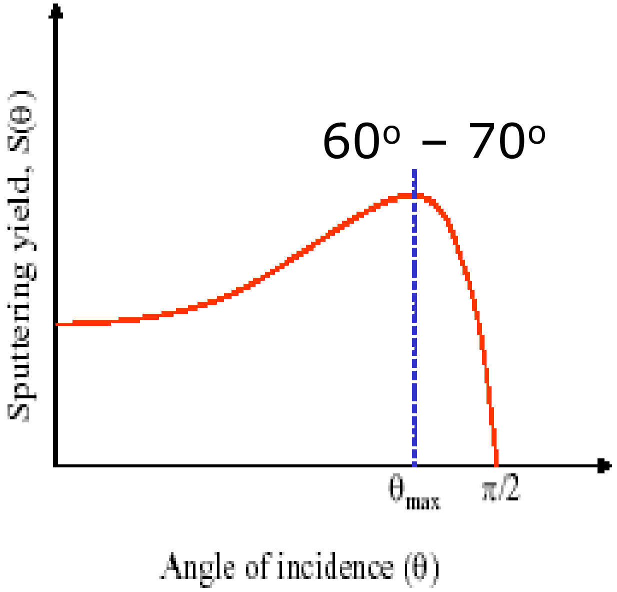
- The yield increases with the ion energy.
- For higher ion energies, the yield approaches saturation, which occurs at higher energies for heavier bombarding particles.
- Sometimes, at very high energies, the yield decreases as argon ions penetrate into sputter target (i.e. atoms beneath the target surface are unable to reach the surface to escape).



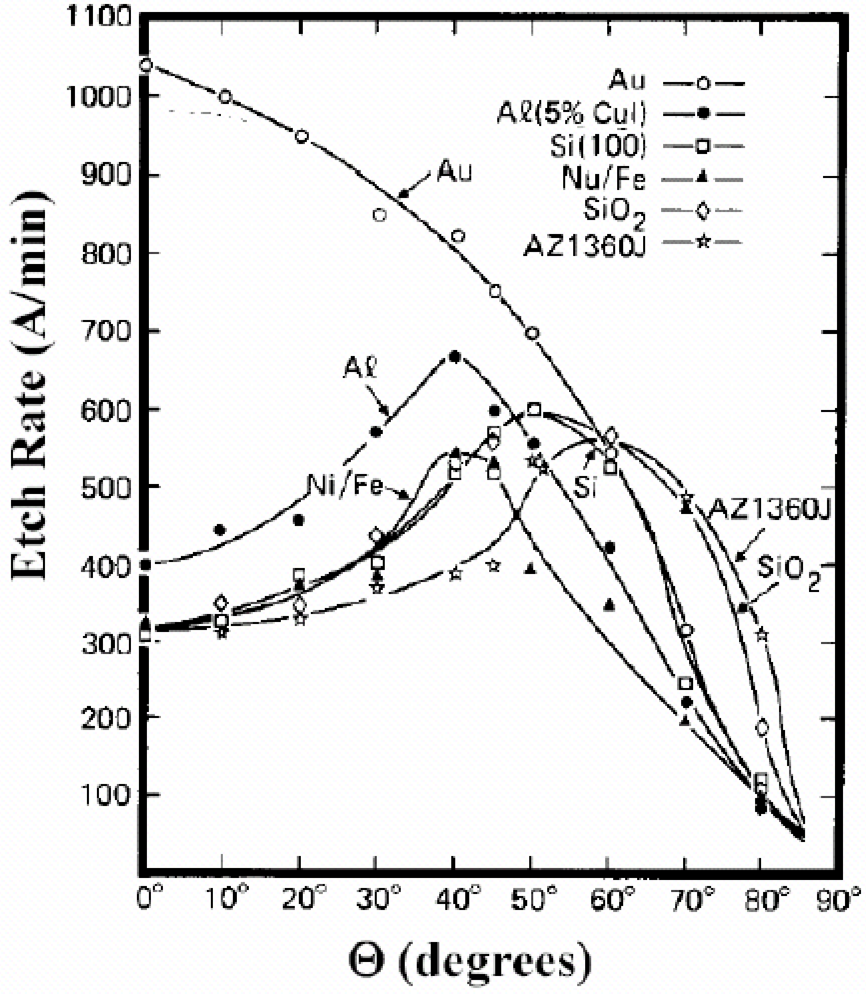
Dependence of Sputter Yield on Ion Incident Angle

- The yield with increasing obliqueness (θ) of the incident ions
- However, at large angles of incidence, the surface penetration effect decrease the yield drastically
- An optimal angle is needed to achieve high sputtering yield

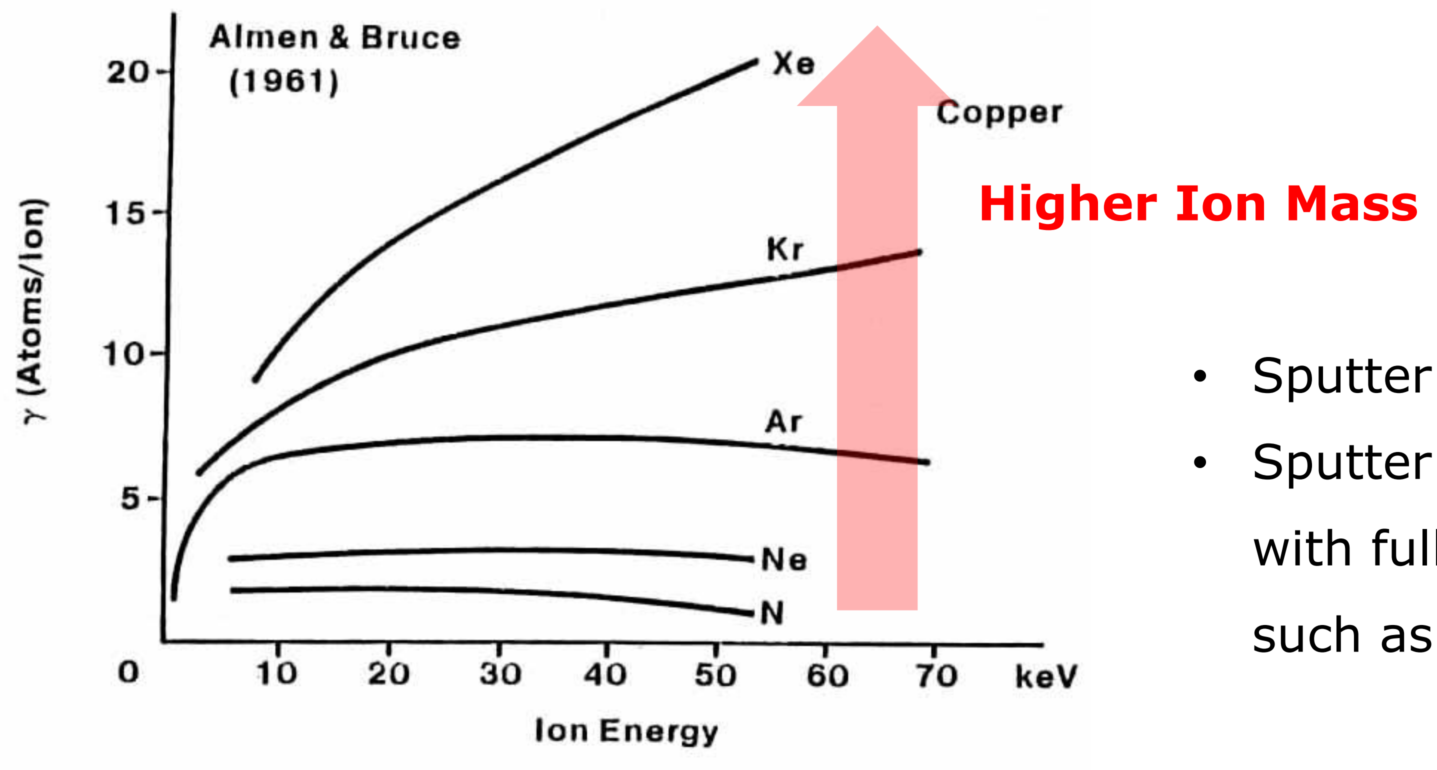




Sputter yield on Si target using Ar gas



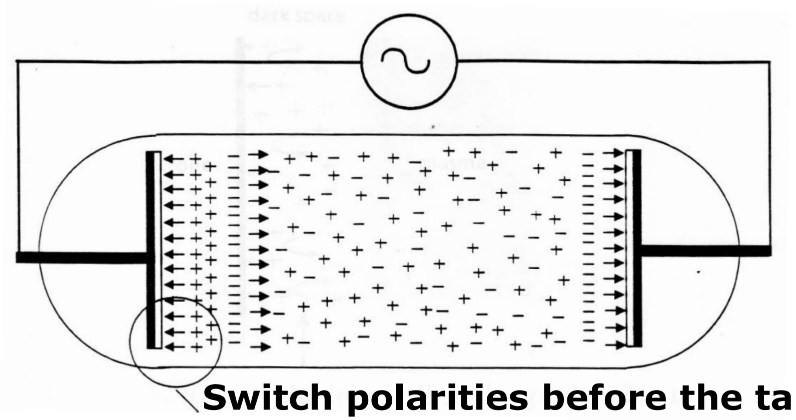
Dependence of Sputter Yield on Ion Mass



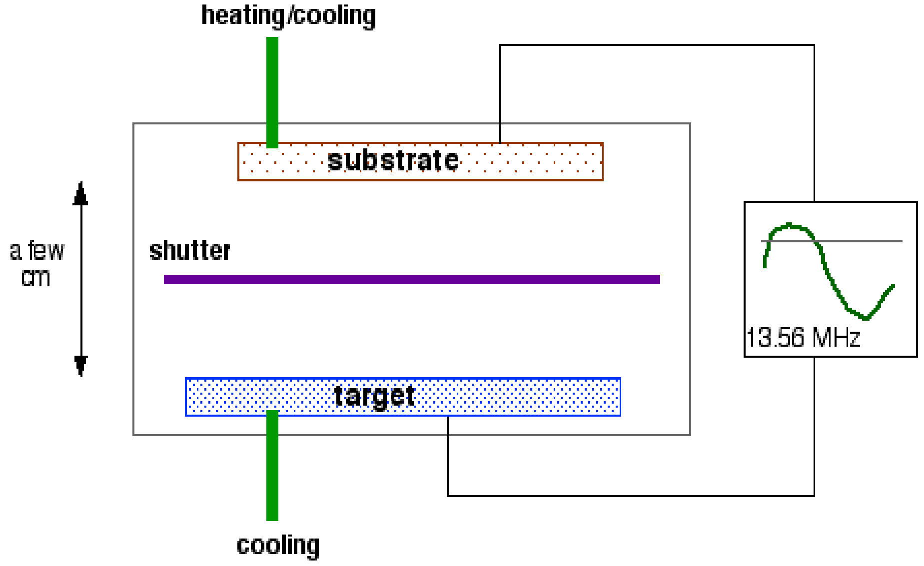
Sputtering yields of the noble gases on copper, as a function of energy.

- Sputter yield increases with ion mass
- Sputter yield is at its maximum for ions with full valence shells. Noble gasses such as Ar, Kr, and Xe have large yields.

RF (Radio Frequency) Sputter Deposition



Switch polarities before the target surface saturates with ions.



- DC sputtering system is unable to sputter insulating/ dielectric materials.
- To resolve this issue, additional Radio Frequency (RF) potential is applied to the cathode (target) of the sputtering system.
- Positive charge (Ar+) builds up on the cathode (target) in DC sputtering systems. Alternating potential can avoid charge build-up.
- Sputtering of insulator become possible because of the RF on the target.

Magnetron Sputter Deposition

Issues

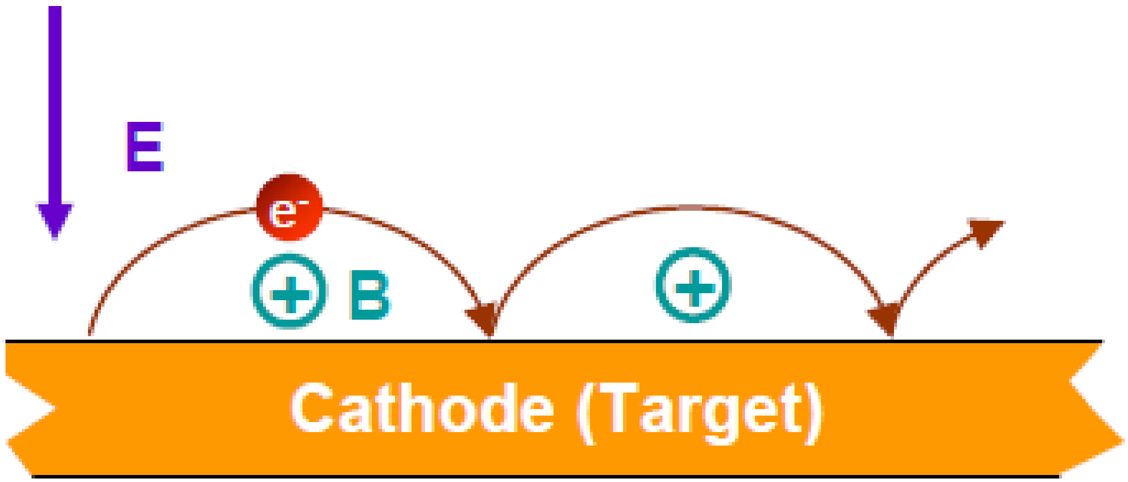
- **Low ionisation efficiency in electron-argon gas collision:** In DC & RF sputtering, the efficiency of ionisation from energetic collisions between the electrons and gas atoms is low. Most electrons lose energy in a non-ionising collisions or are collected by the electrodes. Hence, deposition rates are low.
- **Slight increase in efficacy by RF:** Oscillating RF fields only gives slight increment on the ionisation efficiency.

Solution

- **Magnets used to increase argon ionisation:** To increase deposition rates, magnets are used to increase the percentage of electrons that take part in ionisation events, increasing the ionisation efficiency.
- **The magnetic field causes electrons to move spirally:** Magnetic field is applied perpendicularly to an electric field, to trap electrons near the target surface. It will cause them to move in a spiral motion until they collide with an Ar atom.
- **The ionisation and sputtering efficiencies are increased significantly** - deposition rates increase by 10-100×, to 1 μm per minute.

Magnetron Sputter: High Density of Plasma Near Target

The orbital motion of electrons increases the probability of collision with neutral species and create ions.



- In magnetron sputtering, magnets are employed to capture and restrict the electrons in front of the target
- Increase the ion bombardment rate on the target, produce more secondary electrons, increases the ionisation rate in the plasma
- More ions cause more sputtering of the target which increases the deposition rate without increasing the chamber pressure
- Higher deposition rate

Advantages and Disadvantages of Sputter Deposition

Advantages:

- Able to deposit a wide variety of metals, insulators, alloys, and composites
- Able to deposit compound/ alloy thin film – the film has the same composition as the sputter target
- Better film quality (densified) and step coverage than evaporation. This is partly because adatoms are more energetic
- More reproducible deposition control – same deposition rate for same process parameters (not true for evaporation), so easy film thickness control via time
- Can use large area targets for uniform thickness over large substrates
- Sufficient target material for many depositions
- No x-ray damage

Disadvantages/ Limitations:

- Substrate damage due to possible ion bombardment
- Higher pressures 1 –100Mtorr ($< 10^{-5}$ torr in evaporation), more contaminations unless using ultra clean gasses and ultra clean targets
- The deposition rate of some materials quite low
- Most of the energy incident on the target becomes heat, which must be removed

Comparison between Evaporation and Sputtering

Properties	Evaporation	Sputtering
Rate	1,000 atomic layer/s	1 atomic layer/s
Thickness control	Possible	Easy
Materials	Limited	Almost unlimited
Contaminants	Low	High
Surface roughness	Little	High (ion bombardment)
Adhesion	Medium	Good (higher energy adatoms)
Film properties	Difficult to control	Can be controlled
Step coverage	Poor	Good
Equipment cost	Medium	Expensive

Lesson Summary - PVD

- Step coverage and trench filling are important figure of merit in a thin film deposition, where trench filling is highly dependent on the aspect ratio of the trench.
- PVD can be carried out using evaporation technique or sputtering technique.
- Evaporation technique can either be carried out using thermal evaporation or electron beam evaporation.
- For sputtering process, high energetic argon ions are used to dislodge atoms from target materials for deposition.
- Sputter yield depends on ion energy, ion mass, and the incident angle of the ion.
- RF sputtering can prevent charge accumulation on the substrate, hence, making dielectric deposition possible. However, magnetron sputtering induces spiral motion on ions, which increases the sputter yield.

Practice Question 1

Determine if the statements below are true or false.

Pause and try out this question

a) In a RF sputtering system, the Si wafer is placed on the cathode plate. False

b) In a RF sputtering system, the target is placed on the anode plate. False

c) In a RIE system, the Si wafer is placed on the cathode plate. True

d) Sputter yield depends on ion incident angle. True

e) Physical vapour deposition involves chemical reaction in the nucleation step. False

Practice Question 2

In sputtering, the sputtered atoms condense and form a thin film on the wafer surface with

a) Different material composition than the target
b) The same material composition as the plasma
c) The same material as the target
d) The same material composition as the incoming gas

Pause and try out this question