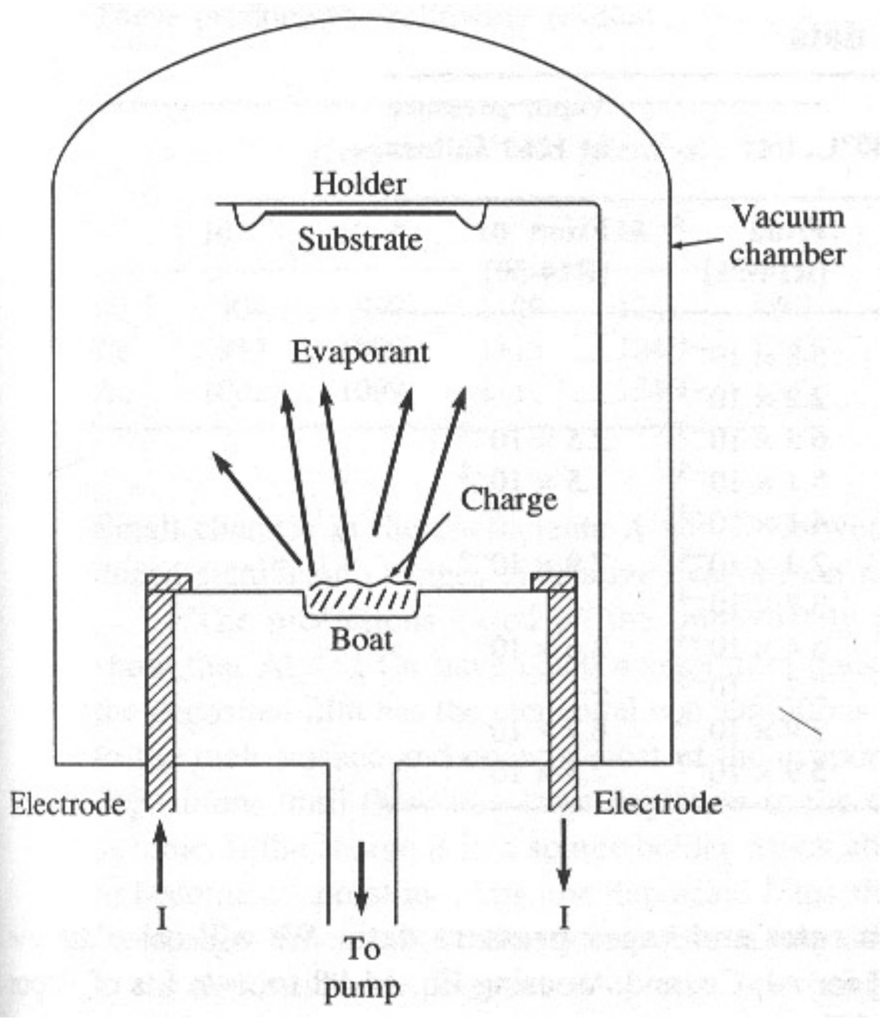
Lecture 6 PVD (Physical vapor deposition):

Evaporation and Sputtering

- **Vacuum evaporation**

1. Fundamental of Evaporation:



- **<u>The material to be evaporated is heated</u> in an evacuated chamber so that it attains a gaseous state. Vapor of this material traverse the space from the source to the substrate.**
- **<u>Typical deposition rates</u> in industry is around 0.5 μm/min (~8 nm/s, for Al), however, in our lab we get around 0.3 ~1 nm/s for better quality. To approach this rate (0.5 μm/min), the vapor pressure in 10 mtorr range is desired.**

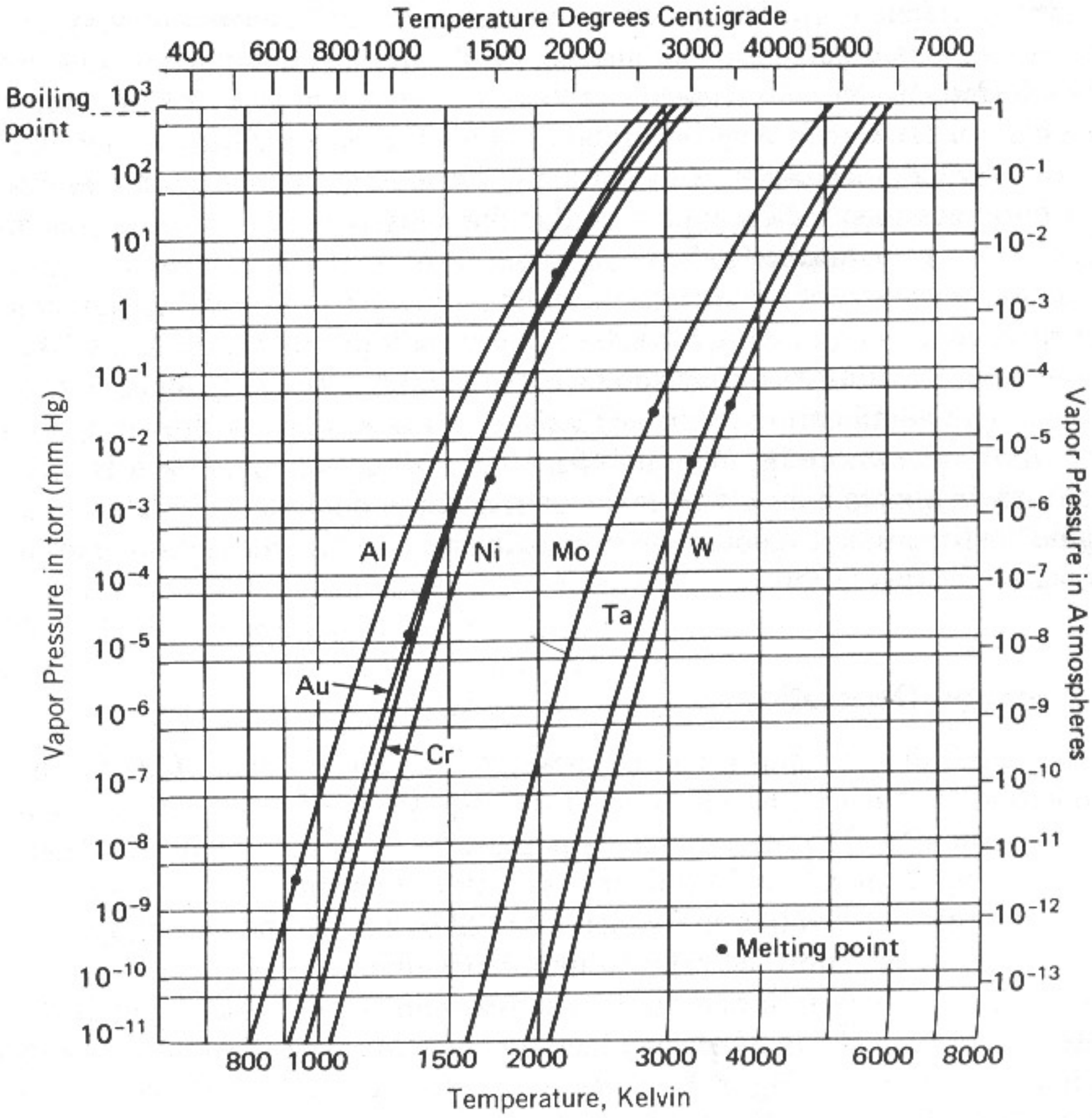


Fig. 8.1 Vapor pressure curves for selected materials. Adapted from [2].

- **Al and Au is quite usable in thermal evaporation system with heated crucible, for they can be melt in crucible and generate enough quantity of vapors. However, W and Ti are not suitable for their low vapor pressure.**
- **Electron-beam evaporation, using an intense beam of energy is applied locally to a target, can be used to develop a sufficiently large flux of evaporate from refractory materials.**

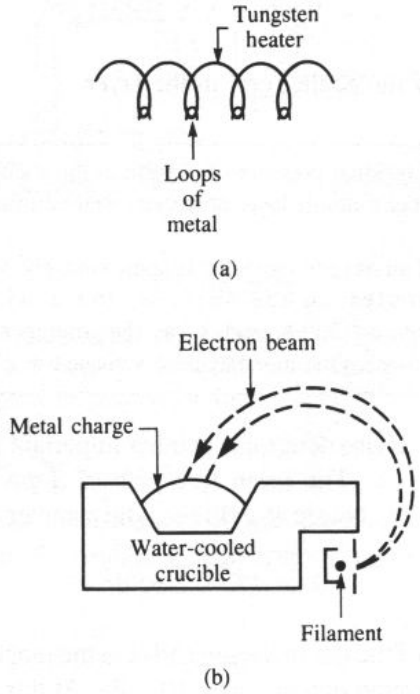


Fig. 6.2 Two forms of evaporation sources. (a) Filament evaporation, in which loops of wire hang from a heated filament; (b) electron-beam source in which a beam of electrons is focused on a metal charge. The beam is bent in a magnetic field.

- **In E-beam, Source is held in a water cooled hearth, and evaporation occurs at a highly localized point on this source, while its bulk remains solid. No contamination from the crucible if the beam strikes only on the target.**

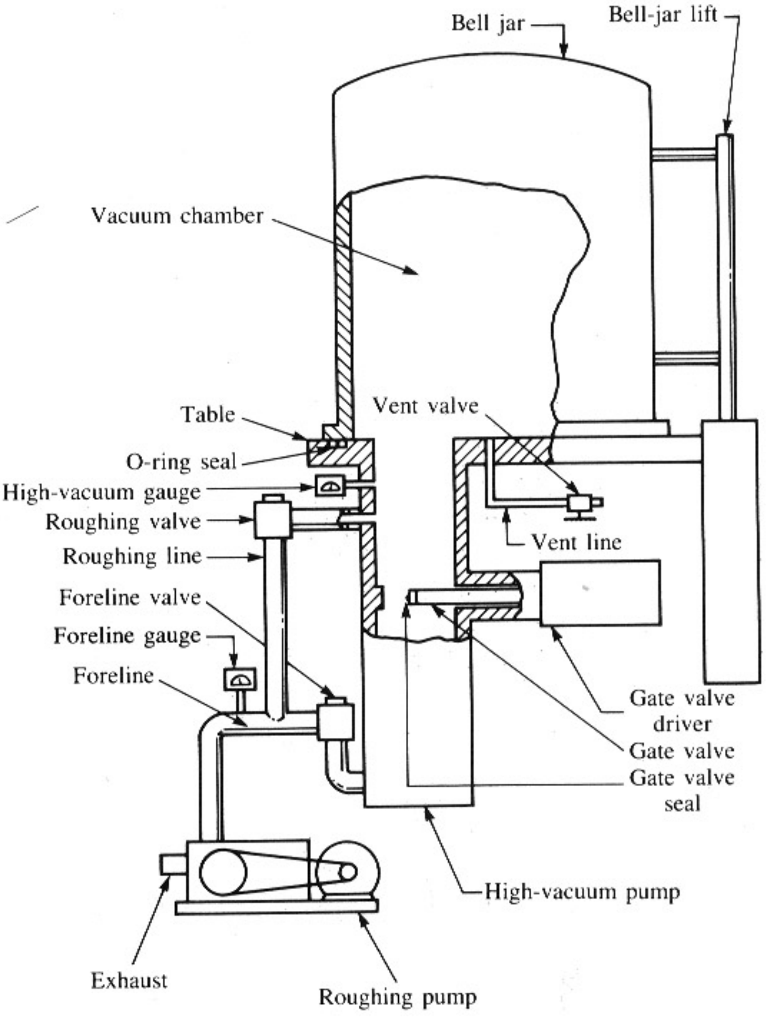
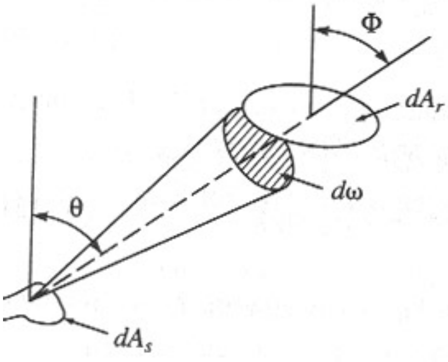
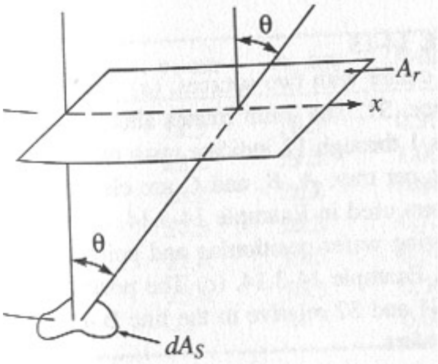


Fig. 6.1 Typical vacuum system used for evaporation including vacuum chamber, roughing pump, high-vacuum pump, and various valves and vacuum gauges. Copyright, 1987, McGraw-Hill Book Company; reprinted with permission from ref. [5].

- **Evaporate from a point source, causing non-uniformity on substrate. Ways to reduce the problem: a. rotating the slices during evaporation, b. Planetary motion system, c. moving the position of point source to simulate a large surface source.**
- **Evaporation Rate:**





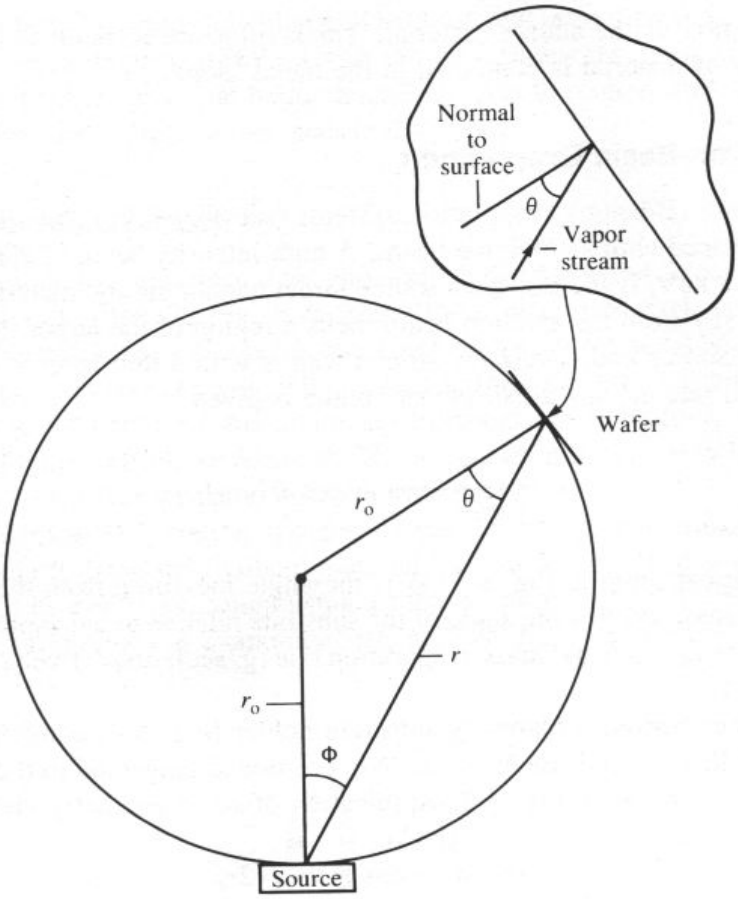


Fig. 6.3 Geometry for evaporation in a system using a planetary substrate holder.

$$G = \frac{m}{\pi\rho r^2}\cos\phi\cos\theta$$ **cm/sec**

for planetary holder, G is independent of substrate position:

$$G = \frac{m}{4\pi\rho {r_0}^2}$$ **for** $\cos\theta=\cos\Phi=r/2r_0$

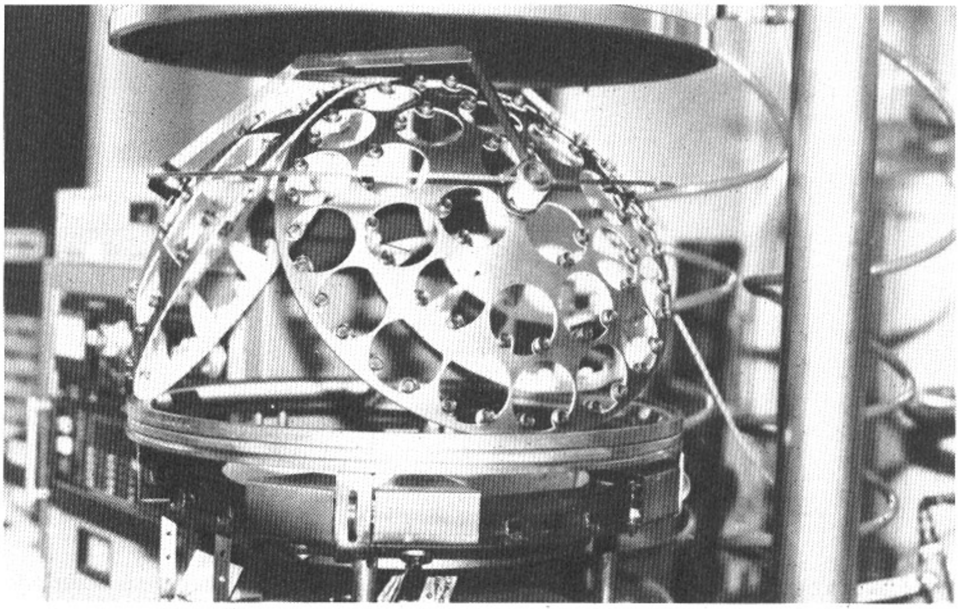


Fig. 6.4 Photograph of an E-beam evaporation system with a planetary substrate holder which rotates simultaneously around two axes.

- **<u>Materials</u>: refractory or non-refractory materials. Compounds or alloys can not get right combination if evaporated from only single source. Multiple hearths evaporated at the same time or using reactive evaporation methods are desired to get right combination. <u>The materials now available in our lab are Al, Au, Ti, Cr, Cu, Ni, Pt, and Ag.</u>**

- **<u>Multiple hearths</u> are incorporated into these systems to permit the deposition of multiplayer films in a sequential**

manner without breaking vacuum and contamination.

- **<u>Path should be collision free</u> to prevent agglomeration (結塊) of material in gas phase, thus the length should be less than mean free path. To have mean free path about 10^3 cm, the pressure should be less than 10^{-5}. The typical vacuum evaporator should by pumped to 10^{-7} torr(most of the depositions used in the lab is in the range of 10^{-6}-10^{-7} torr).**

- **Kinetic gas theory**

Idea gas law:

$$PV = N_{av}kT$$

P: pressure, V: Volume, T: temperature, N_{av}: Avogadro's number (6.02×10^{23} molecules/mole).

The mean free path, λ, of a gas molecule is the average distance the molecule travels before it collides with another molecule, and a parameter determined by temperature and pressure. λ is given by:

$$\lambda = kT / \sqrt{2}\pi P d^2$$

d: is the diameter of gas molecule, in the range of 2-5 A. For a 4 A molecule at 10^{-4} Pa (~10^{-6} torr), the mean free path is around 60 m. Molecules travel in a straight line in a vacuum system.

- **Cadmium and Zinc has high vapor pressure and seems easily to contaminate the entire system during high vacuum process.**

- **During vacuum evaporation, substrates are essentially unheated, except for radiation from the evaporant source (usually give substrate 50-100°C depending on temp). To improve the adhesion for the evaporant to substrate, elevate temp is sometime used by infrared heaters. However, care need to be taken if the substrate has PR for lift off process, and temperature need to be less than the hard bake temp.**

- **Thermal evaporation provides energy in the 0.1-0.15 eV range, thus does not damage substrate surface, especially good for gate oxide. However, e-beam evaporation uses high voltage (>10 kV), may produces x-ray, which increase fixed oxide charge and density of interface traps.**

- **In-situ cleaning is not practical in evaporation system thus sometime pose adhesion problem. Aluminum film has fine adhesion on oxide substrate, but most of the metals (especially noble metal) have poor adhesion on silicon or silicon oxide surface, as a result, Chromium (Cr) and Titanium (Ti) are often used for this purpose.**

- **Step coverage**

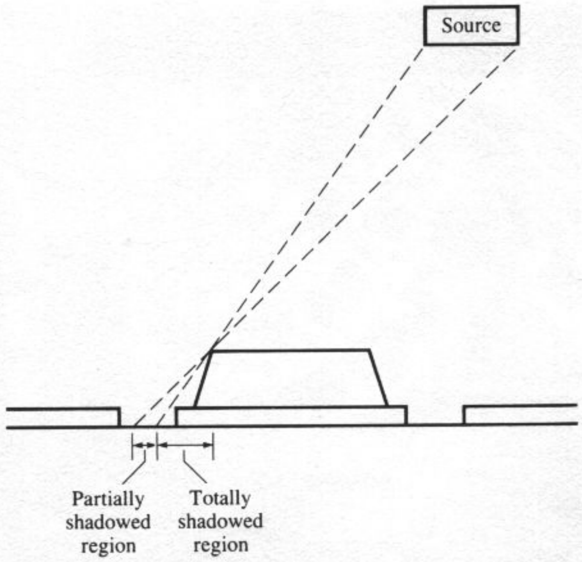


Fig. 6.5 An example of the shadowing problem that can occur in low-pressure vacuum deposition in which the molecular mean free path is large.

● Sputtering and sputtering etching

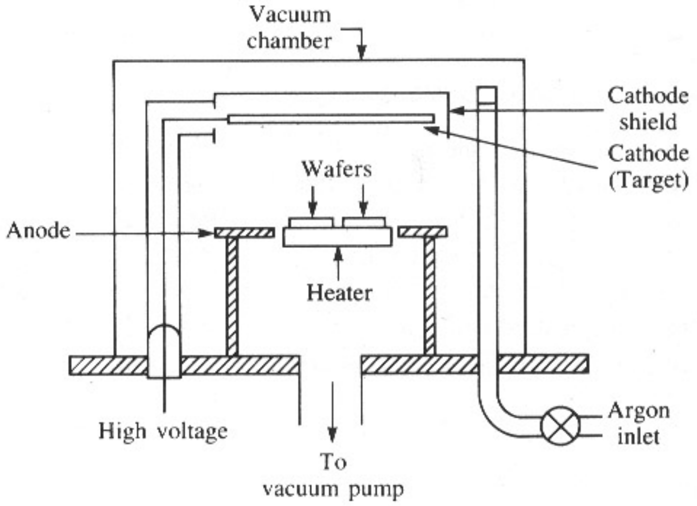


Fig. 6.6 A dc sputtering system in which the target material acts as the cathode of a diode and the wafers are mounted on the system anode.

- **More versatile than vacuum evaporation: (a) ability to deposit a wide variety of metal s and insulators, as well as their mixtures, (b) the replication of target composition in the deposited film, and (c) the capability for in-situ cleaning of the substrate prior to film deposition.**

- **Self-sustained glow discharge which is created by the breakdown of a heavy inert gas such as argon.**

- **A d.c. electric field impressed across two water-cooled electrodes which are located in this gas. Current (electrons) flow between electrodes in sufficient electrical field. Electrons collide with argon to produce Ar^+, and Ar^+ collide with other argon molecules and cause avalanche multiplication effect and produce large number of Ar^+ and electrons. This effect $\sim E/\lambda$, and also effected by electrode distance. Here $\lambda \sim 1/P$, and E: electrical field density, λ: mean free path, P: pressure.**

- **Ar^+ ions bombard the cathode, resulting in sputtering of its surface material by momentum transfer. Secondary electrons emitted at the cathode participate in sustaining the discharge by ionizing collisions with argon molecules.**

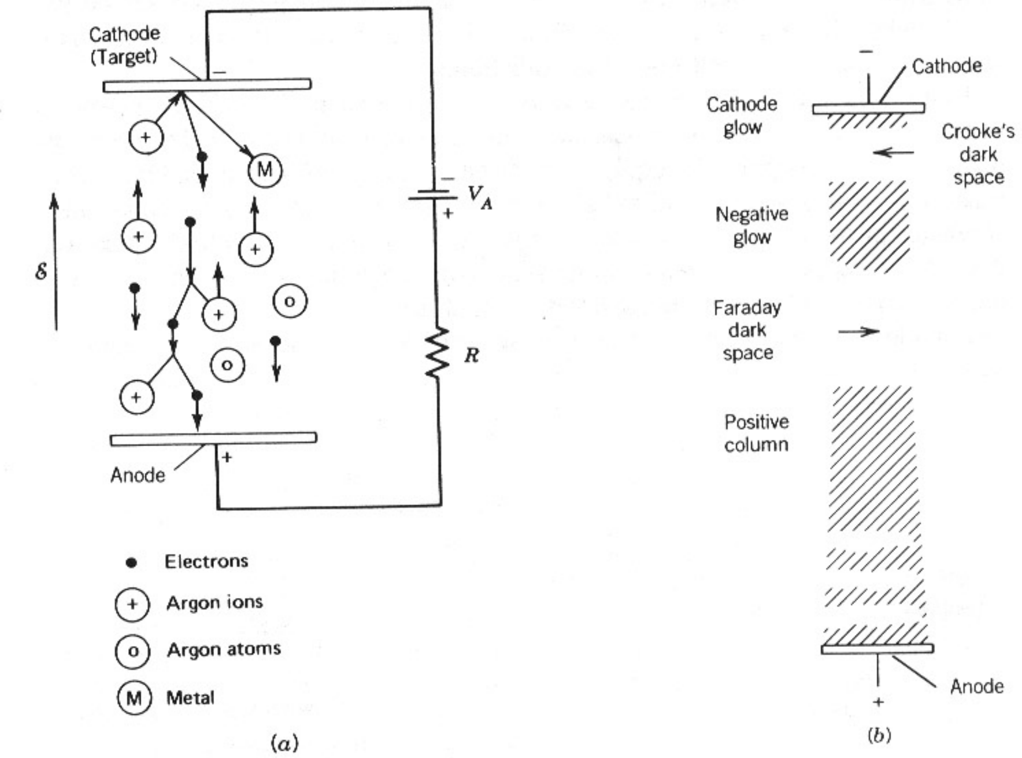


Fig. 8.2 Sputtering in a d.c.-excited glow discharge.

- **Electrically conductive materials such as Al, W, and Ti can use a dc power source, in which the target acts as the cathode in a diode system. Sputtering of dielectrics such as silicon dioxide or aluminum oxide requires an RF power to supply energy to the argon atoms. (usually 1-3kV and 13.56 MHz)**

- **Most of the voltage drop is in the vicinity of the cathode, resulting in its bombardment by high-velocity Ar^+ ions. The anode is a relatively field-free region. The neutral atoms ejected from the cathode, having a energy 0-20eV, diffuse to the anode or the chamber walls and arrive in a relatively no-directed manner, posing better step coverage and adhesion from the ion mixing resulting from the energy spread.**

- **Sputtering yield**

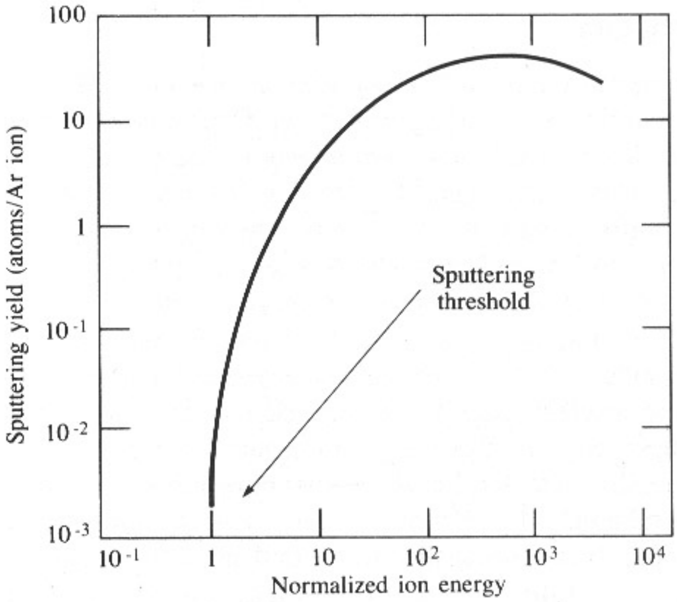


Fig. 6.7 Sputtering yield versus ion energy for a dc sputtering system using argon.

◆ **Alloy content of a multi-component target is replicated in the source film even if it consists materials with widely different sputter yield. (the first altered layer can be as thin as few tens of angstroms for metal alloys and 1000 angstroms for targets of oxide mixtures) This can not be easily obtained by evaporation.**

◆ **Back-sputtering by reverse system polarity in dc sputtering can be used to clean substrate surface in-situ before film deposition, which affects electrical and mechanical properties of film-substrate combination.**

◆ **Sputtering can damage substrate surface for the impact of high energy species, not suitable for deposition material on gate oxide.**

- **Magnetron sputtering: Magnetic field can be used to confine electrons near the target surface to greatly increases the possibility of ionizing collisions with at the argon gas molecules.**

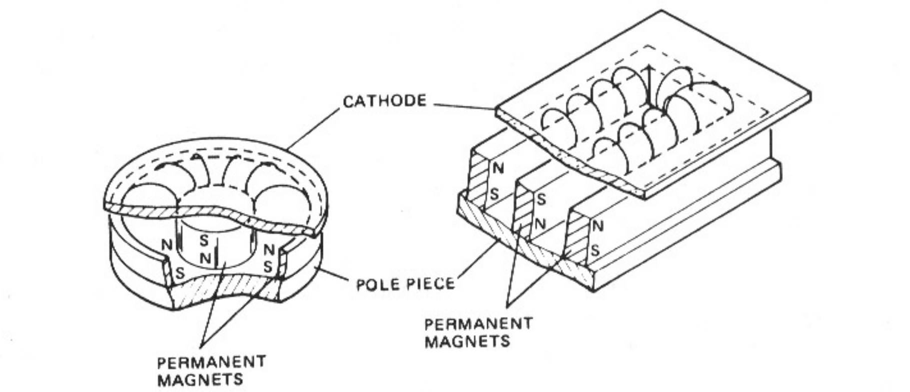


Fig. 8.4 Circular and rectangular magnetron sputtering targets. The curved lines represent magnetic field lines. From Vossen and Kern [1]. Reprinted with permission from Academic Press.

References:

1. Sorab K. Ghandhi, "VLSI Fabrication Principles-silicon and gallium arsenide", John Wiley $ Sons, Inc, New York, 1994.
2. Richard c. Jaeger, "Introduction to Microelectronic Fabrication-Modular series on solid state devices", Addision-Wesley Publishing company, New York, 1993.
3. S. Middleman, and A. K. Hochberg, "Process Engineering Analysis in Semiconductor Device Fabrication", McGRAW International Editions, New York, 1993.