3.3 Thin Film Deposition by PVD

3.3.1 Overview

PVD = Physical Vapor Deposition

Typical vacuum process: the materials will be deposited on the substrate via

→**Evaporation** (e-beam / thermal) or **Sputtering** (using a sputtering target)

Principle:

- The material will be transferred in a molecular or atomic state and transported to the substrate.
- On the surface of the substrate the **condensation** takes place and therewith the deposition of the film.

Main field of application: **Generation of conductive metal films**

Process flow

- Surface preparation (cleaning, e.g. sputter etching)
- Deposition process
- Post-treatment (annealing)

3.3.2 Thin Film Deposition: role of the plasma

Plasma

- **sputtering**
- **PECVD**
- **Plasma activated evaporation**
- **Sputter etching**
- **Plasma etching**
- **Plasma polymerization**
- **Ion etching**

kinetic energy	The plasma provides charged particles important for: ***sputtering (plasma sputtering)*** ***sputter etching (Al, TiN, $MoSi_2$...)***
radicals	Generation of species with a high chemical reactivity (radicals, radical ions) important for: ***reactive etching (Cu, TiN, SiO_2, Si_3N_4...)***

Thin Film Deposition: What is a plasma ?

Plasma

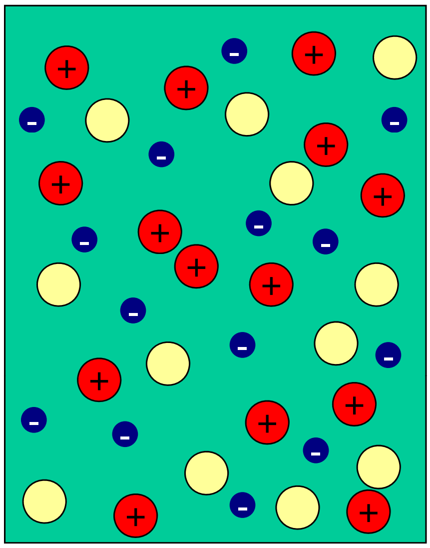
→ electrical conductive gas
→ mixture of free electrons, ions and atoms or molecules (formation of radicals* is also possible)

Appearance:

- from a gas
- caused by ionization (generation of electrons and ions from atoms and molecules)
  - collision ionization (collision of fast particles)
  - photo ionization (absorption of photons)
  - high temperatures (x · 1000 K)

→ required energy of ionization:

3.9 ... 24.6 eV



* radical: uncharged rest of a splitted molecule

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Thin Film Deposition: What is a plasma ?

Properties of low pressure plasmas

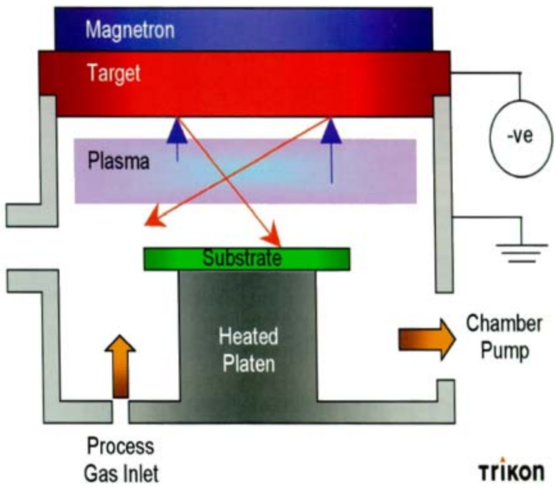
- External charge neutrality
- Electron density: 10^9 ... 10^{12} cm^{-3} , degree of ionization 10^{-6} ... 10^{-4}
  electron energy: 1 ... 20 eV
  ↓
  „temperature“ of the electrons is nearly 30 ... 1000 times higher than the average temperature of the molecules
- The excited atoms and molecules convert in the initial state after a defined time. During the process a characteristic radiation will be emitted.

→ Glow of the plasma (optical emission)

Applications in the microelectronics technology

- CVD, etching, ion implantation, sputtering
  arc discharge- and low pressure- plasmas
  (CVD, etching 10 ... 200 Pa; sputtering 0,1 … 1 Pa; ion impl. 10^{-5} Pa)

3.3.3 Sputtering Process



Principle:

The target consists of the material, which should be deposited on the wafer.

→ Area of ionization will not be separated from the area of deposition !

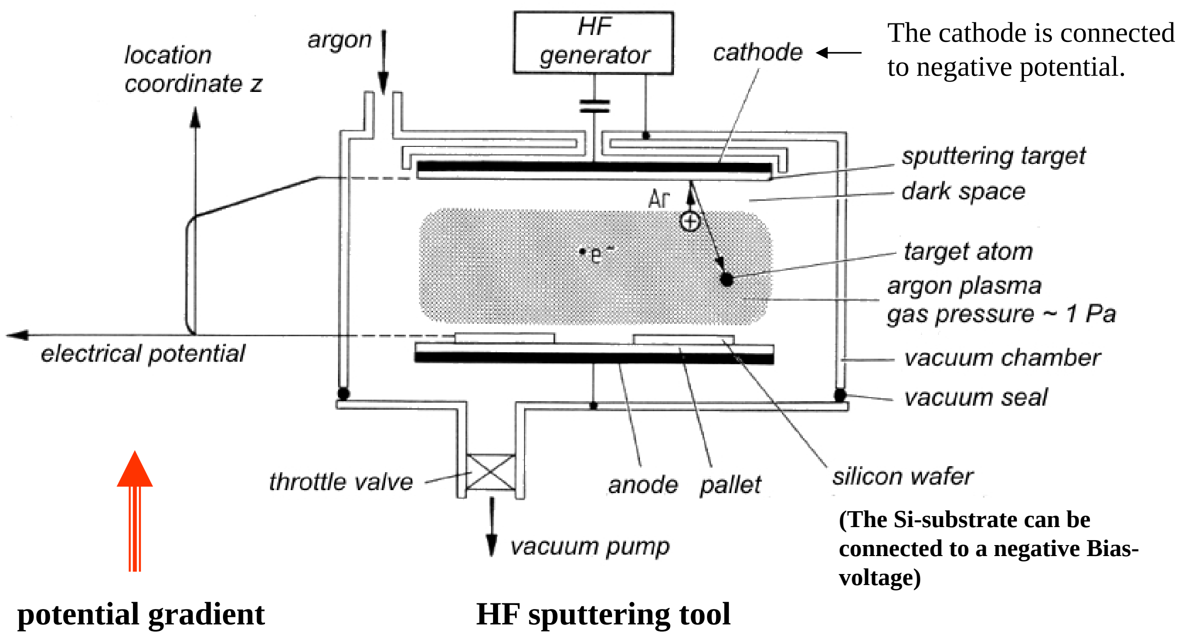
→ The pressure will be defined by the plasma.

→ Ballistic transport of the target atoms to the wafer (few collisions on the way to to the substrate)

→ Main field of application today in the microelectronic technology and technology of MEMS

reason: productivity and purity of the targets *e.g.: 99.9995 %* ***[5N5]***

Sputtering

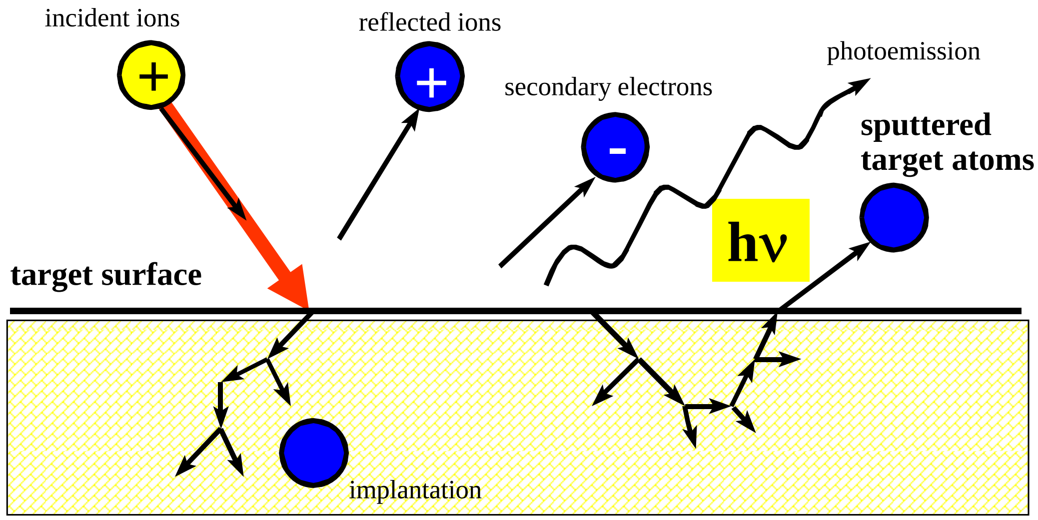


HF sputtering tool

/Widmann/

- DC or RF mode
- dark spaces → see also CVD (PE)
- pressure range: 1 ... 10 Pa, voltage: x · 1000 V

Elementary processes of sputtering



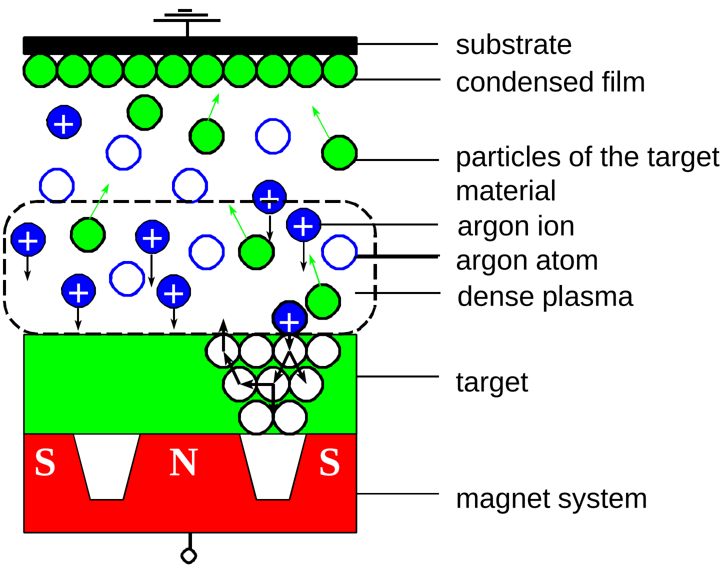
Interaction of ions with the surface

reflection	secondary electrons	change of stoichiometry
lattice defects	radiation damages	ion implantation

Sputtering: Generation of a collision cascade

It differs, if the last collision hits an atom in the bulk or at the surface of the target. Only in the latter case an emission takes place - efficiency 5% to 25 %!

Sputtering: DC magnetron sputtering

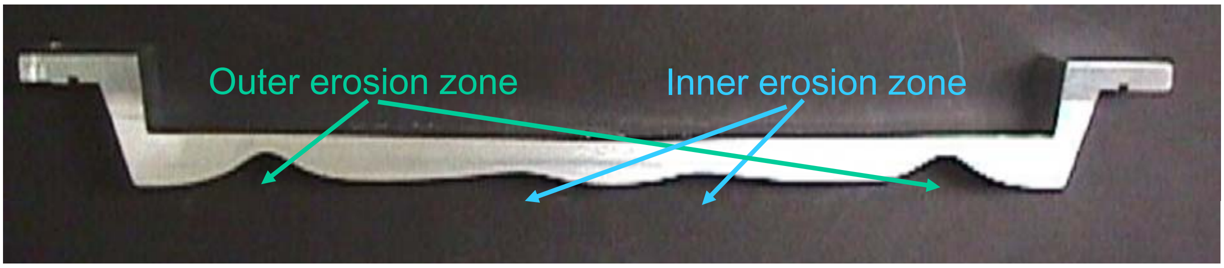


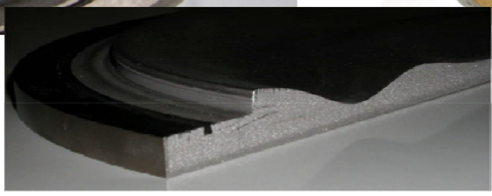
- Plasma (Ar^+, e^-) generated by glow discharge
- the magnetic field elongates the trajectory of the electrons
- DC:
  for conducting target materials
  - o average kinetic energy approx. 2-10 eV
  - o insulator would be charged →
- RF:
  for insulating target materials (electrons compensate for positive charges on the target)

Sputtering – cathode sputtering

Accelerated positively charged gas ions with an enough amount of kinetic energy collide with the cathode (target); by collision processes atoms at the surface will be ejected; these atoms left the surface with preferential direction (cosine distribution); the energy of the atoms decrease by interaction with the plasma from initial approx. 10 eV to 1 to 2 eV (compare with e-beam evaporation: approx. 0.1 eV).

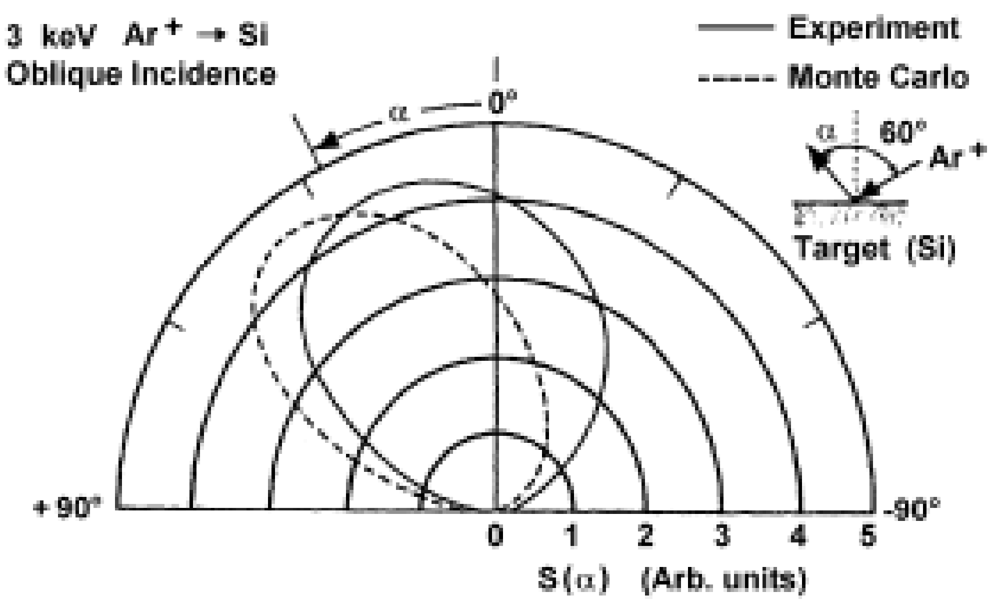
Erosion trench on a magnetron target





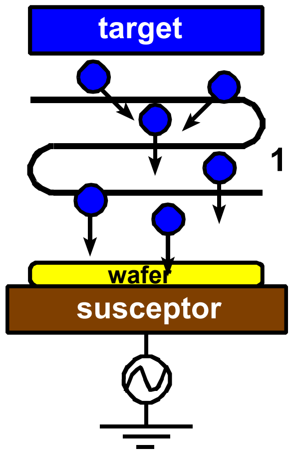
Target, diameter approx. 400 mm

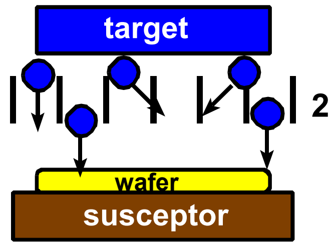
The angular distribution of sputtered atoms

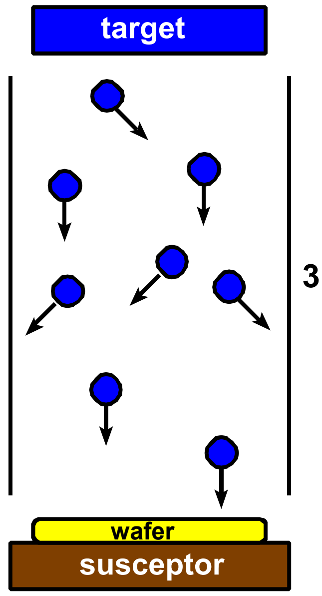


Angular distributions of sputtered Si atoms for 3 keV, Ar^+ ion bombardment at an incident angle of 60

Thin Film Deposition: Sputtering – advanced techniques







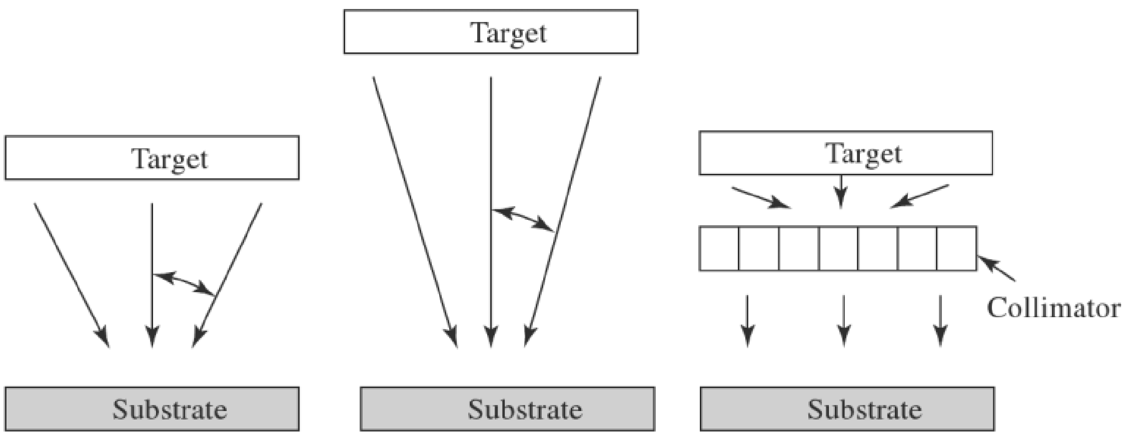
1 water-cooled RF-electrode 1,985 MHz
2 collimator
3 chamber wall

ionized metal deposition | *collimated sputtering* | *long throw sputtering*

Modern principles to coat contact and via holes with a high aspect ratio (e.g. TiN, TaN or WN barriers for the copper metallization)

Only target particles with a small angle to the substrate normal reach the surface !

The goal is to coat high aspect ratio patterns more conformally by more directional sputtering with narrow arrival angle distribution.



(a) (b) (c)

Figure 2.27. (a) Standard sputtering; (b) long-throw sputtering; (c) sputtering through a collimator [1].

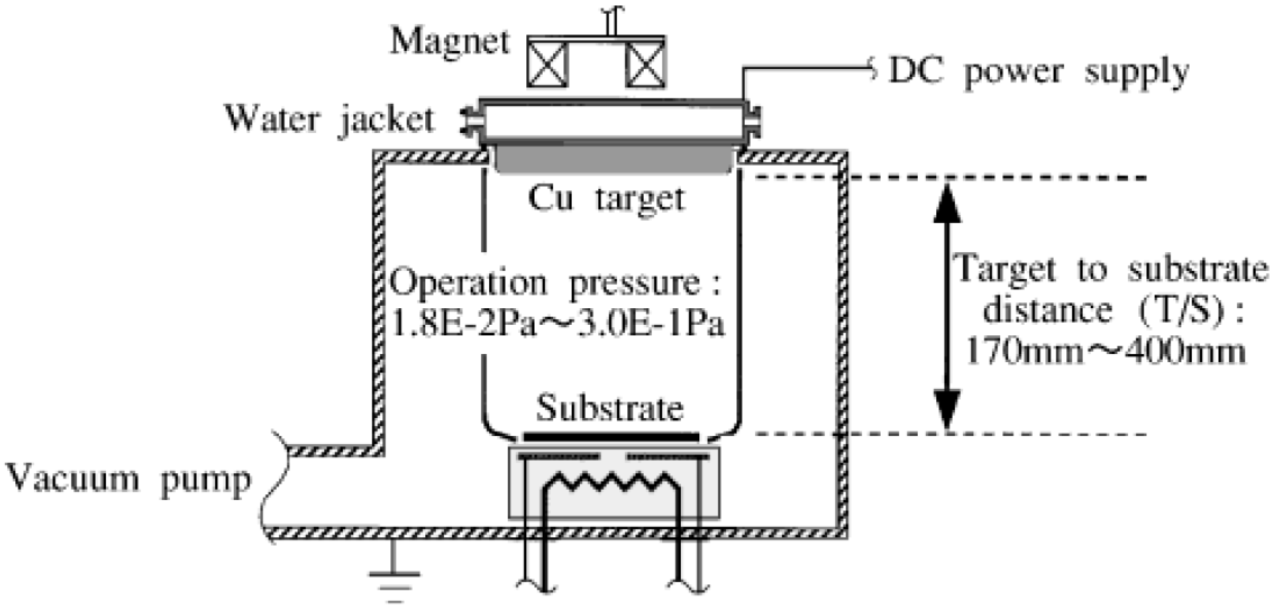


Fig. 1 Schematic diagram of low pressure long throw sputtering system.

T. Saito, Materials Transactions, Vol. 43, No.7 (2002) pp. 1599-1604

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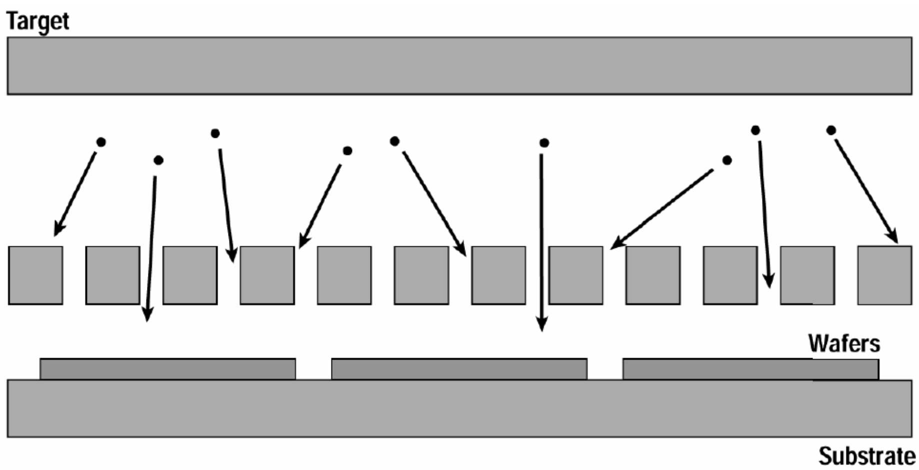
Collimated sputtering



- Insert a plate with high-aspect-ratio holes.
- Sputter at low pressure, mean path is long enough that few collisions occur between collimator and wafer.
- Species with velocities nearly perpendicular to wafer surface pass through the holes.
- Reduce deposition rate considerably (most sputtered atoms cannot reach the substrate).

ZfM Fraunhofer ENAS
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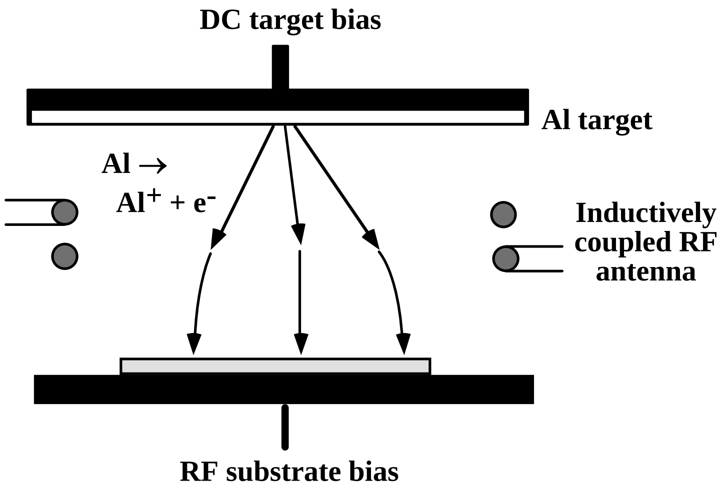
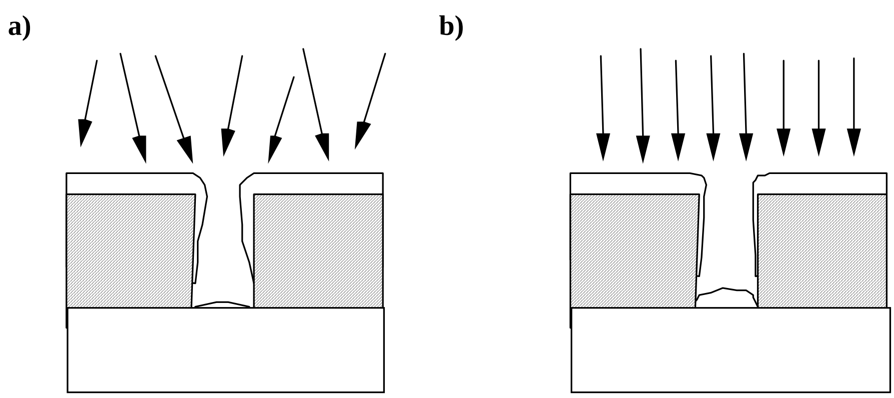
Ionized sputter deposition



- The depositing atoms themselves are ionized.
- An RF coil around the plasma induces collisions in the plasma, creating the ions (50-85% ionized).
- Most sputtered atoms can reach the substrate (better solution than a collimator).
- Provides a narrow distribution of arrival angles, which may be useful when filling or coating high AR patterns.

(a) Regular sputter deposition.

(b) Sputter deposition, by using long throw configuration, a collimator, or ionized sputter deposition.



Reactive sputtering

From a metallic target

Deposition of a compound, which derives from target material and reactive gas

TiN (Ti in Ar/N_2)

TaN (Ta in Ar/N_2)

From a compound target

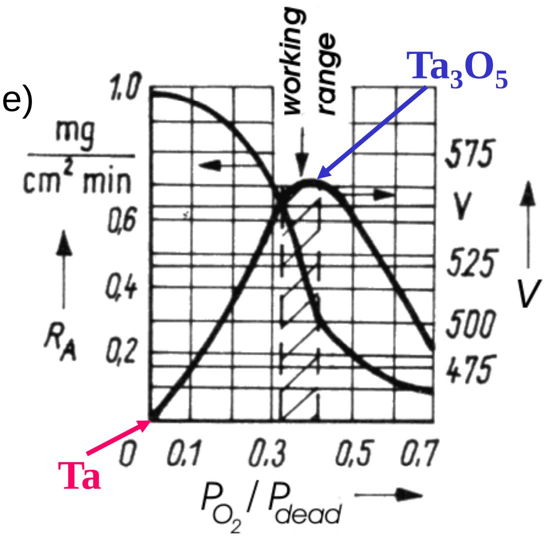
Prevention of the decomposition of the compound during sputtering: stoichiometric film deposition

SiO_2 (SiO_2 in Ar/O_2)

Reactive gases:

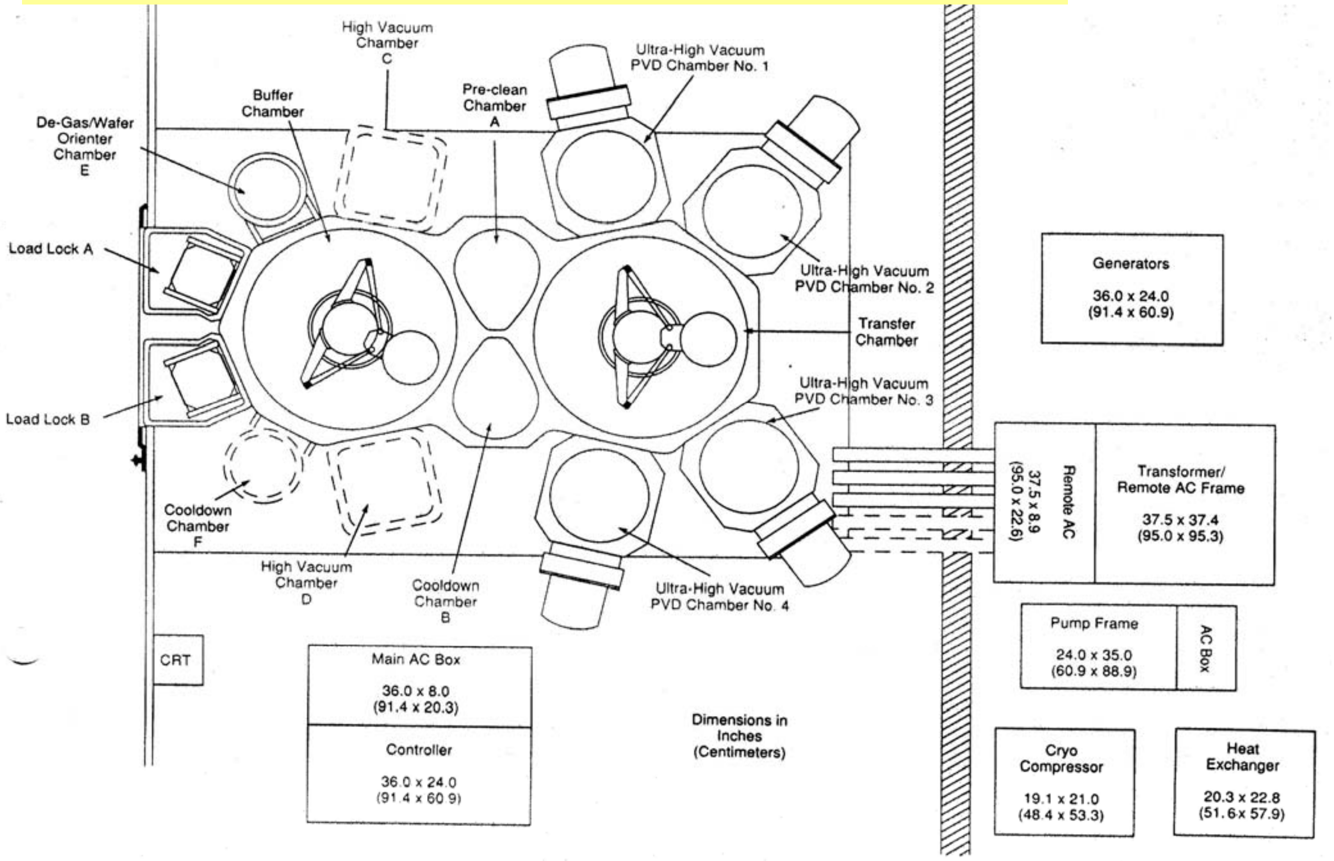
O_2 (oxide), **N_2 or NH_3** (nitride), **O_2/N_2** (oxynitride)
C_2H_2 or CH_4 (carbide), **SiH_4** (silicide)

- The reactive gas is consumed during film deposition.
- Compensation using a higher flow rate.
- Control of the reactive gas is realized using a selected emission line of the sputtered target atoms.
- This procedure is complex → a special adaptation to the used target-gas system is necessary.



Deposition rate, $V_{cathode}$ as a function of p_{O_2}/p_{tot} (p_{tot}= 0.3 Pa; P = 5 kW)

Sputtering Systems – Single wafer systems



Endura 5500: cluster tool. Applied Materials, USA

Endura 5500: cluster tool   Applied Materials, USA

Selected application examples for PVD

Microelectronic production

Al	→	**Interconnect lines**
W	→	**Interconnect lines (M0/M1)**
Cu	→	**seed layer for damascene structures (afterwards filling with electroplating)**
TiN	→	**barrier, seed layer (liner) for W-CVD, ARC** (antireflection coating)
Ta, TaN/Ta	→	**barrier against Cu diffusion / liner**
Ti, Co, Ni, Pt	→	**for silicide contacts**
TiW	→	**barriers (especially for the packaging)**