Chapter 5

Sputter Deposition Processes

What is Sputtering?

How are energetic particles generated

Efficient Trapping of Electrons leads to

Magnetron Sputter Deposition

~~Reactive Magnetron Sputter Deposition~~

~~Moving Towards the Substrate~~

Sputtered Deposited Thin Films:

Morphology and Microstructure

- Introduction
  - Physical Vapor Deposition: Vacuum Evaporation, Pulsed Laser Deposition
  - Magnetron Source: positive ions from Magnetically Enhanced Plasma hit the target, biased DC for conductive targets and RF for non-conductive
  - What is Sputtering?
    - Ejection of atoms from surfaces/targets by ion/particle bombardment

- Sputter Yield ϒ
- Ar$^+$ on Cu

$$Y = \frac{3}{4\pi^2}\alpha\frac{4M_1M_2}{(M_1+M_2)^2}\frac{E}{U_s}$$

U_s-surface binding energy

α-depends upon mass ratio and IE

α remains 0.2 for low energies

M_1=M_2 max momentum transfer

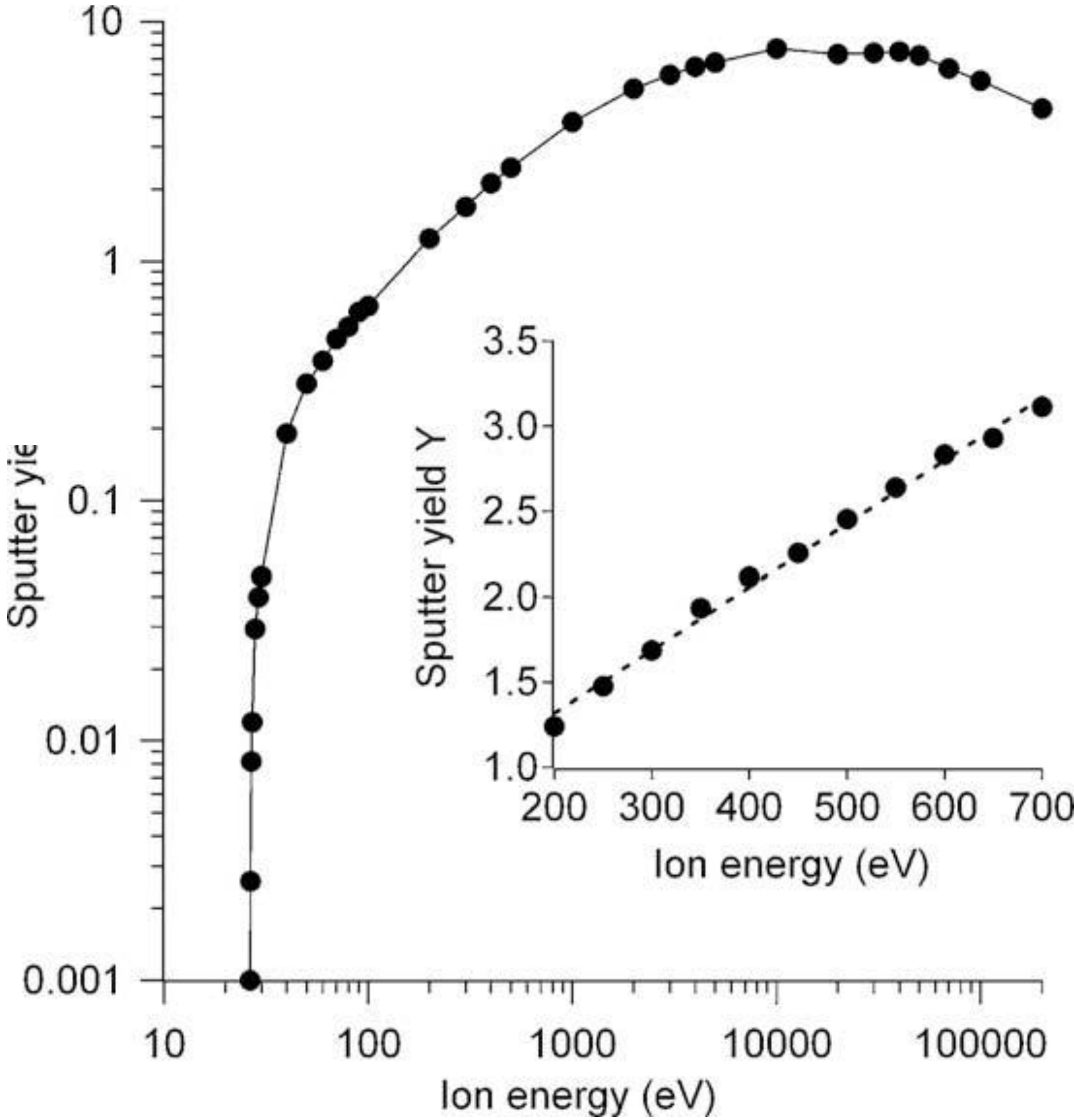


Figure 5.2: Sputtering yield *Y* of Cu as a function of the energy of Ar$^+$ at normal incidence as calculated using the SRIM code. Note that $Y(E_{Ar^+})$ is linear over the typical range of operation during magnetron sputtering (E_{Ar^+} = 250–750 eV).

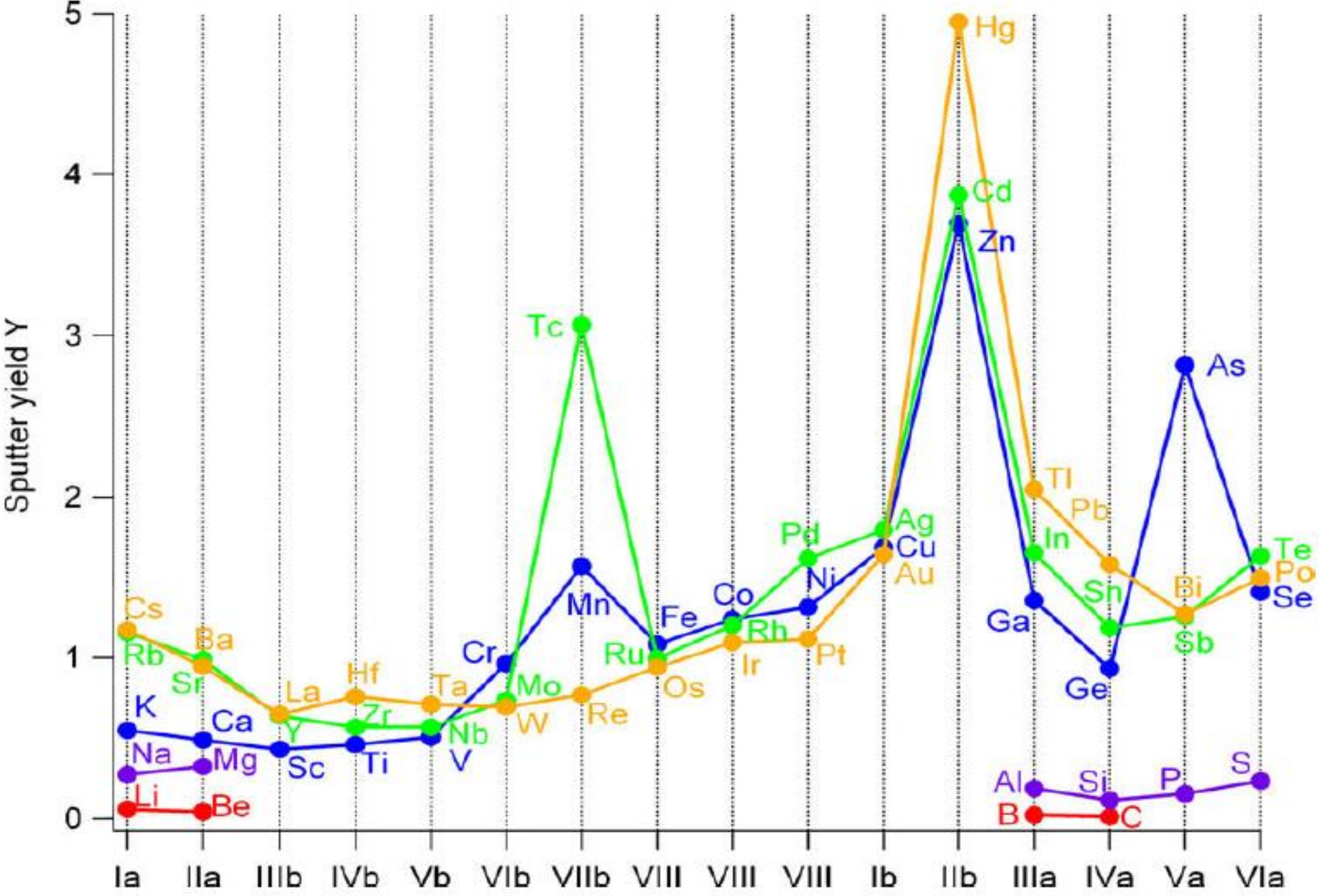
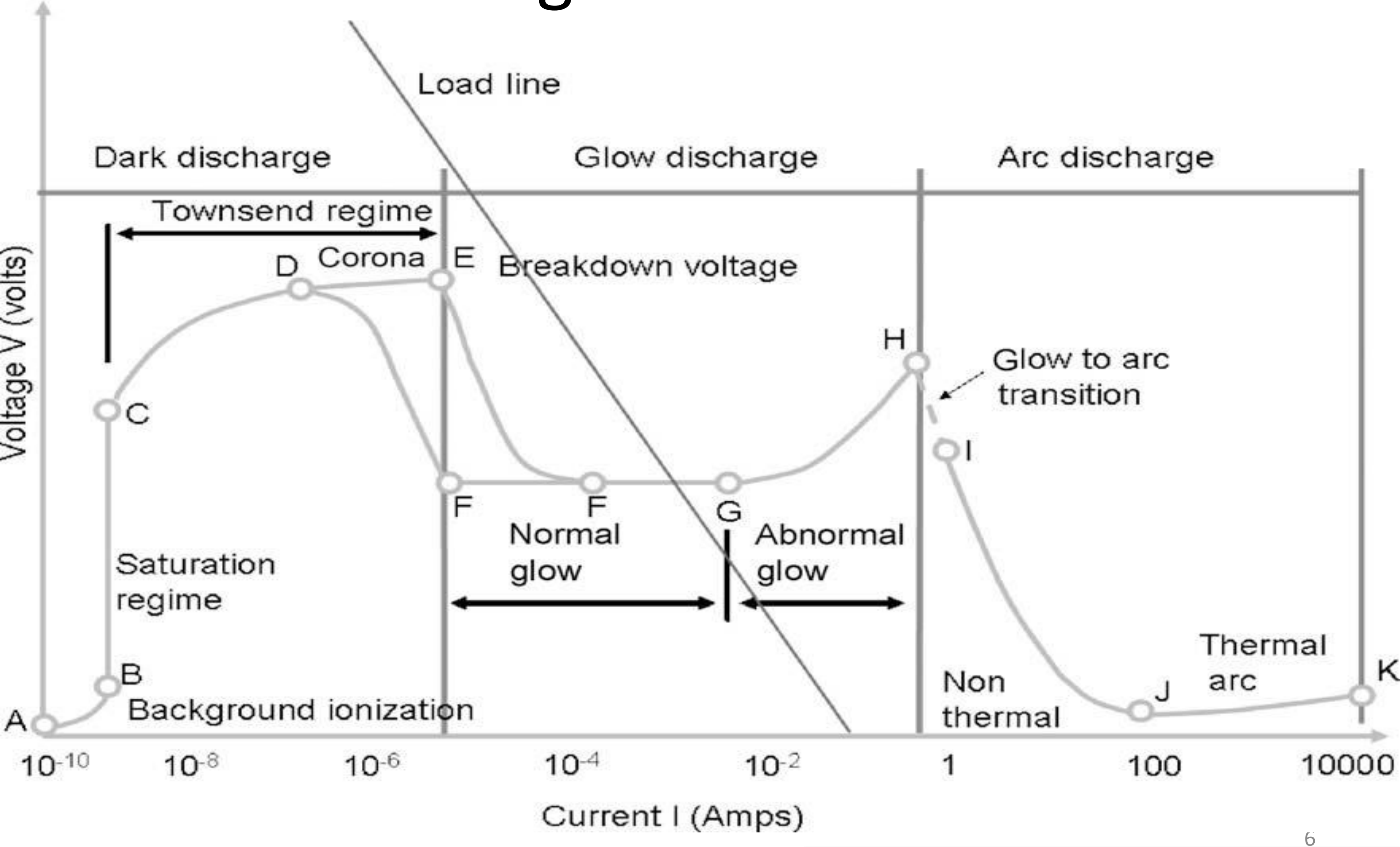


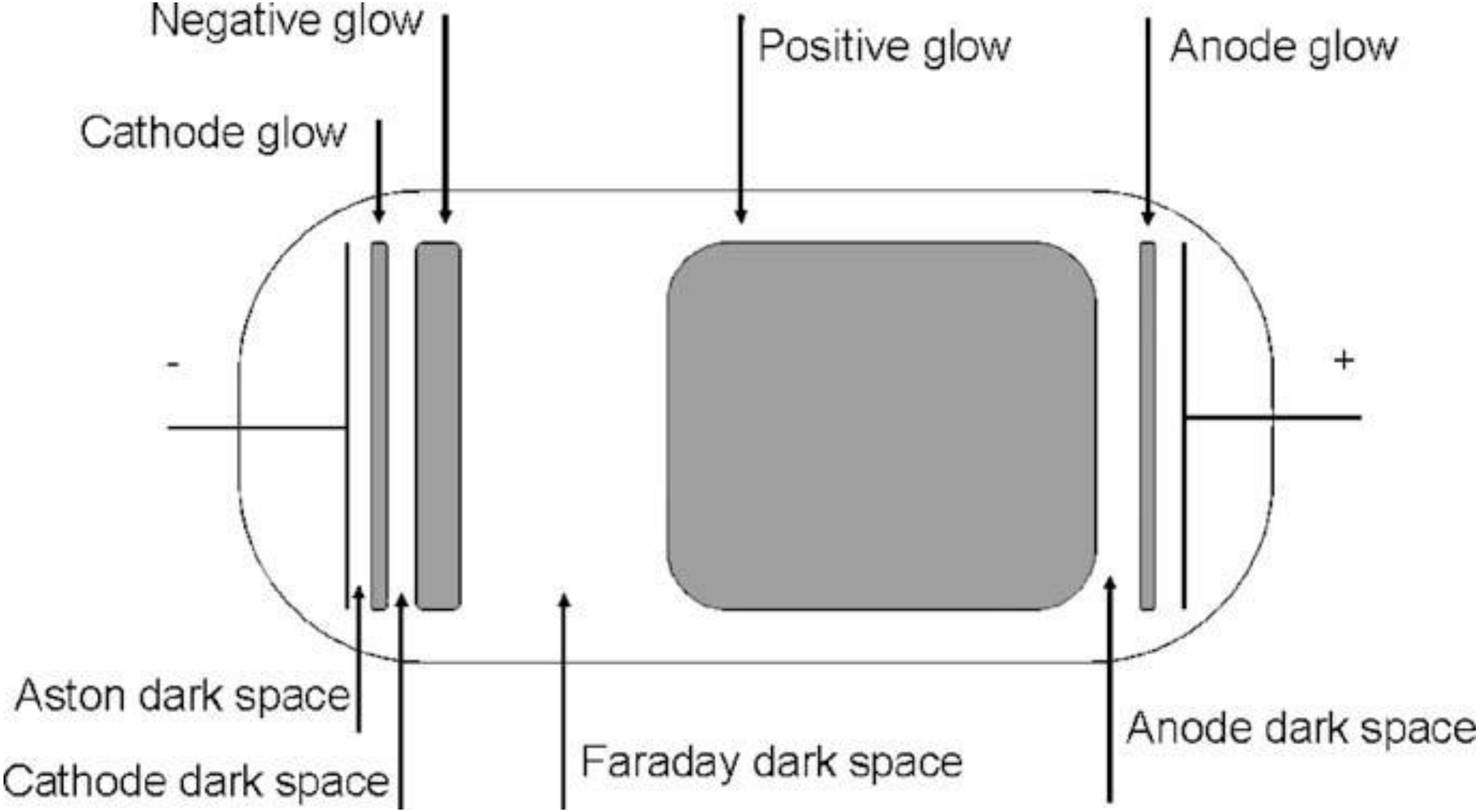
Figure 5.3: Dependence of the sputter yield of several elements (ordered according their position in the periodic table) calculated using SRIM (initial conditions: 300 eV Ar, other input parameters where set at the standard values given by SRIM: lattice binding energy, surface binding energy displacement energy, and normal incidence).

How are Energetic Particles generated?

- Ions from Ion Source
- Ions from Plasma
  - Cathode and Anode at opposite places in chamber
  - Base Pressure 10^{-4} Pa, Ar at 1-10 Pa
  - 2000 V, Glow Discharge
  - Main Characteristics of Discharge
    - Breakdown Voltage, I-V Characteristics, Structure of Discharge…depend upon
    - Geometry of Electrodes and Vacuum Vessel, Gas used, Electrode Material

How are Energetic Particles generated? DC Glow Discharge





$$V_{\text{breakdown}} = \frac{B\,Pd}{\ln(A\,Pd) + \ln\left(\ln\left[\frac{1}{\gamma} + 1\right]\right)}$$

How are Energetic Particles generated?

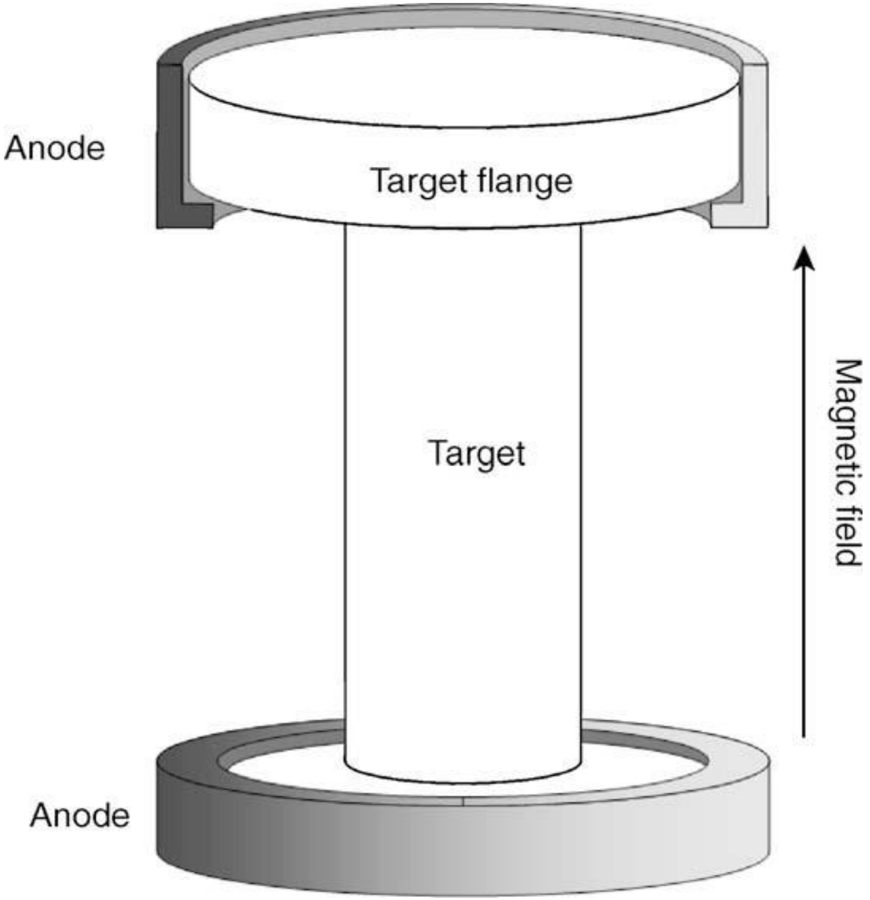
- Sputter yield is determined by the energy and mass of the ions
- High Pressure-scattering-ion and sputtered atoms arrival
- High Discharge Voltage-Energetic electrons result higher e^- current density at Anode-Heating
- Magnetic Field traps e^-s, required Discharge Pressure decreases, Ion can reach cathode, Sputtering yield is Improved respectively Deposition Rate

Efficient Trapping of e$^-$s leads to Magnetron Sputter Deposition

- Post Magnetron

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$r_L = \frac{m v_\perp}{q B}$$



Post Magnetron

- Average e$^-$ loss per ionization W

$$\frac{eV_d}{W}\gamma_e = 1$$

Ion induced e$^-$
emission yield

$$V_{\mathrm{T}} = \frac{W}{e\gamma_{\mathrm{e}}\varepsilon_{\mathrm{i}}\varepsilon_{\mathrm{e}}}$$

Ion and e$^-$
collection efficiency

$$V_{\mathrm{T}} = \frac{W}{e\gamma_{\mathrm{e}}\varepsilon_{\mathrm{i}}\varepsilon_{\mathrm{e}}m}$$

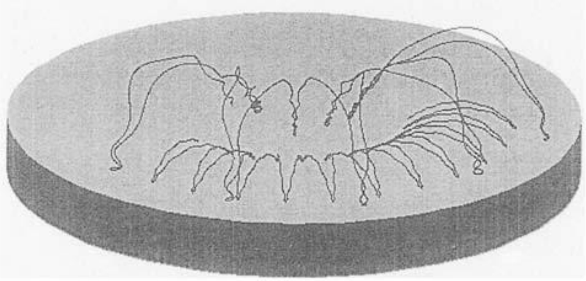
Multiplication Factor for
Sheath Ionization

$$V_{\mathrm{T}} = \frac{W}{e\gamma_{\mathrm{e}}\varepsilon_{\mathrm{i}}\varepsilon_{\mathrm{e}}mf}$$

Effective ionization
probability

Planar Magnetrons

- Permanent magnets are generally placed behind the target. For a circular target, there is a central disk magnetic pole and an annular pole so that the magnetic field lines between the poles have a circular symmetry
- Parallel and Vertical Components of B
- Electromagnetic Bottle
- Resulting Max. Ionization


(a)


(b)

Planar Magnetrons

- For Circular Magnetron, Torus Shaped Plasma is formed-racetrack
- Stronger B as material erodes i.e. recedes towards magnet. Erosion rate increases with sputtering time

- Rotating Cylinder Magnetrons
- Rotating cylindrical target around stationary magnet
- A complex target design and fabrication

General Features of Magnetrons and Magnetron Discharges

- Discharge Voltage
  - Groove formation-Higher B-more e^-s at target-sheath ionization is high-m is high-V is low
  - Depends upon target material(Ion induced e^- emission yield) and its condition
- I-V Characteristics
  - At constant pressure

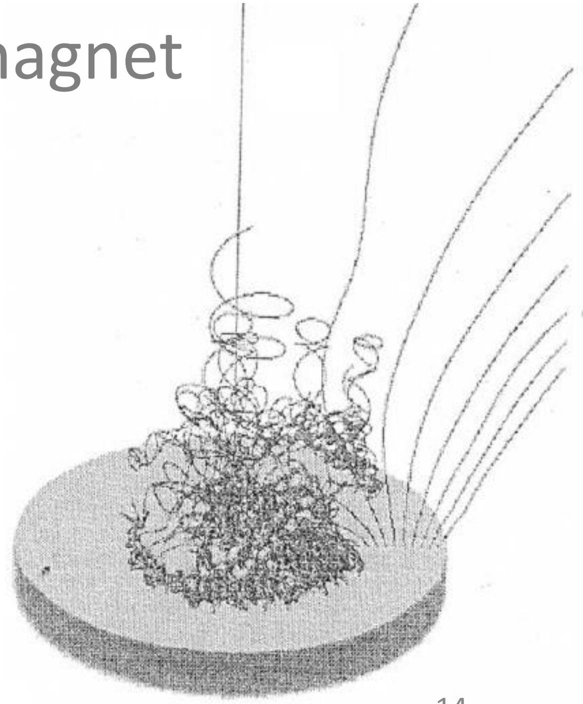
    $I=kV^n$ Magnetron Efficiency=10
  - Low B, n increases with P
  - High B, n decreases with P

General Features of Magnetrons and Magnetron Discharges

- Magnet Balance
  - e^{-}s are lost from target area i.e. only low energy e-s are present in bulk plasma region and in the vicinity
  - Unbalancing the magnetron configuration i.e. Changing the B in inner versus outer magnet
  - e^{-}s escape towards substrate

1.Tuning the e- flux and ion flux

$$K = \frac{\Phi_{\text{out}}}{\Phi_{\text{in}}} = \frac{\int_{S_{\text{out}}} B_{\perp \text{out}} \, dS_{\text{out}}}{\int_{S_{\text{in}}} B_{\perp in} \, dS_{\text{in}}}$$

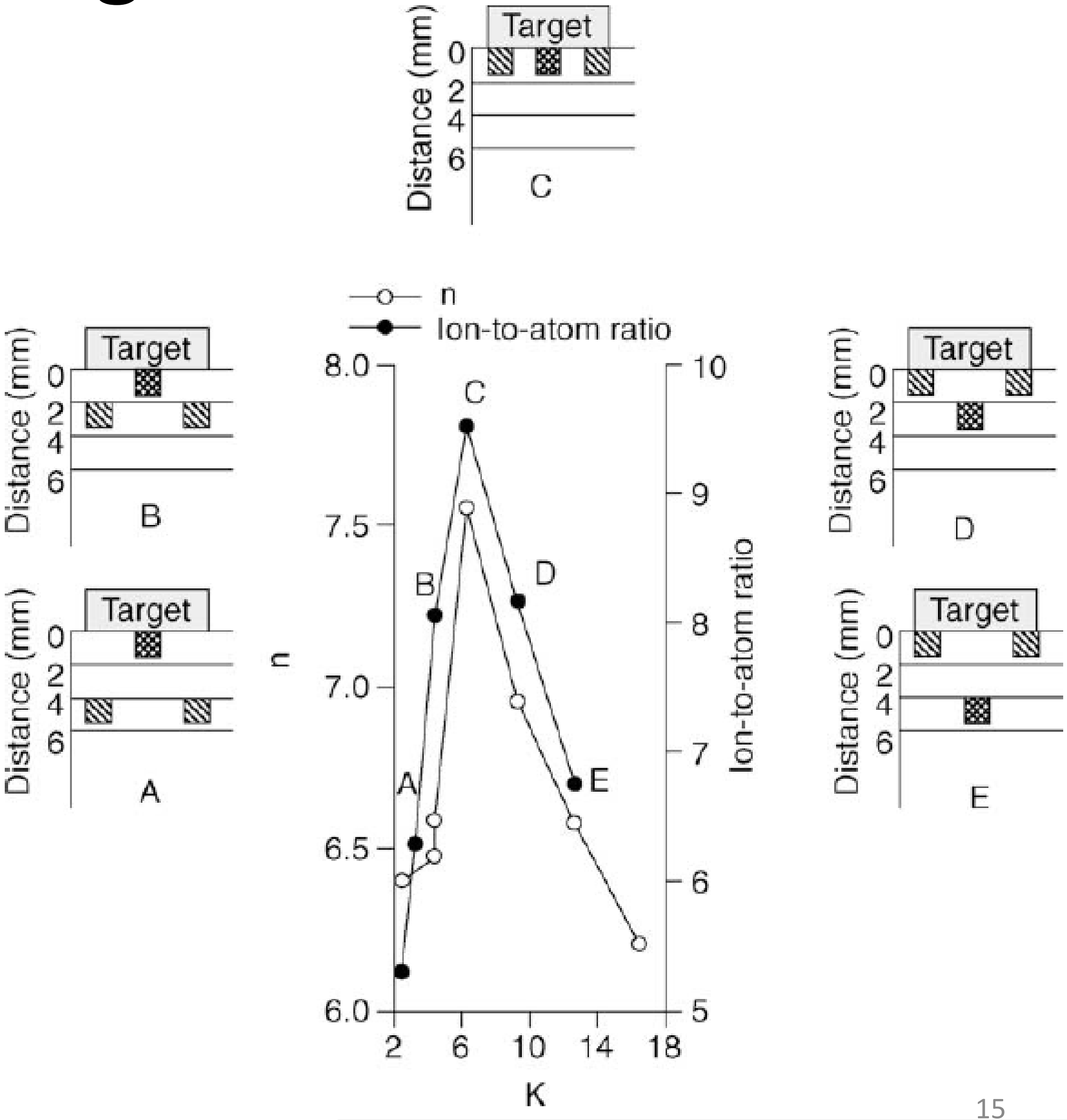


General Features of Magnetrons and Magnetron Discharges

- Magnet Balance

2.Shifting the inner and outer magnets

3.Helmholtz Coils



Moving towards the Substrate

- SiMTRA (Simulation of Metal Transport)
  - Energy, Direction and Flux of sputtered particles
  - Assumes the sputtered particles are neutrals in ground state and undergo elastic collision with neutral gas atoms

  For DC

  1. Degree of ionization is very low i.e. 0.1 %
  2. Sputtered particle density is much less than that from gas i.e. 10^{-4}

  - Trajectory is straight terminated by binary elastic collision with a gas atom until deposits

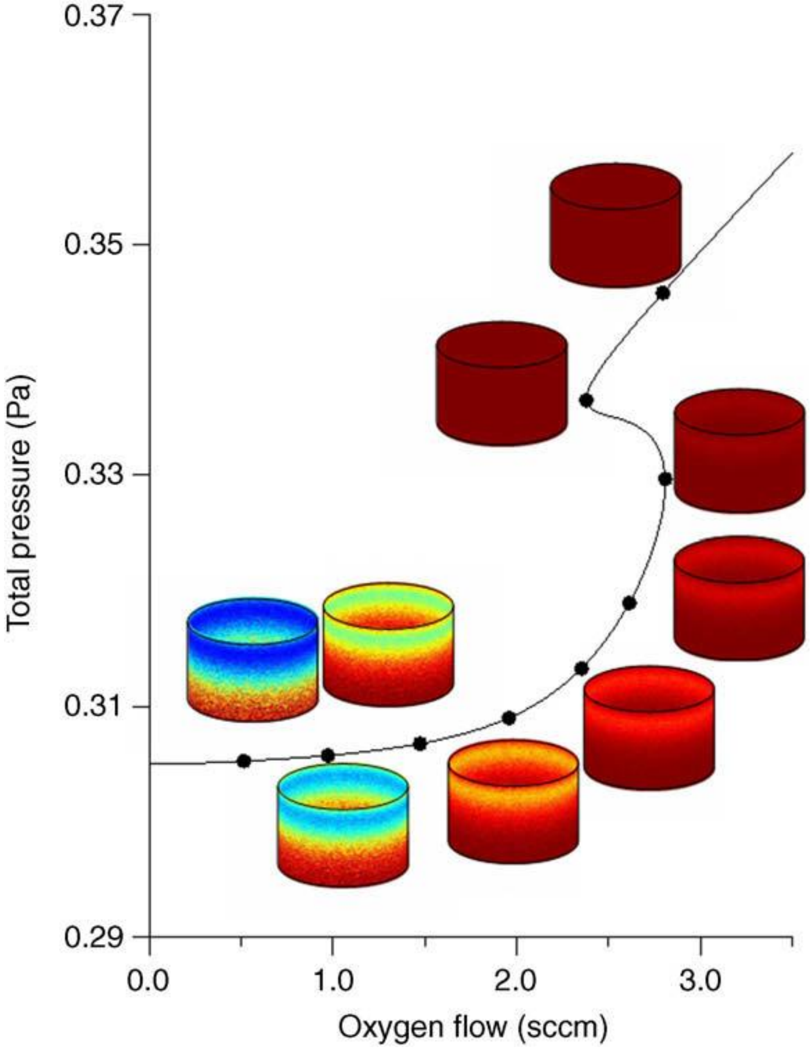


Figure 5.19: By placing a 5 cm diameter magnetron source in the upper part of a tube, the surface on which material is deposited is well defined, and the influence of the area of this surface and the deposition profile on the hysteresis behavior during reactive magnetron sputtering can be studied. The illustrations shows the result of a simulation in which the deposition profile is included. The oxidation of the deposited target material is shown on the cylinder. Black represents a fully oxidized surface, while white represents a pure metal surface. Experimental conditions: constant argon pressure 0.3 Pa, constant discharge current 0.43 A, pumping speed, 100 l/s. The tube had a diameter of 26 cm and a height of 53 cm. The oxygen was introduced at the bottom of the tube. The target material was Al.

Moving towards the Substrate

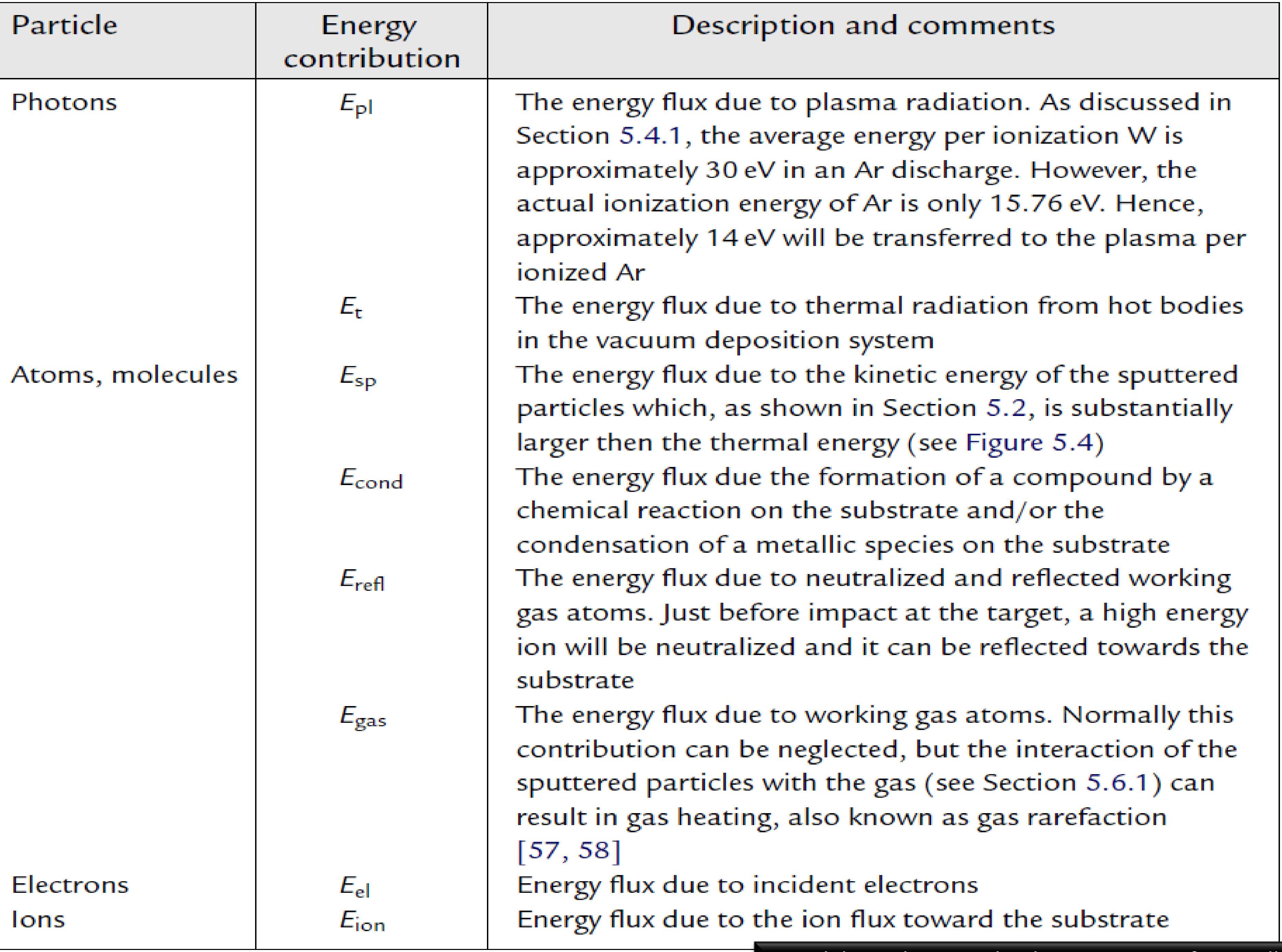
- SiMTRA (Simulation of Metal Transport)
  - Free Path Length λ $\lambda = -\lambda_m \ln r_1$ depends upon v_s/v_p i.e. if $v_s>5v_p$, gas is stationary, otherwise thermal
  - Energy of sputtered particles lies below 3/2kT, particle is thermalized
- Other species

$$E_{\mathrm{tot}} = E_{\mathrm{cond}} + E_{\mathrm{pl}} + E_{\mathrm{t}} + E_{\mathrm{sp}} + E_{\mathrm{refl}} + E_{\mathrm{gas}} + E_{\mathrm{el}} + E_{\mathrm{ion}}$$

Mahieu et al. by

Langmuir probe, RFA, QMB, ER MS

On TiN films



Particle	Energy contribution	Description and comments
Photons	E_{pl}	The energy flux due to plasma radiation. As discussed in Section 5.4.1, the average energy per ionization W is approximately 30 eV in an Ar discharge. However, the actual ionization energy of Ar is only 15.76 eV. Hence, approximately 14 eV will be transferred to the plasma per ionized Ar
	E_t	The energy flux due to thermal radiation from hot bodies in the vacuum deposition system
Atoms, molecules	E_{sp}	The energy flux due to the kinetic energy of the sputtered particles which, as shown in Section 5.2, is substantially larger then the thermal energy (see Figure 5.4)
	E_{cond}	The energy flux due the formation of a compound by a chemical reaction on the substrate and/or the condensation of a metallic species on the substrate
	E_{refl}	The energy flux due to neutralized and reflected working gas atoms. Just before impact at the target, a high energy ion will be neutralized and it can be reflected towards the substrate
	E_{gas}	The energy flux due to working gas atoms. Normally this contribution can be neglected, but the interaction of the sputtered particles with the gas (see Section 5.6.1) can result in gas heating, also known as gas rarefaction [57, 58]
Electrons	E_{el}	Energy flux due to incident electrons
Ions	E_{ion}	Energy flux due to the ion flux toward the substrate

Morphology and Microstructure

- Structure Zone Models
  - Diagram that summarizes influence of deposition parameters on film Morphology and Microstructure
  - Thornton-as a function of pressure and temp.
  - Mahieu-ESZM-film growth
- Zone I Films
  - Hit and stick method (shadowing)
  - Small crystallites, amorphous appearance
  - Density can be improved by Bombardment of energetic particles-reorganization/destroying the overhang structure
  - Increasing Energy Flux mobilizes the adatom resulting compact crystalline islands
  - Normal growth rate depends upon
    - Sticking coefficients *S* vs adatom mobility
    - Mobility

Morphology and Microstructure

- Zone T Films
  - Crystallographic Orientation
  - Clearly faceted surface
  - V shaped columns
- Zone II Films