Plasma Physics

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Definitions

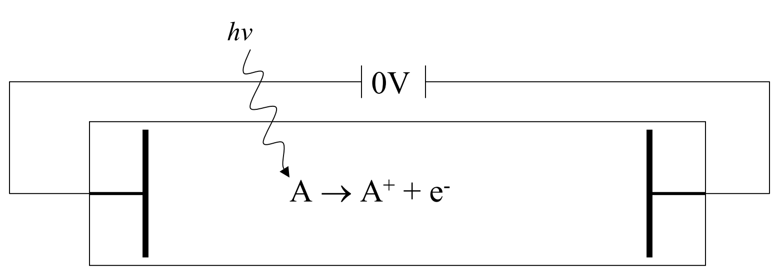
- Plasma - partially ionized gas containing an equal number of positive and negative charges, as well as some other number of none ionized gas particles
- Glow discharge - globally neutral, but contains regions of net positive and negative charge
- **Most thin film processes utilize glow discharges, but "plasmas" and "glow discharges" are often used interchangeably**

Plasma Properties

- Plasma Density (n) – number of species/cm3
  - $10^7 - 10^{20}$
  - Typical glow discharges and arcs have an electron and ion density ~ $10^8 - 10^{14}$

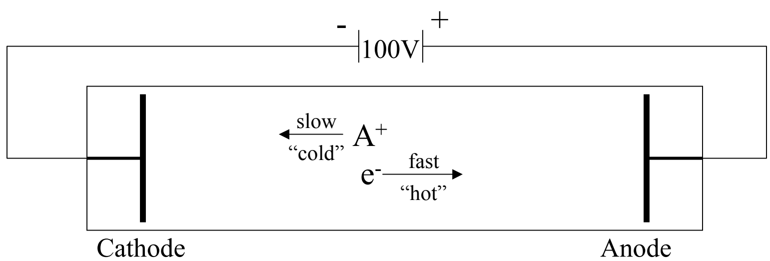
DC Glow Discharge

- Before application of the potential, gas molecules are electrically neutral and the gas at room temperature will contain very few if any charged particles. Occasionally however, a free electron may be released from a molecule by the interaction of, for example, a cosmic ray or other natural radiation, a photon, or a random high energy collision with another particle.



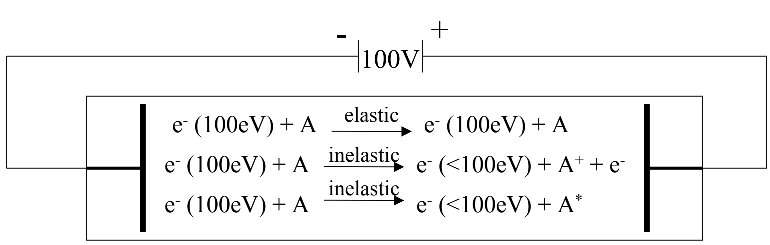
DC Glow Discharge

- When a large voltage is applied between the electrodes, say 100 V/cm, any free electrons which may be present are rapidly accelerated toward the anode. They quickly attain high velocity (kinetic energy) because THEY HAVE SUCH LOW MASS. Since kinetic energy can be related to temperature, the electrons are “hot” - they achieve extremely high temperatures because of their low mass, in an environment of heavy, slow-moving “cold” gas molecules.



DC Glow Discharge

- Electrons begin to collide with gas molecules, and the collisions can be either elastic or inelastic.
  - Elastic collisions deplete very little of the electron’s energy and do not significantly influence the molecules because of the great mass difference between electrons and molecules: Mass of electron = 9.11 e-31 kg, Mass of Argon = 6.64e20 kg.
  - Inelastic collisions excite the molecules of gas or ionize them by completely removing an electron. (The excitation - relaxation processes are responsible for the glow)



$A^* \longrightarrow$ A + photon (glow)

Ionization and Plasma Current

$$i = i_0 \frac{\exp(\alpha d)}{[1-\gamma_e(\exp \alpha d - 1)]}$$

<u>Townsend Equation</u>

where

α = Townsend ionization coefficient

γ_e = Townsend secondary-electron coefficient

d = distance between electrodes

i_0 = initial current

$$\alpha = \frac{1}{\lambda}\exp\left(\frac{-V_i}{qE\lambda}\right)$$

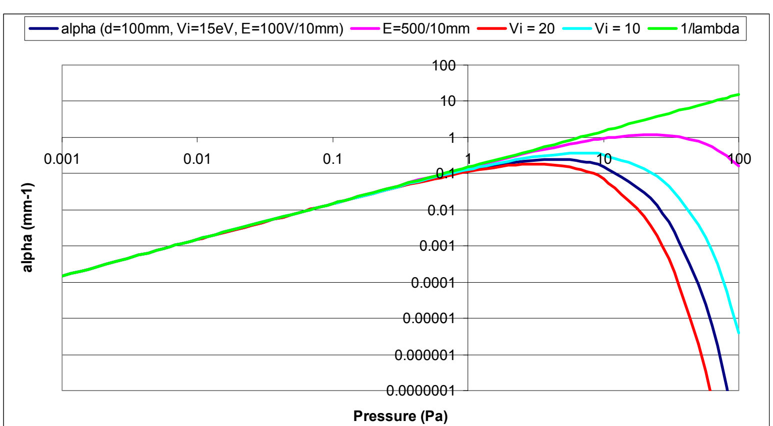
V_i = ionization potential

q = electron charge

E = electric field

λ = mean free path

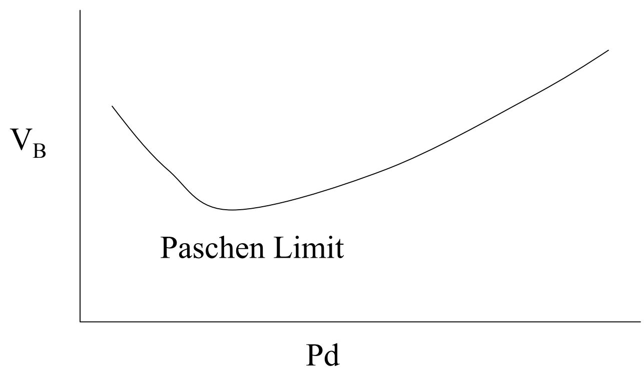
Townsend Ionization Coefficient



The probability per unit length of ionization occurring during an Electron-gas collision. Increase Field, decrease Ionization Potential you will increase α. At low pressure α approaches the mean free path.

Paschen Curve

$$V_B = \frac{APd}{\ln(Pd) + B}$$



DC Glow Discharge

- Other electron/particleinelastic events

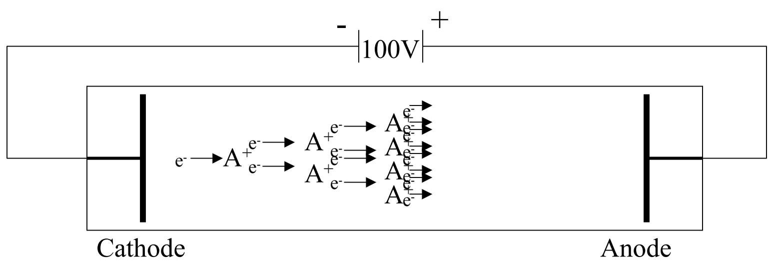
e^- (100eV) + AB $\xrightarrow{\text{inelastic}}$ e^- (<100eV) + A + B + e^- — Dissociation/ Fragmentation

e^- (100eV) + AB $\xrightarrow{\text{inelastic}}$ e^- (<100eV) + A^+ + B + $2e^-$ — Dissociative Ionization

e^- (100eV) + AB $\xrightarrow{\text{inelastic}}$ e^- (<100eV) + A^+ + B^- + e^- — Dissociative Ionization with Attachment

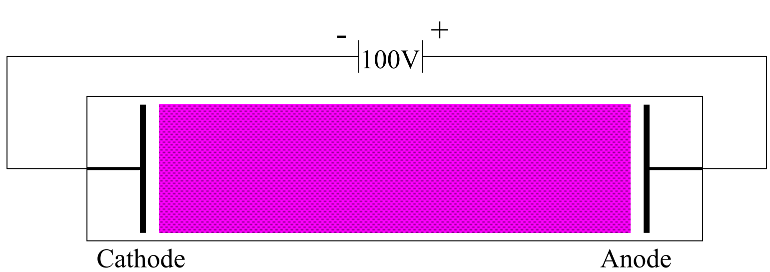
DC Glow Discharge

- Newly produced electrons are accelerated toward the anode and the process **cascades** (Breakdown).



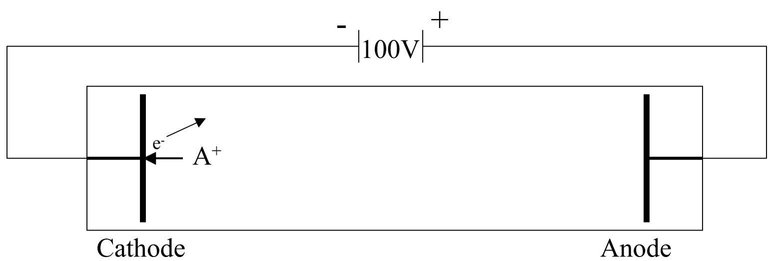
DC Glow Discharge

- With sufficient voltage, the gas rapidly becomes filled with positive and negative particles throughout its volume, i.e. it becomes ionized.



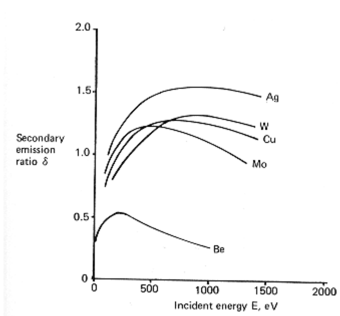
DC Glow Discharge

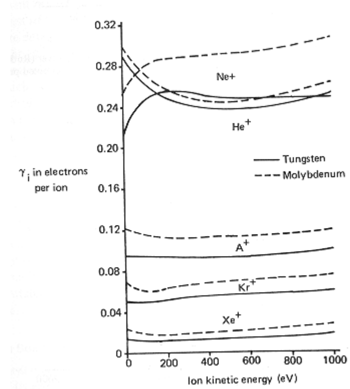
- Positive ions are accelerated toward the negative electrode (cathode). Collision with the cathode causes the emission of **secondary electrons** which are emitted from the cathode into the plasma.



Secondary Electron Coefficient

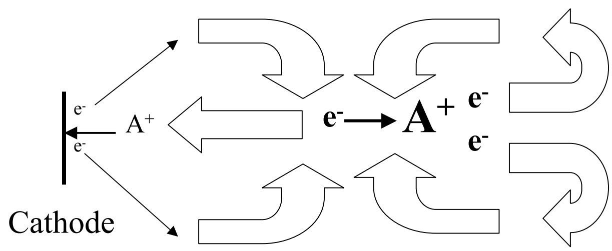
- Secondary Electron Coefficient (δ) vs Incident **Electron** Energy
- Secondary Electron Coefficient (γ_i) vs Incident **Ion** Energy





DC Glow Discharge

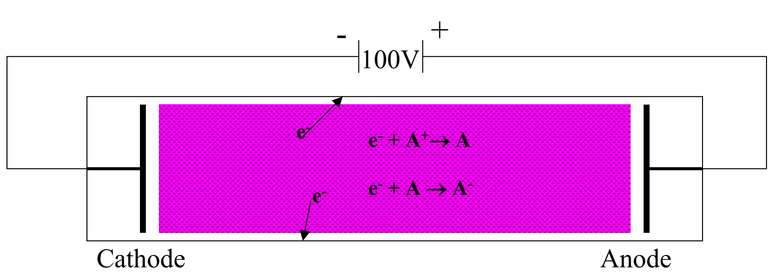
- Free electrons from secondary emission and from ionization are accelerated in the field to continue the above processes, and a steady state self-sustaining discharge is obtained.



Plasma Physics

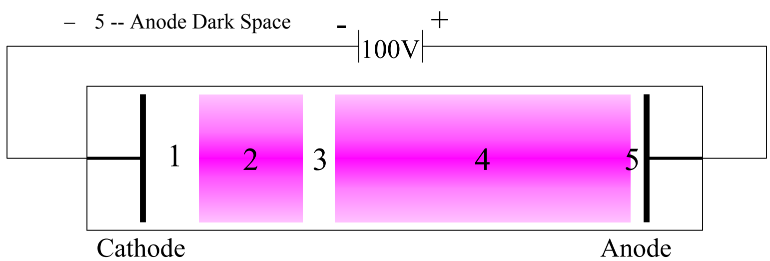
DC Glow Discharge

- Electrons are lost by: (a) Drift and diffusion to the chamber walls, (b) recombination with positive ions, (c) attachment to neutral molecules to form negative ions.

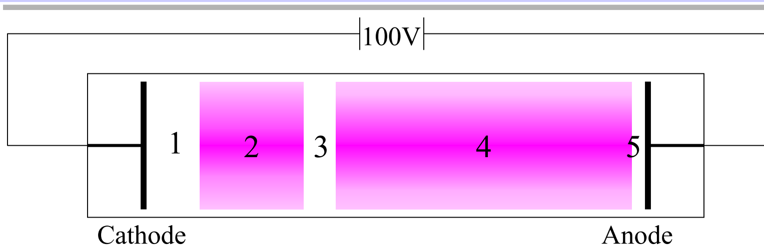


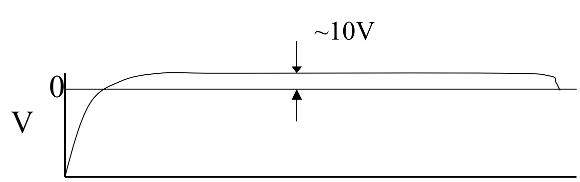
DC Glow Discharge Regions

- The glow discharge, overall, must always remain neutral, although portions of it may be charged negatively or positively.
- Glow Discharge Regions
  - 1 -- Cathode Dark Space (Crooke's Dark Space)
  - 2 -- Negative Glow
  - 3 -- Faraday Dark Space
  - 4 -- Positive Column
  - 5 -- Anode Dark Space



Current and Potential Distributions in a DC Glow Discharge





Most of the voltage drop is across the cathode dark space

Plasma Species

- A plasma contains:
  - Neutral Atomic and/or molecular species
  - An equal number of (+) ions and (-) electrons
- Degree of ionization:
  - $f_i = n_e/(n_e+n_0)$, where: n_e is the number of electrons and n0 is the number of neutral atoms or molecules.
  - Typical glow discharge 10mTorr (n_0~10^{14} cm^{-3}) and f_i=10^{-4}
  - High density plasmas can reach 10^{-2} or electron densities of $10^{12}/cm^3$

Particle Energies and Temperatures

- Electrons
  - Energy: E_e 1-10eV with an average temperature of ~ 2eV
  - Temperature: E=2eV, T = E/k_B: T= ~ 23,000K
- Neutral particles
  - E~0.025eV
  - Temperature = room temperature (293K)

DC versus RF Plasmas

- Insulating materials will not sustain a plasma
  - Ion current charges the insulator positively and ultimately extinguishes the plasma (ie. Can not bleed off charge)
- Use rf power to deposit insulating materials

RF Plasma

- At frequencies > 100kHz electrons respond and ions do not
  - Typical rf frequency - 13.56 MHz (designated by FCC)
- High mobility of electrons causes a dc "self bias" to develop on target after the first ac cycles(~1/2 rf peak-to-peak)

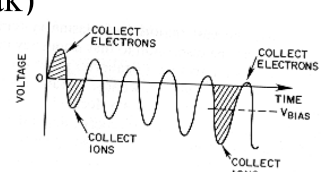


Fig. 9. The potential on the powered electrode of Fig. 8b as a function of time for the first several rf cycles.

Magnetic Field Effects

- Magnetic field strength (B) superimposed on the electric Field (*E*)
  - Lorentz force (F)

$$\overline{F} = m\frac{dv}{dt} = -q(\vec{E} + \vec{v} \times \vec{B})$$

where:

q is chare of particle

v is particle velocity

E is electric field vector

B is magnetic field vector

Magnetrons

- Magnetic fields change trajectory of electrons in a magnetic field
  - Imposing a magnetic field effectively increases the distance an electron travels, this in turn increases the ionization rate (and subsequently the sputtering rate)

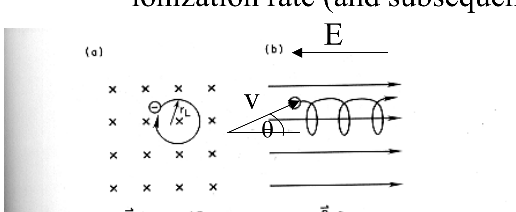


Fig. 23. (a) The motion of an electron in a magnetic field oriented perpendicular to the page. (b) The same motion viewed from the side. The motion along the direction of the magnetic field line is unaffected by the field.

$$r = \frac{mv\sin(\theta)}{qB}$$

Various Magnetron Configurations

- Planar Magetron

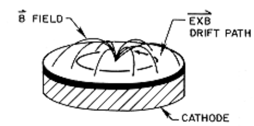


Fig. 30. A circular planar magnetron cathode, showing the shape of the magnetic field and the resulting drift path. Not shown is the plasma (close to the cathode) or the power supplies and anode.

- Enhanced rate in high ion region

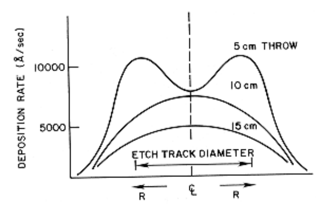


Fig. 33. The deposition profile on a sample in front of a magnetron cathode as a function of sample distance.

Plasma Physics

Various Magnetron Configurations

- S-gun

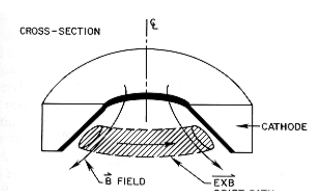


Fig. 37. S-gun class of conical magnetrons.

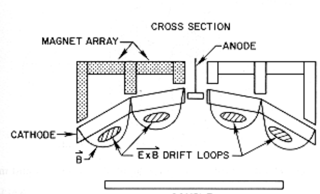
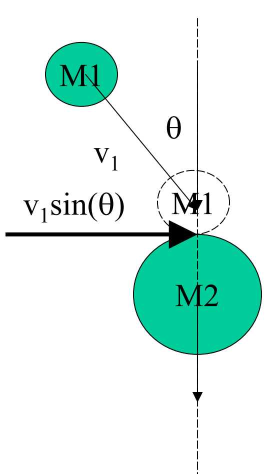


Fig. 38. An S-gun type of magnetron with two $\hat{E} \times \hat{B}$ drift paths on the same axis.

Collision Processes

- Elastic – (billiard ball collisions) – only kinetic energy is exchanged. Conservation of both momentum and translational kinetic energy.
- Inelastic – change in the internal (potential) energy of the particles change (ionization, excitation, dissociation…)

Elastic Collisions



$$\frac{E_2}{E_1} = \frac{\frac{1}{2}M_2 v_2^{\,2}}{\frac{1}{2}M_1 v_1^{\,2}} = \frac{4M_1M_2}{(M_1+M_2)^2}\cos^2\theta$$

where:

$$\frac{4M_1M_2}{(M_1+M_2)^2} = \gamma$$

where γ is the energy transfer function

Electron mass << ion/molecule, therefore γ is ~ 10^{-4}

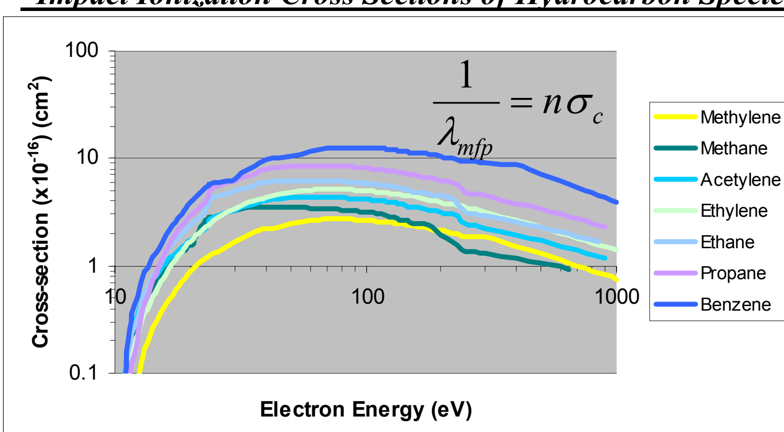
Inelastic Collisions

$$\frac{\Delta U}{\frac{1}{2}M_1 v_1^{\,2}} = \frac{M_2}{M_1 + M_2}\cos^2\theta$$

If M1 is an electron and M2 is an ion (M2 >> M1) the energy Transferred from an electron to an atom or molecule can approach Unity for θ = 0.

Cross-Sections

Impact Ionization Cross Sections of Hydrocarbon Species



*Y.-K. Kim1, K. K. Irikura2, and M. E. Rudd3
http://physics.nist.gov/PhysRefData/Ionization/Xsection.html

Inelastic Events

- Ionization
- Dissociation
- Vibrational
- Rotational
- Dissociative ionization
- Dissociative ionization with attachment

Chemical Reaction Rates

Bi-molecular Reactions:

A+B →P

$$\frac{dn_p}{dt} = k_{AB}(T)n_A n_B$$

where k_{AB} is the thermally activated reaction rate constant $k_{AB}(T) = k_0 \exp\left(-E/kT\right)$

Chemical Reaction Rates

Electron stimulated reactions:

e- + A →P

$$\frac{dn_p}{dt} = k(e,T)n_e n_A$$

$$k(e,T) = \int_0^\infty f(E_e)v_e(E)\sigma_T(E)dE$$

where:

$f(E_e)$ is the electron energy distribution

$v_e(E)$ is the electron velocity distribution

$\sigma_T(E)$ is the total electron collisional cross-section

Electron Stimulated Reactions

SF6 + e →SF_5 + F + e, Si + 4F→SiF_4↑