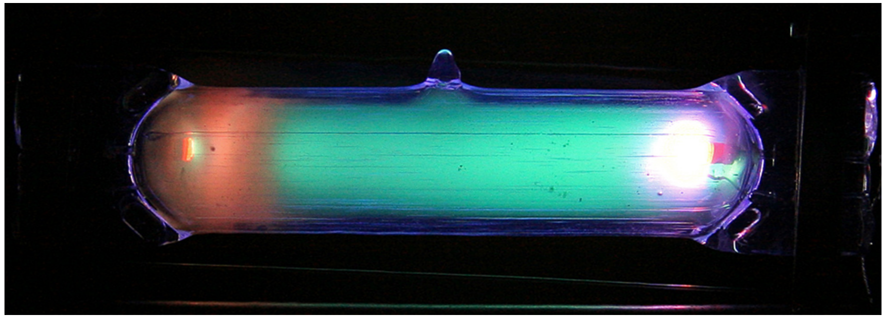
Chapter VI: Cold plasma generation

Introduction

- This photo shows the electrical discharge inside a high-pressure mercury vapor lamp (Philips HO 250) just after ignition (Hg + Ar)



Anode Positive column Cathode

http://flickr.com/photos/37643027@N00/316288117

1. *DC Glow discharges*

1.1 Discharge in a tube of length L

From: “Industrial Plasma Engineering”, J. Reece Roth, ISBN: 0 7503 0317 4

LOW PRESSURE ELECTRICAL DISCHARGE 149

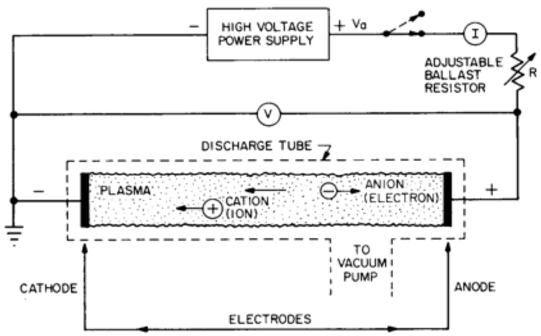
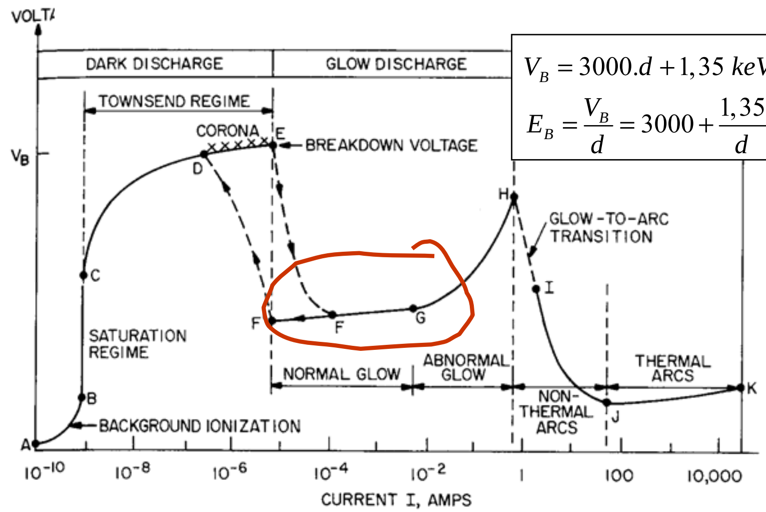


Figure 4.11 Schematic of the low pressure electrical discharge tube.



$$V_B = 3000.d + 1,35\ keV \quad for \quad air$$

$$E_B = \frac{V_B}{d} = 3000 + \frac{1,35}{d} \quad \text{kV/m}$$

Figure 10.1 Universal voltage–current characteristic of the DC electrical discharge tube.

1. *DC Glow discharges*

1.2 I-V Characteristics

A-B: Background ionization regime (XRay or gamma): electrons & ions created are swept out by the voltage.

B-C: V ↑, I = cst. → no new charge creation → electrons & ions are removed from the discharge volume, and electrons do not have enough energy to multiply.

C-E: Townsend regime: e + neutral gaz → N x e + gas+ → I ↑.

[D,E]: Electric field at sharp points, edges: → breakdown strength is exceeded locally: CORONA discharge.

E: Electrical breakdown: “Avalanche”: secondary electrons are injected into the tube, originating from the bombardment of cathode by ions

So far: no glow → DARK DISCHARGE

E-F: [Neutral gas]** ↑↑ → glow

F: Only the rim of the cathode is covered by the plasma

F-G: Plasma covers the whole cathode

(F, F-G: V ≈ Cst, mA/cm^2≈cst)

G-H: Abnormal glow regime: V ↑ if I ↑

H: Cathode starts to emit thermo-electrons → [e] ↑, V ↓

H-J: Non thermal equilibrium: Te > Ti = Tg

J-K: Thermal Arc: Te = Ti = Tg : all species are in thermal equilibrium.

1. DC Glow discharges

1.3 Characteristics of a low pressure DC glow discharge

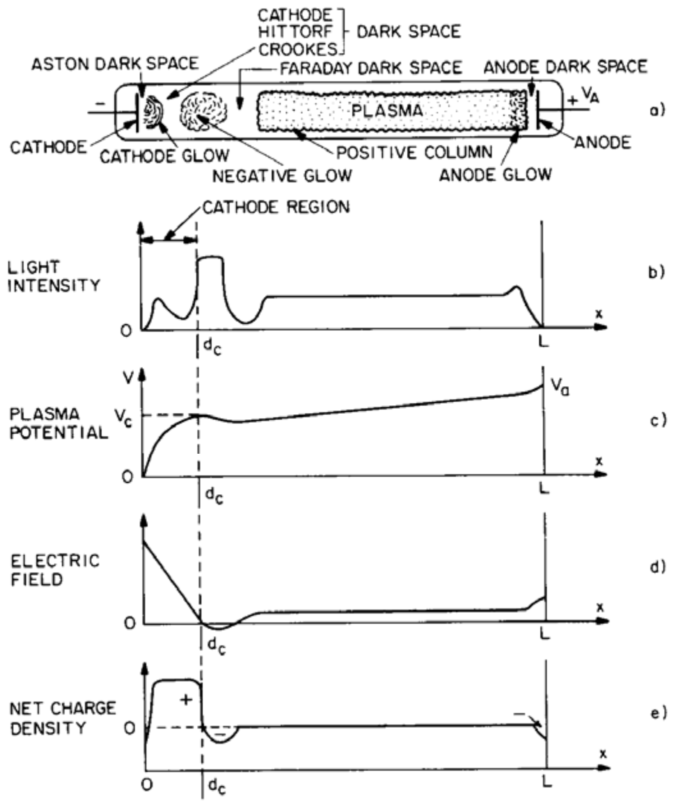


Figure 9.4 Axial variation of the characteristics of the normal glow discharge.

Lightening: positive column

1. DC Glow discharges

The dark regions: Cathode, Crooke's dark space, Faraday Dark space and anode dark space..

The luminous regions: Cathode glow, negative glow and positive column.

Colors of luminous zones in a glow discharge			
Gas	Cathode layer	Negative glow	Positive column
He	red	pink	red-pink
Ne	yellow	orange	read-brown
Ar	pink	dark-blue	dark-red
Kr	-	green	blue-purple
Xe	-	orange-green	white-green
H_2	red-brown	thin-blue	pink
N_2	pink	blue	red-yellow
O_2	red	yellow-white	red-yellow
Air	pink	blue	red-yellow

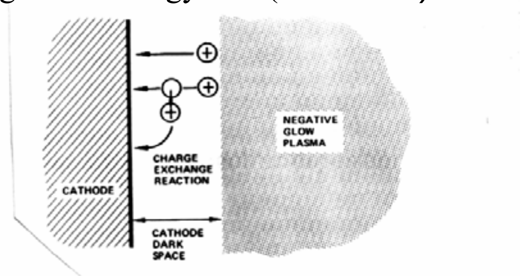
1. DC Glow discharges

The cathode region:

- Ion bombardment induces low energy (<10 eV) secondary electron emission at the cathode. Those electrons sustain the discharge and gain energy within the sheet and once the energy corresponds to the maximum excitation probability, cathode glows. When the energy exceeds the maximum value of the excitation probability, there is formation of a dark region.
- The cathode dark space is a positive space charge plasma sheath. (Ions are arriving, electrons are leaving).
- Since the plasma is more positive than the potential of any surface in the discharge, the action of the sheath is to accelerate electrons from the surface in the glow, giving both electrons and energy to the discharge.
- Depending on the plasma characteristics (pressure, excitation, ...) There is no or there are collisions within the sheet.

Conditions:	Collisionless	Collisional
	$d_s <$ mfp	$d_s \geq$ mfp

- When collisions occurs, ion charge exchange takes place within the sheet leading to ion energy loss (10→20 %): $Ar+Ar^{+} \rightarrow Ar^{+}+Ar$



Schematic representation of charge exchange reactions in the cathode fall region of a glow discharge.

1. DC Glow discharges

The glow regions:

- Two types of electrons are present in a glow discharge: Fast electrons, Thermal electrons (from inelastic collisions)
- Aston dark space: thin region with strong E. [Primary and secondary electrons] > [ions] -> negative space charge.
- The cathode glow results from electronic excitation of the gas by secondary electrons emitted by the cathode.
- The secondary electrons are accelerated though the Crook dark space. Some of them will travel across the positive columns without loosing energy and will hit the anode (fast electrons).
- Negative glow: electron density is large. Fast electrons produce ionization necessary to sustain the discharge, slow electrons have energy tuned to allow inelastic gas-molecules excitation (light).
- In the Faraday dark space, the slow electrons's energy is further reduced ☞ no excitation or recombination with ions ☞ no glow. Fast electrons have energy above the maximum excitation or recombination energy, ☞ no glow.
- In the positive column, the electric field is uniform. The ionization of molecules is caused by the random movement of the electrons. If both electrodes are bring together, that region disappears.

1. DC Glow discharges

The anode region:

- In the anode vicinity, some electrons are accelerated and ions are repelled. When electrons have max excitation energy, anode glows.
- Some of the fast electrons coming from the cathode bombard the anode generating secondary electrons emission. These electrons are accelerated back to the glow, increasing the glow intensity.
- The anode sheath is usually one order of magnitude thinner than the cathode sheath. It is usually collisionless.

Anode polarity.

- The plasma potential is not alway > than the anode.
  If $\delta > 1$, the anode polarity can be reversed
  If the anode area ↓↓ , the polarity is reversed.

Rem:

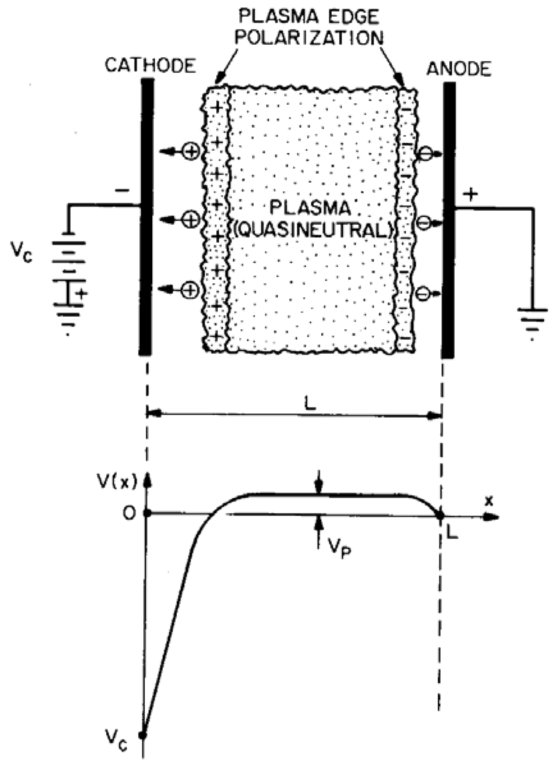
To sustain the discharge, ionization must occur in the negative glow ☞ $d_{interelectrode} \gg \lambda$ ☞ DC discharges are sustained at relatively high pressures (50 - 100 mTorr).

1. DC Glow discharges

1.4 Obstructed discharge

Only the negative glow exists, with the cathode and anode dark space.

Length $L \leq d_c$ (Cathode region where ΔV & ΔE are max)



Rem: The negative potential drop V_w across the sheath is often used to accelerate ions into the surface of the cathode

2. Electromagnetic waves

2.1 Frequency bands allowed for industrial , scientific and medical applications.

Frequency bands designated by the International Telecommunication Union for ISM applications		
Centre frequency (MHz)	Frequency band (MHz)	Validity
6.78	6.765-6.795	*[1]
13.56	13.553-13.567	WW[2]
27.12	26.957-27.282	WW
40.68	40.66-40.70	WW
433.92	433.05-434.79	Africa, Europe, URSS, Turkey, Mongolia
915.00	902.00-928.00	America
GHz	GHz	
2.45	2.4-2.5	WW
5.8	5.725-5.875	WW
24.125	24.00-24.25	WW
61.25	61.00-61.50	*
122.50	122.00-123.00	*
245.00	244.00-246.00	*

*[1]: special authorization requested
WW[2]: World-Wide.

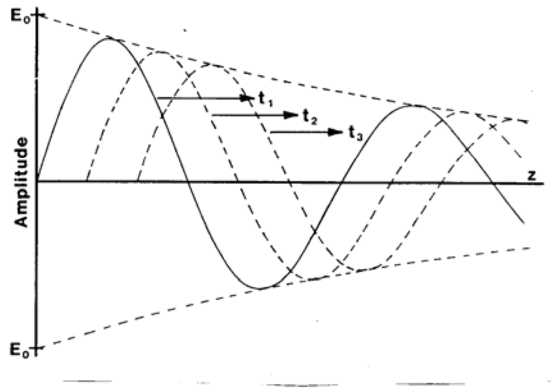
2. Electromagnetic waves

2.2 Characteristics

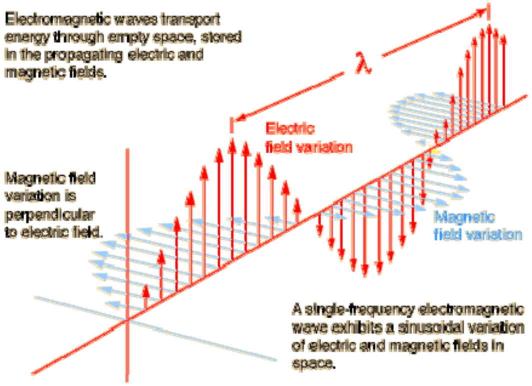
Electromagnetic waves propagate through free space at the speed of the light (c=3x10^8 m/s). In real life, its propagation and attenuation can be expressed as:

$$E = E_0 e^{-\alpha z} \sin(wt - \gamma z) = E_0 e^{-\alpha z} \sin(\phi_0)$$

where: E_0 is the peak value of the electric field,
w the angular frequency,
γ the propagation constant,
α is the rate of attenuation,
t and z, time and distance.



An electromagnetic wave has both a magnetic and an electric component:



$$\lambda = \frac{c}{f}$$

For a wave propagating in free space, the amplitude of the E and B field are such that the resistance (impedance) of the material must be 377 Ω to prevent reflexions:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\,\Omega$$

where the magnetic permeability μ_0 = 4πx10-7 Henrys/m and the dielectric constant $\varepsilon_0 = 1/36\pi x10^{-9}$ Farads/m.

Rem:

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}} = 3x10^8\ m/s$$

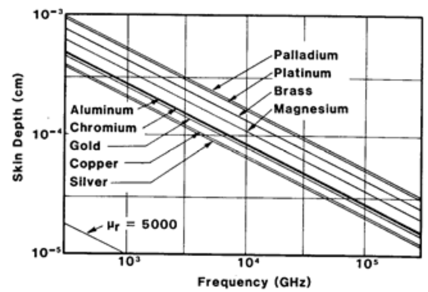
For values of μ and ε ≠ than those of the free space, the impedance and speed change accordingly.
Ex: Al_2O_3: ε ≈ 9 ε_0 ☞ c and Z in Al_2O_3 ≈ 1/3 of c_0 and Z_0.

2.3 Skin effect

When an EM wave impinges on a good conductor, most of the energy is reflected because of the impedance mismatch between the air and the conductor.
The current density generated at the surface of the conductor decreases exponentially with its depth. The skin depth can be expressed as:

$$\delta\,(cm) = \frac{1}{2\pi}\sqrt{\frac{\rho\,(ohm\ cm)}{f\ (GHz)\,\mu_r}}$$

where μ_r is the relative permeability (relative to the free space).



Skin Depth for Several Commonly Used Metals

Conductor resistance within the skin can be expressed as:

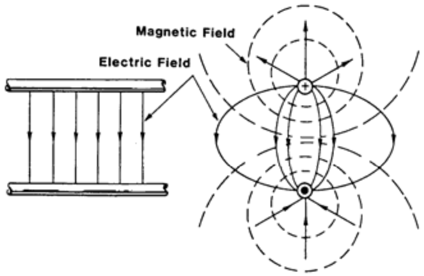
$$R_s = \frac{\rho}{\delta} = 2\pi\sqrt{\rho f \mu_r}$$

2. Electromagnetic waves

2.4 High frequency EM wave transmission

High frequency EM waves are transmitted though coaxial lines and waveguides. Conventional two wires conductors can't be used because:

1: Signal coupling from one set of two conductors to another set:



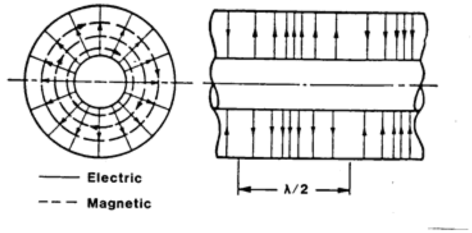
Electric and Magnetic Fields Surrounding Current-Carrying Wires

2:If f ⬀, the wires act as antennas

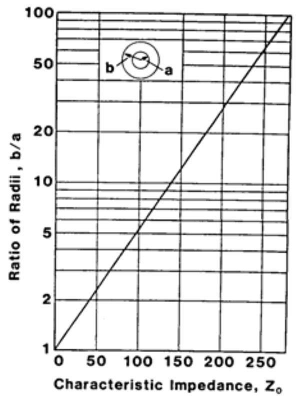
3:A wire has its own impedance, that is related to its size and its position relative to another conductor. If along a wire, there is change of the impedance from place to place, reflection may occurs at each change in impedance.

2. Electromagnetic waves

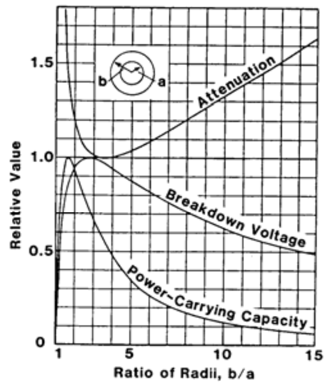
Coaxial lines



$$Z_0 = \sqrt{\frac{L}{C}} \quad \div \quad \frac{a}{b}$$



Characteristic Impedance of an Air-Insulated Coaxial Line



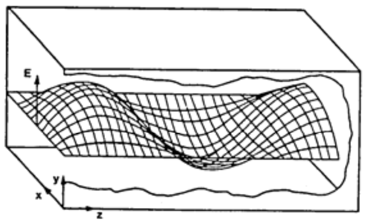
Characteristics of Air-Filled Coaxial Lines

2. Electromagnetic waves

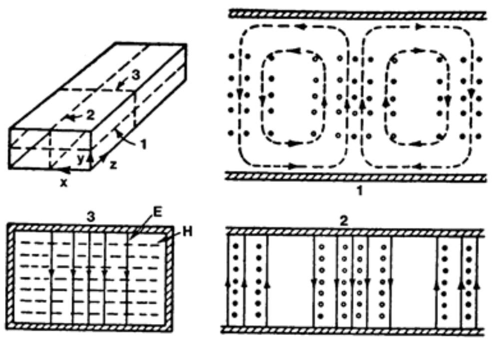
Wave guides

• Waveguides is a metallic pipe usually made from copper and having either a rectangular or circular cross section.

• The waves are reflected on internal-sides, and travel without power loss.



Amplitude of Electric Field as a Function of Position in Wave-guide



Electric and Magnetic Field Components in Waveguide for TE_{10} Mode

Solution: coaxial lines and wave guides

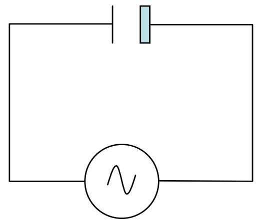
3. RF discharges

3.1 Caracteristics of a RF capacitive discharge

• Generally used with insulating electrodes, for insulator deposition. Wide application in the electronic industry (GaAs, GaN, AlN, CDs, Al_2O_3, ...).

• If DC sputtering of SiO2 (ρ =10^{16} Ω-cm), and 1 mA/cm^2, Cathode needs V = ρ.I : 1x10^{13} V/cm:
impossible

• But, discharge can be produced almost continuously for frequencies > 100 kHz.



• Operating frequency is generally 13.56 MHZ that is allocated by the “International Telecommunication Union”.
• At high frequency (10 MHZ), only electrons can follow the variation of potential. ☞ equivalent to electron gas moving back and forth in a sea of relatively stationary ions. When electron cloud is close to one electrode, it uncovers ions at the opposite electrode leading to the formation of a positive ion sheath. Therefore within one cycle, one dark space is observed on each electrode ☞ there is essentially formation of a DC discharge with alterning polarity.
• Ions flowing out of the plasma can be accelerated within each sheets leading to the bombardment of each electrodes.

3. RF discharges

Electrons are lost to the electrodes when the oscillating cloud is close to them making sheath potential collapse to zero allowing electrons to escape to balance the ion charge delivered to the electrode.

In a collisionless situation (low pressure plasma), electrons will oscillates as:

$$\vec{F} = m\frac{d\ddot{\vec{x}}}{dt} = q\vec{E} = e.\vec{E}$$

If we integrate it: $\dot{x} = \frac{e.E}{m_e}.t \ \ (\mathrm{C} = 0 \text{ for } \mathrm{t} = 0 \, , \dot{x} = 0)$

$$x = \frac{e.E}{2.m_e}.t^2 \qquad \textit{Final kinetic energy} = \frac{m.\dot{x}^2}{2}$$

If f = 13.56 MHZ and E_0 = 10 V/cm (very high value),

☞ x =2.42 cm, speed = 2.1×10^8 cm s^{-1},

☞ Energy = 11.3 eV

☞ Too low to ionize Ar (15,7 eV)

☞ ***<u>How can we have a plasma ?</u>***

<u>In practice, E > 11.3 eV because of (e-gas) elastic collisions occurring at the same time field changes polarity (RF field in phase with collisions).</u>

3. RF discharges

<u>Rem:</u>

- Electrons accumulate enough energy to cause ionization,
- Discharge dependence on δ is greatly reduced,
- Ionization efficiency (α) of RF >> α of DC ($10^{-2} >> 10^{-4}$),
- Large ionization efficiency -> large polymerisation rate
- Can operate at lower pressures than DC planar diode because of the increase of the ionization efficiency (electrons remain longer in the discharge).
- if f ⬀, less time is available for charged particles to reach the walls or electrodes. ☞ elect. are kept in the plasma.
- No need to have electrodes (Inductive heating)

3.2 Self bias

Without blocking capacitor (symmetrically driven)

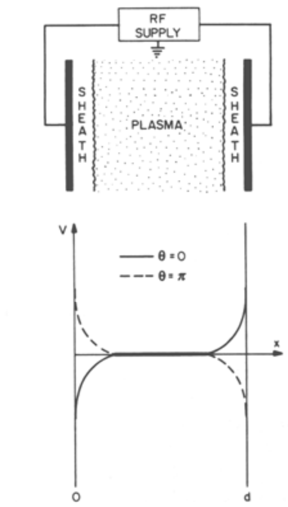


Figure 12.4 Sheaths and potential distribution in a symmetrically driven RF glow discharge at two RF phase angles 180° out of phase.

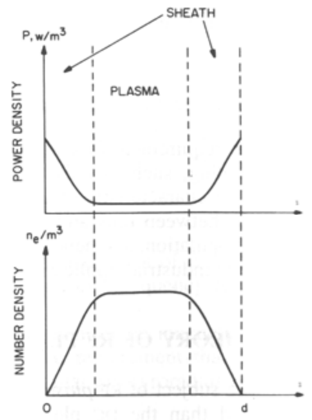


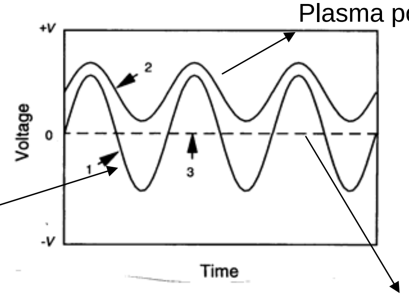
Figure 12.5 Schematic of the power and number density distribution across the symmetrically driven RF discharge of figure 12.4.

Time averaged:

$V_1 = V_2$

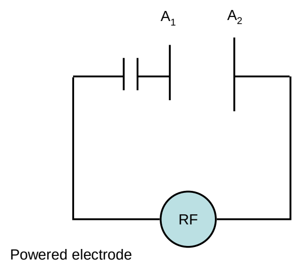
$d_{sheath\ 1} = d_{sheath\ 2}$

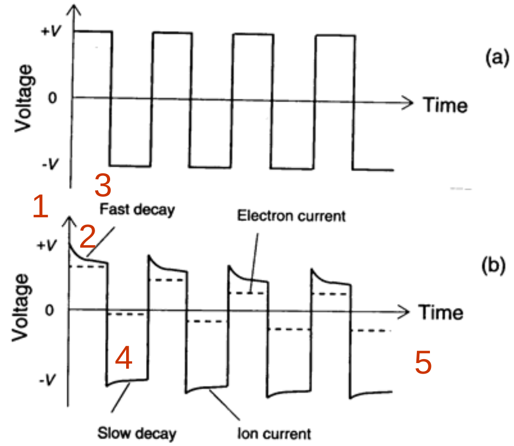
Time behavior



3.2 Self bias

With blocking capacitor (non-symmetrically driven)





0. Let's look on the capacitor side

- V across the plasma is = to applied V
- Capacitor charges up by electron current and V ↓ (fast decay)
- V changes sign and V across plasma drops (- 2.V)
- V decays but less rapidly because the capacitor charges by the current of less mobile ions
- Process continue until the time averaged ion and current are equals (remember plasma potential and negative bias in DC mode) (--- pos and --- neg are equals)

3. RF discharges

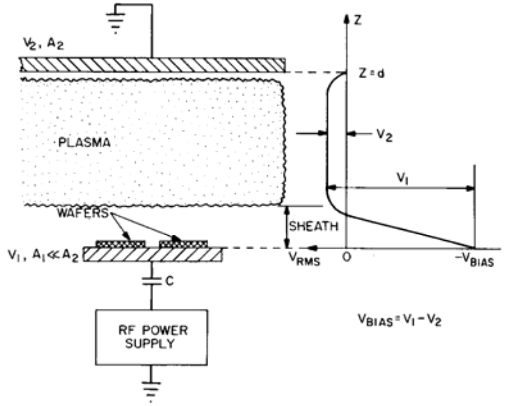


Figure 12.6 A plane parallel RF plasma reactor with electrodes of unequal surface area, and unequal electrode voltage drops.

Relation between $V_{electode\ 1}$ and $V_{electrode\ 2}$

Real ion current flowing to both 1 & 2 electrodes:

$$\begin{cases} I_1 = A_1.J_1 = A_1.e.<V_{i1}>.n_i \\ I_2 = A_2.J_2 = A_2.e.<V_{i2}>.n_i \end{cases}$$

$$\frac{m_i.<V_i>^2}{2} = e.V_{Volts} \rightarrow \sqrt{\frac{2.e.V_1}{m_i}} = <V_i>$$

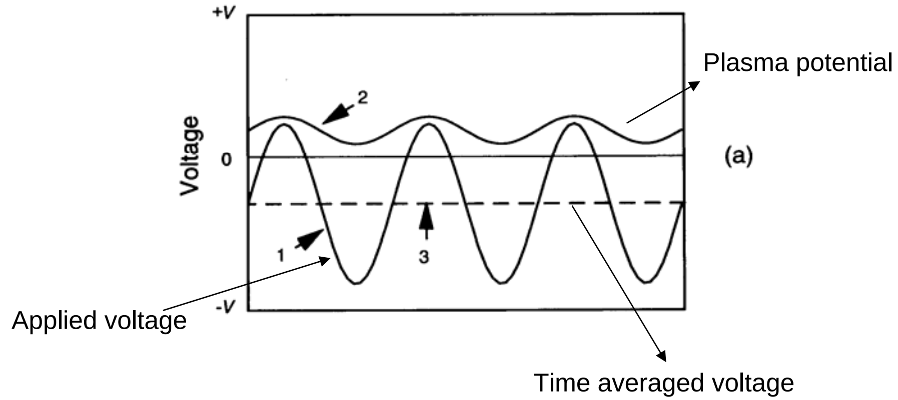
If ions of sames masses and same electron density at both sheath: $I_1 = I_2$

$$\frac{I_2}{I_1} = 1 \rightarrow \frac{A_2}{A_1} x \frac{\sqrt{\frac{2.e.V_2}{m_i}}}{\sqrt{\frac{2.e.V_1}{m_i}}} = 1$$

$$\left(\frac{A_2}{A_1}\right)^2 = \frac{V_1}{V_2} \rightarrow \text{in reality: } \left(\frac{A_2}{A_1}\right)^q = \frac{V_1}{V_2},\ 2<q<4$$

3. RF discharges

Time behavior



At A_1/A_2 fixed:

$$V_B \approx \sqrt{\frac{P_{RF}}{pressure}}$$

4. Microwave discharges

Very popular in microelectronic for etching and deposition.

4.1 Characteristics of a μW discharge

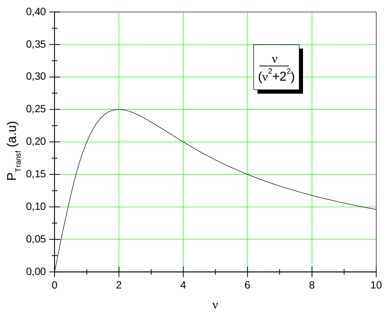
In a collisionless plasma, If ν=2.45 GHz, $E_0 \approx 30$ V/cm,
☞ x < 10^{-3} cm, W ≈ 0.03 eV, ☞ too low to sustain the discharge.

<u>But:</u> In a collision plasma:

$$\overline{P_{transf}} = \frac{n_e e^2 E_0^2}{2\, m_e}\left(\frac{\nu}{\nu^2+\omega^2}\right)$$

ν = elastic collision frequency of an electron with an atom.

ω = frequency of applied wave



For a given ω, that function has a maximum when ν = ω ☞ absorption power is a function of the collisions frequency of the e-atoms, ☞ is a function of the gas pressure.

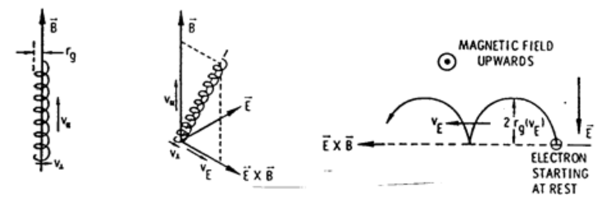
If ν<<ω or ν>>ω, P_{transf} is very low.

4. Microwave discharges

4.2 In presence of an external B

<u>E and B uniform.</u>

Suppose an electron moving in a B and E.



• If E=0, electrons drift along the field line and orbit the field lines with a gyro or cyclotron frequency.
• When B and E are uniform and B is // to E, electrons are accelerated and r_g ⬀ continuously.
• If there is a E ⊥ B, then electrons have a drift speed (V_E) ⊥ to the plane (E,B).

Cyclotron angular frequency: $\omega_c = \frac{e\,B}{m} = 1.76x10^7\ B\ \ (rad/s)$

Larmor radius $r_g = \frac{m\,V_\perp}{e\,B} = 3.37\frac{\sqrt{W_\perp}}{B}\ \ (cm)$

Drift speed $V_E = 10^8\,\frac{E_\perp}{B}\,(cm/s)$

B in Gauss, E in V/cm, V in cm/s, W in eV.

4. Microwave discharges

4.2 In presence of an external B

E non uniform: E is rotating (circularity polarisation)

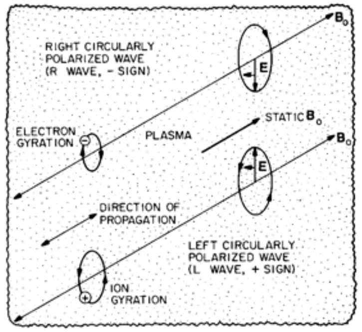
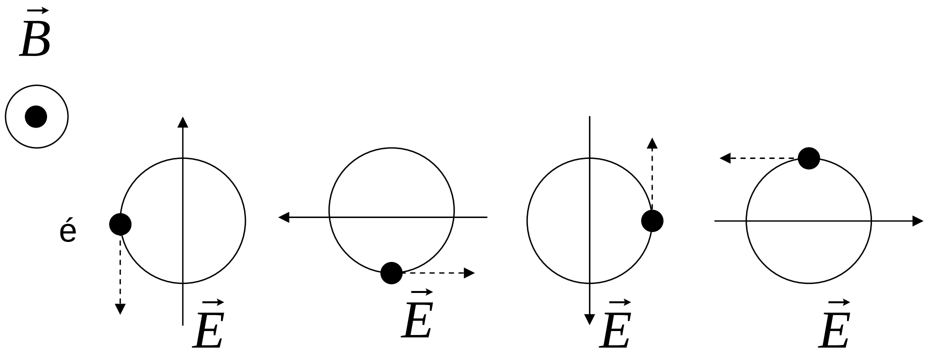


Figure 13.7 The polarization convention for parallel propagation of electromagnetic radiation in a magnetized plasma with $\theta = 0$. In the right circularly polarized wave, the electric field rotates in the direction of the electron gyration. In the left circularly polarized wave, the electric field rotates in the direction of ion gyration.

ECR heating:



Gain in energy only for left-hand polarisation (Zero on average for righ polarisation)

4. Microwave discharges

4.2 In presence of an external B

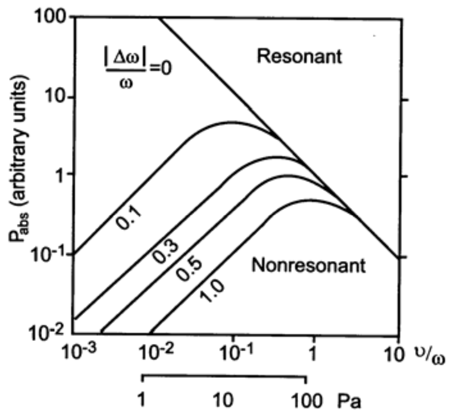
E non uniform: E is rotating (circularity polarisation)

Power transfered to electrons:

$$\overline{P_{transf}} = \frac{n_e e^2 E_0^2}{2\, m_e}\left(\frac{\nu}{\nu^2 + (\omega - \omega_c)^2}\right)$$

ω: wave frequency
ω_c: electron frequency

When $\omega=\omega_c$, P transferred is max



- If $\Delta\omega/\omega = 0.1$ (close to resonance), and B = 875 Gauss, m = m_e,
  - ☞ P = 10 Pa (0.075 Torr)
  - ☞ $\omega_c \approx 2.45$ GHz
- If the microwave frequency is also 2.45 GHz, there is a so called ECR effect.

5. Comparison RF <-> µW

Comparison RF, µW		
	µW	RF
Typical pressure (Torr)	10^{-5} to 10^{-3}	10^{-2} to 10
Ion energy (eV)	10-20	200-1000
Electron T° (eV)	2-7	1-5
Ionisation degree	10^{-4} to 10^{-1}	10^{-6} to 10^{-3}
Plasma density (cm^{-3})	10^{10} to 10^{12}	10^{9} to 10^{11}