Bounded Plasma

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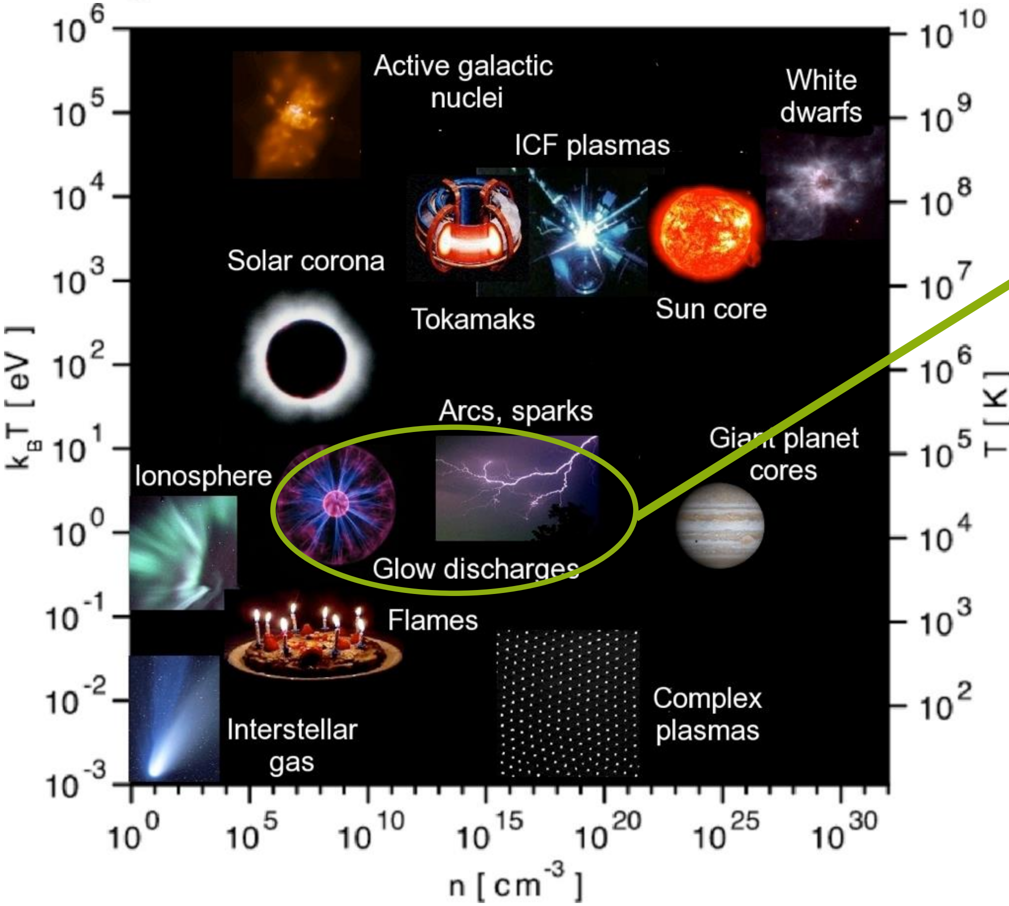
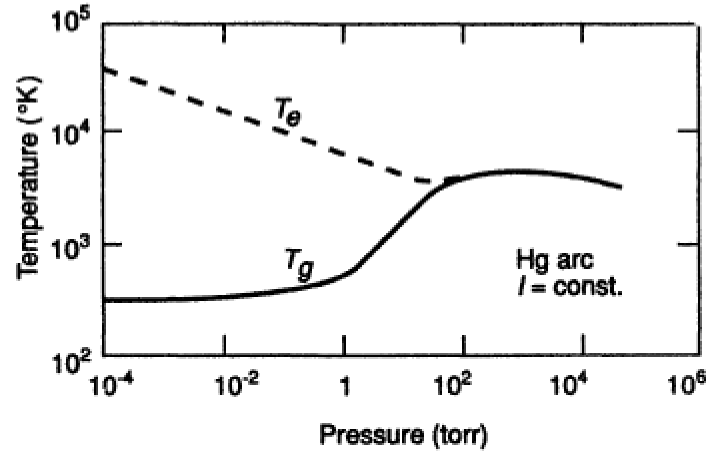
Low Temperature Plasma



- Low degree of ionization
- Neutral background 10^6 the ion and electron density
- Collisions with the background gas is dominant compared to electron ion collisions

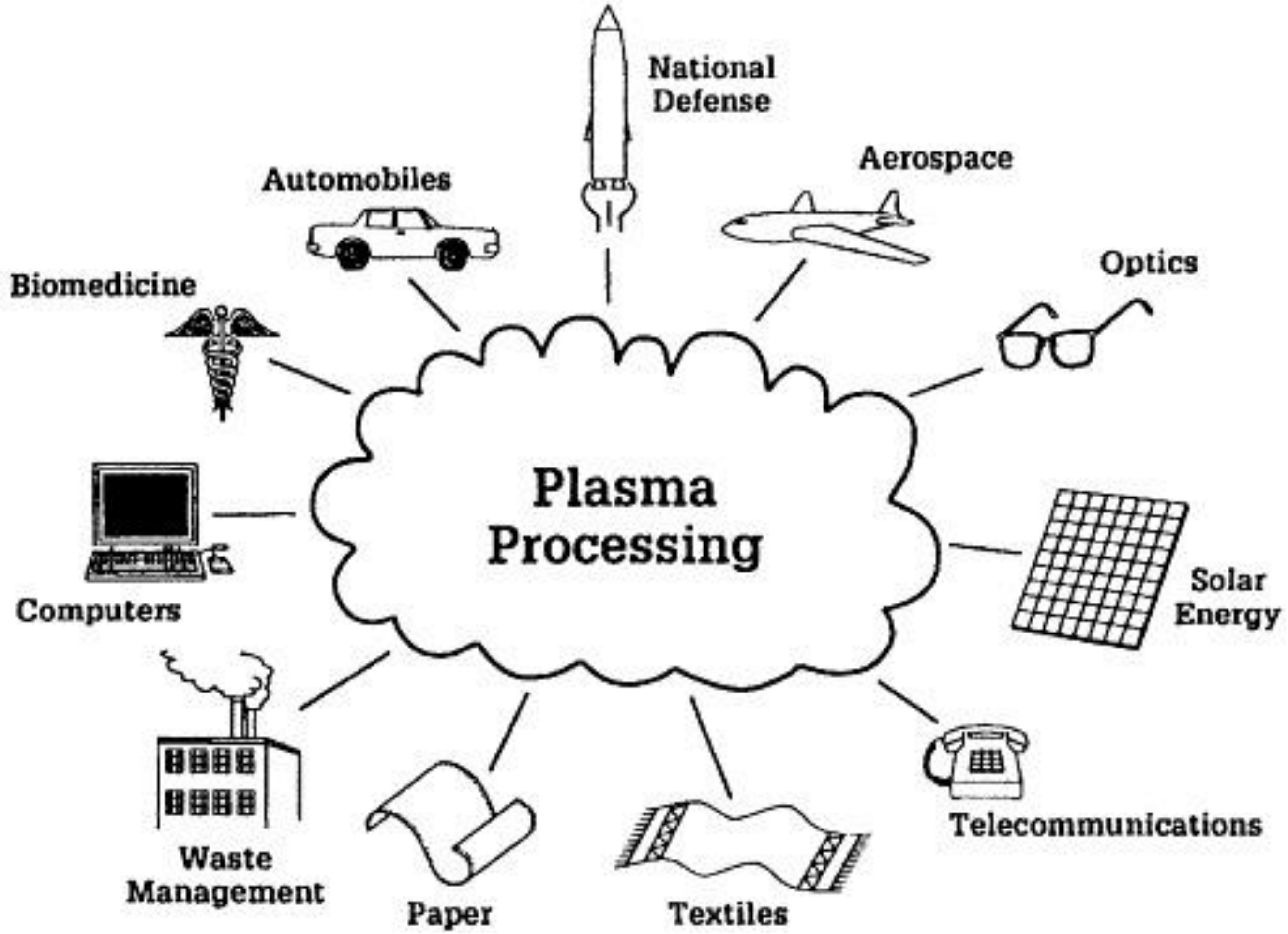


- Non-equilibrium plasmas at low pressures

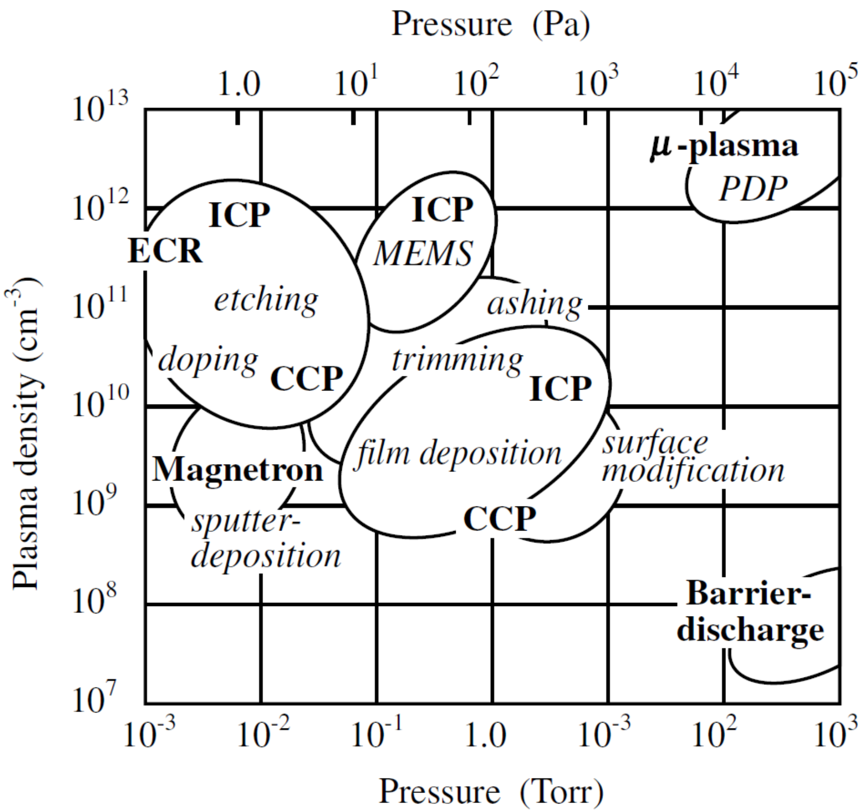
$T_e = 11000 - 60000\mathrm{K}$

$T_e = 1 - 5\mathrm{eV}$ $\quad T_i = 300\mathrm{K}$

Various applications

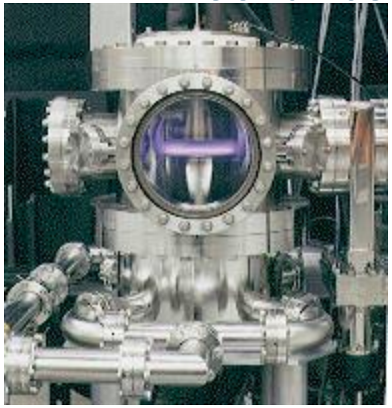


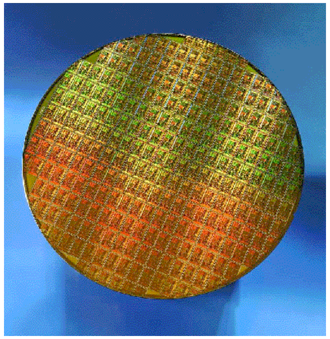
Devices

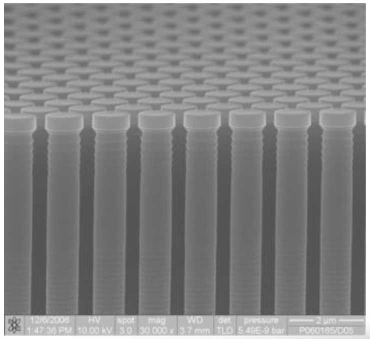


Plasma electronics,
Applications in Microelectronic Device Fabrication

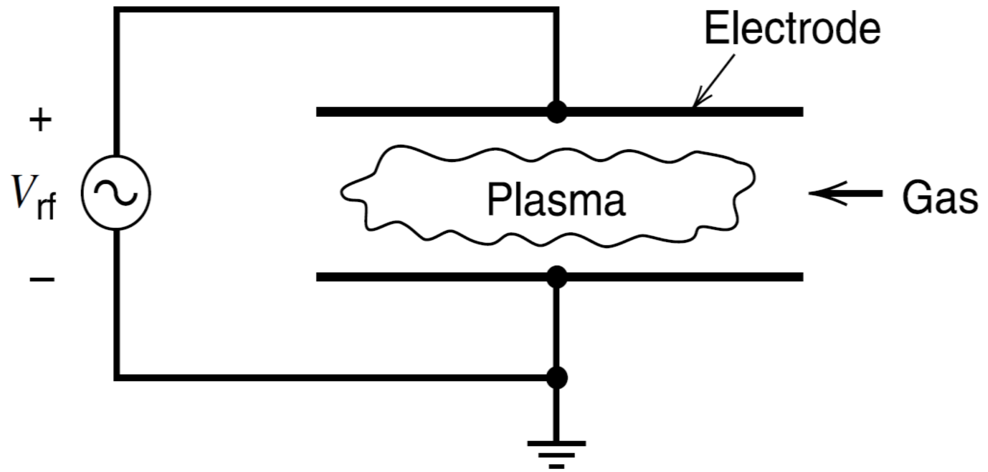
- **Capacitive coupled plasma** are used in plasma etching and deposition process for production of:
  - Integrated circuits
  - Sollar cells

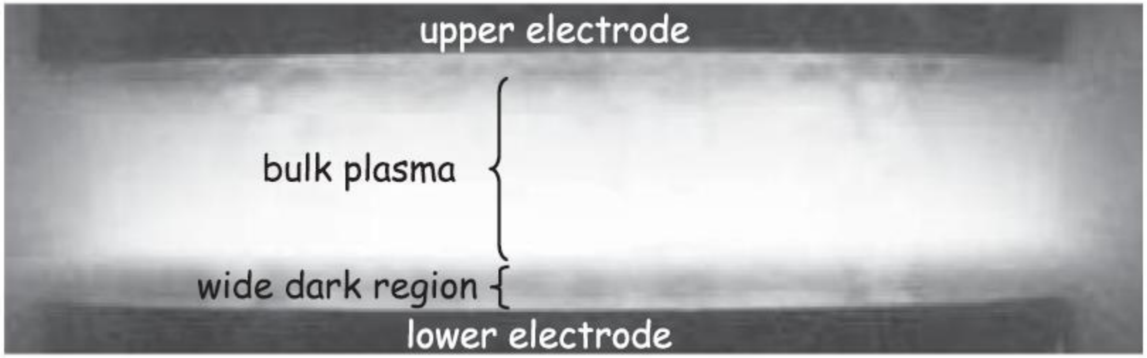






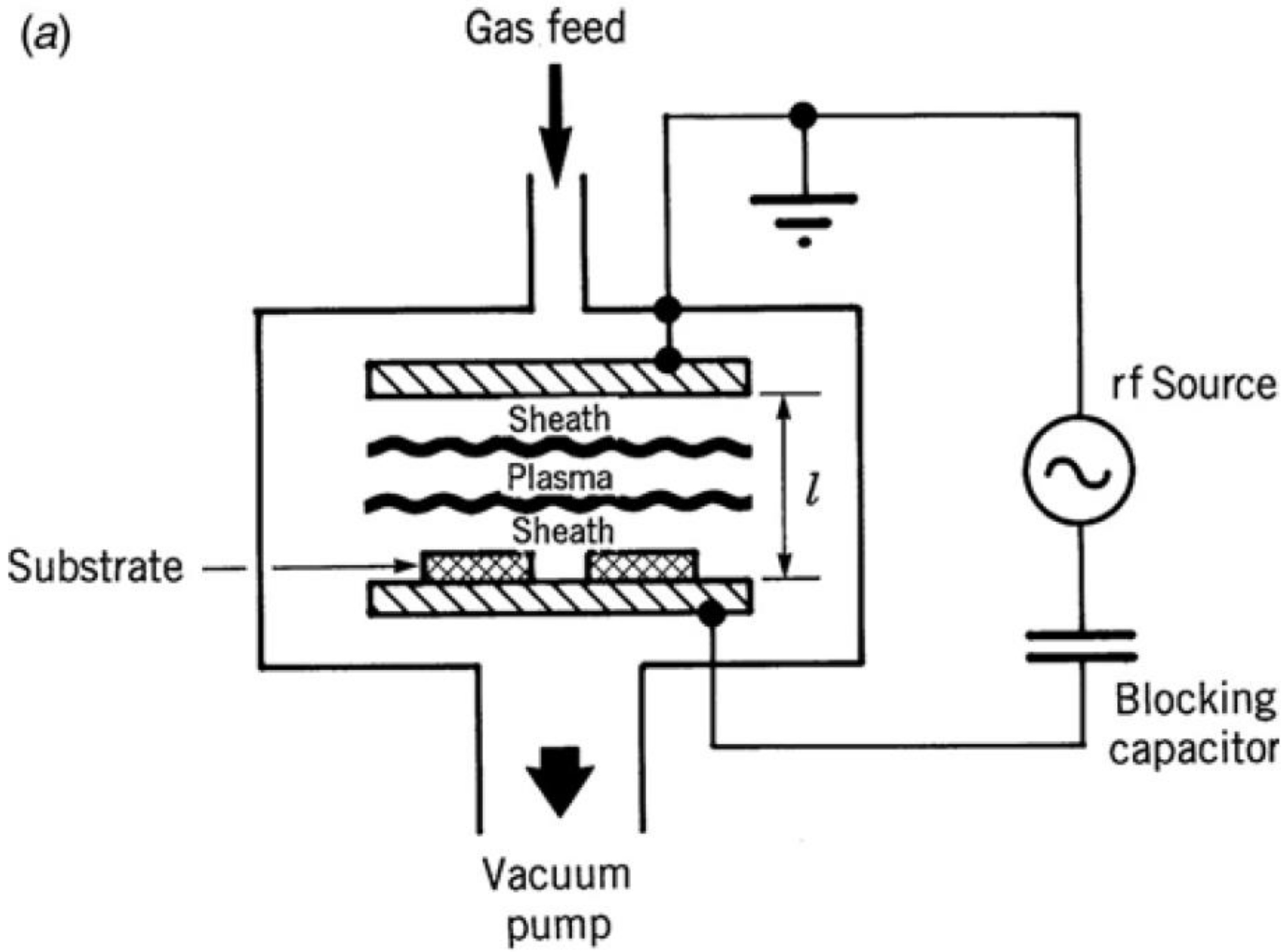
Symmetric CCP discharge



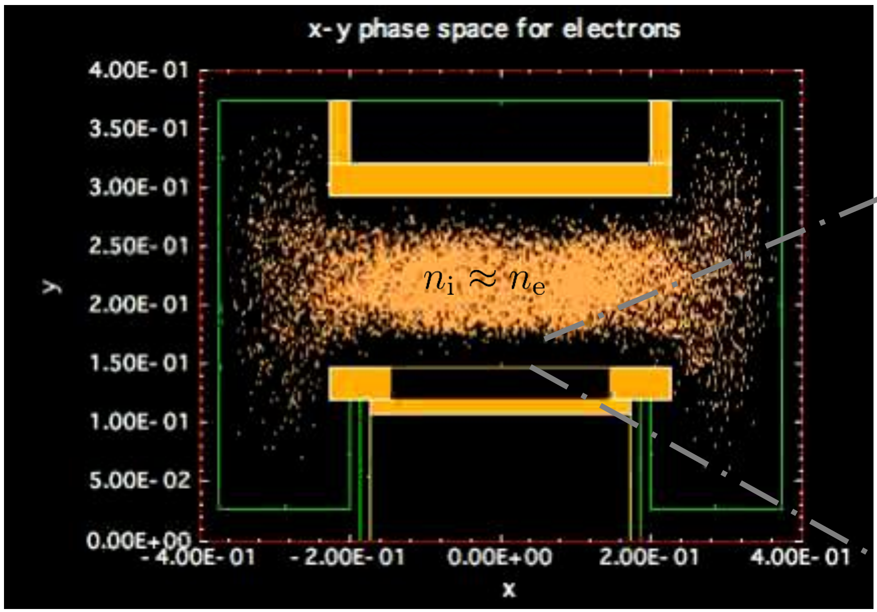


- **The ion flux and the ion energies increase (decreases) by increasing (decreasing) the dreving frequency.**

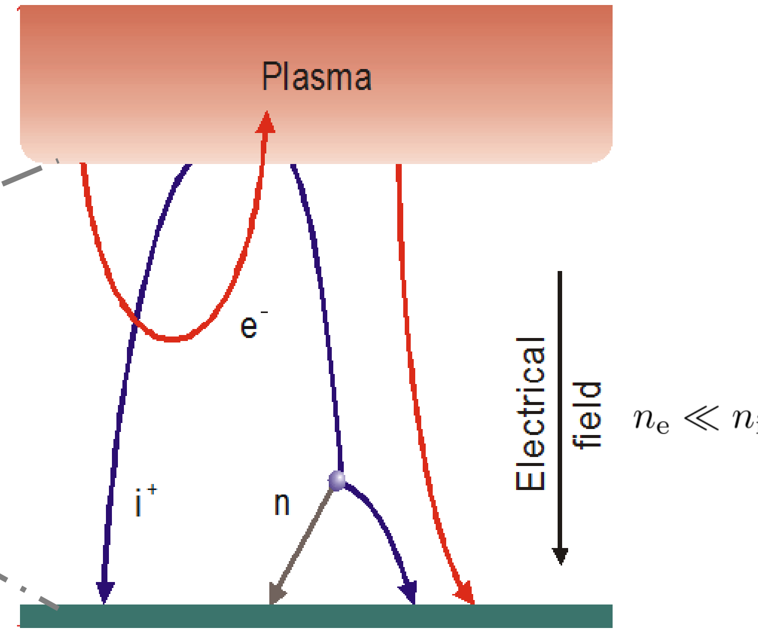
CCPs & blocking a Capacitor



Plasma Sheaths



TET



- RF sheaths:
  - High frequency regime
  - Intermediate frequency regime
  - Low frequency regime

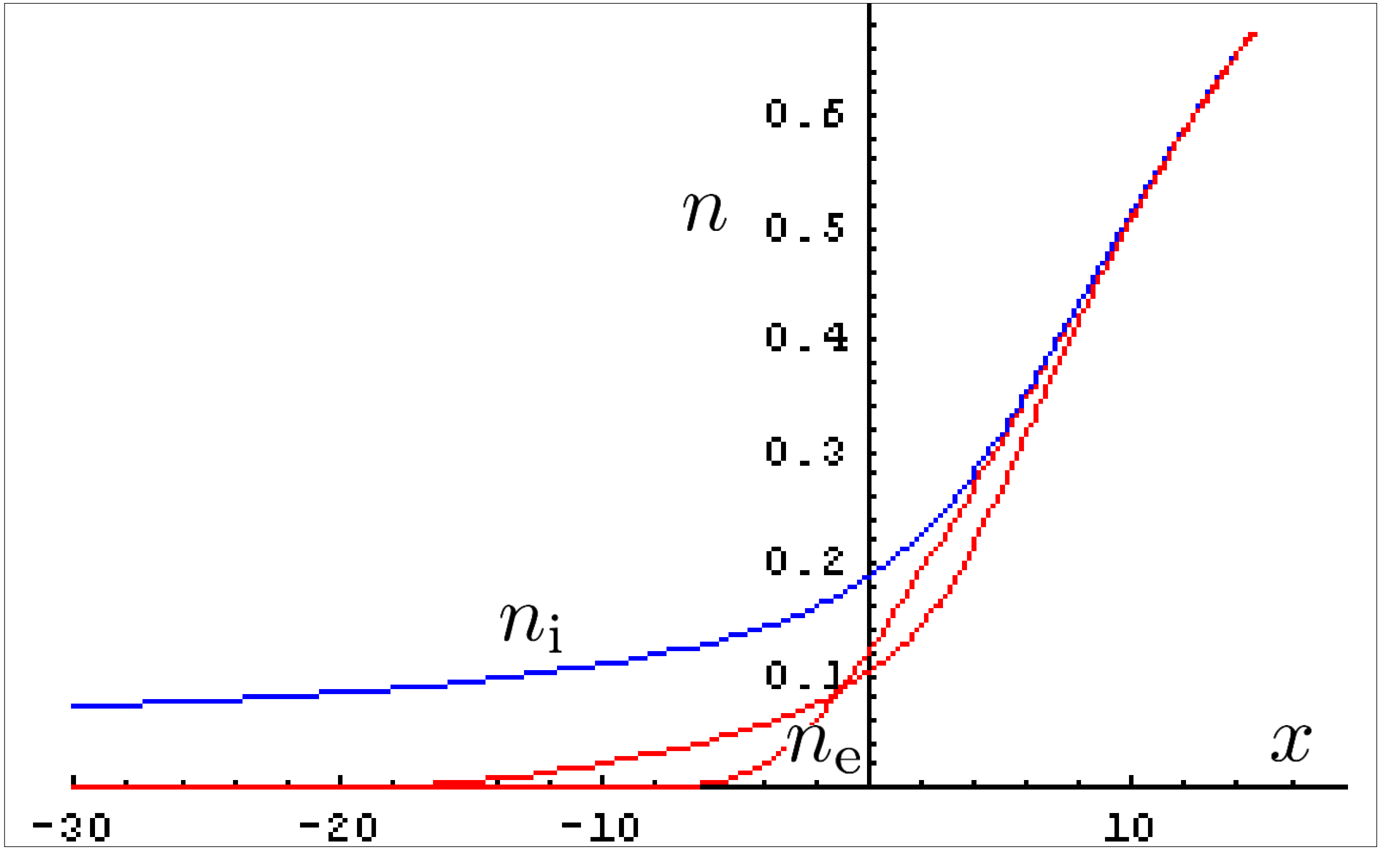
$\omega_{RF} \gg \omega_{pi}$ $\quad n_i(x) \Leftrightarrow \bar{E}(x)$

$\omega_{RF} \approx \omega_{pi}$

$\omega_{RF} \ll \omega_{pi}$ $\quad n_i(x,t) \Leftrightarrow E(x,t)$

Plasma Sheaths

$$\omega_{\rm pe} \gg \omega_{\rm RF} \gg \omega_{\rm pi}$$



Sheath formation

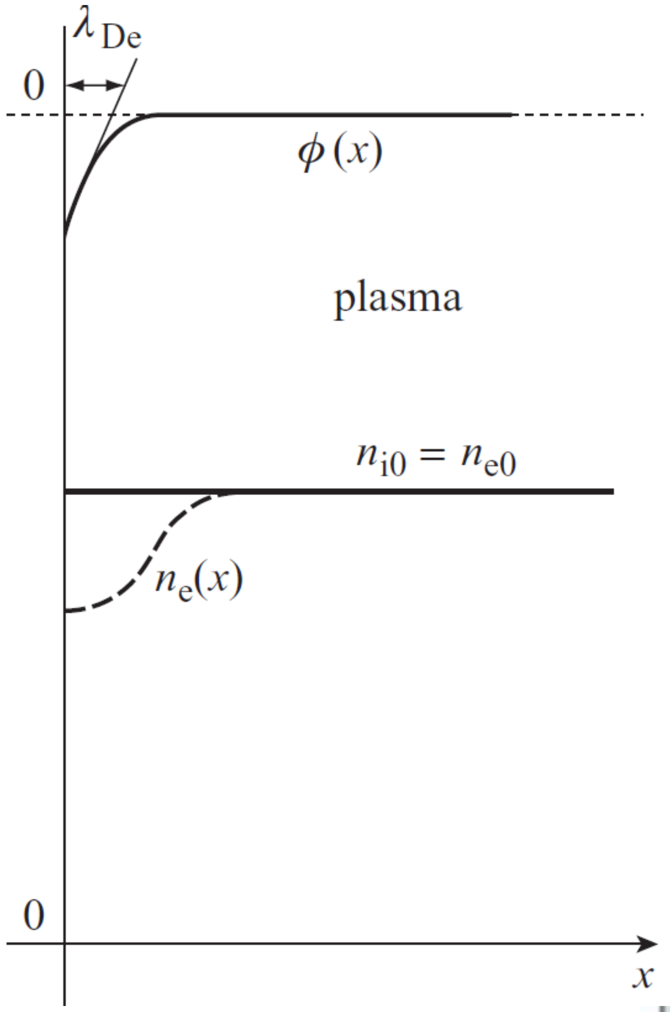
$$J_e = -e\Gamma_e = -\frac{1}{4}en_e\bar{v}_e = -en_e\sqrt{\frac{kT_e}{2\pi m}},$$

$$J_i = e\Gamma_i = \frac{1}{4}en_i\bar{v}_i = en_i\sqrt{\frac{kT_i}{2\pi M}}.$$

A steady state would be reached when the potential of the object is sufficiently negative for the electron flux to exactly balance that of the positive ions. Such a potential is called the *DC floating potential*. At balance:

$$n_e\sqrt{T_e/m} = n_i\sqrt{T_i/M}$$

$$n_i > n_e$$



Floating Sheath

$$\frac{(n_i - n_e)e}{\varepsilon_0} = \frac{dE}{dx} = -\frac{d^2\phi}{dx^2}.$$

$$e(n_i - n_e) = en_{e0}\left[1 - \exp\left(\frac{e\phi}{kT_e}\right)\right] \simeq -\frac{e^2 n_{e0}\ \phi(x)}{kT_e},$$

$$\frac{d^2\phi}{dx^2} = \frac{e^2 n_{e0}\ \phi}{\varepsilon_0 kT_e}. \qquad \phi(x) = \phi_0 \exp\left(-\frac{x}{\lambda_{De}}\right),$$

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 kT_e}{n_{e0}e^2}}$$

Exercise 3.1: Debye length Calculate the Debye length for a plasma in which the electron density is $n_{e0} = 1.0 \times 10^{16}\ \text{m}^{-3}$ and $kT_e/e = 2.0$ V.

Floating Potential

$$\Gamma_e = \frac{n_s \bar{v}_e}{4} \exp\left(-\frac{e\Delta\phi}{kT_e}\right).$$

$$\bar{v} = \left(\frac{8kT}{\pi m}\right)^{1/2}$$

The formation of the sheath retards electrons with a temperature T_e, Only electrons with energy greater than $e\Delta\phi$ can reach the electrode.

$$\Gamma_e = \Gamma_i$$

$$\Delta\phi = -V_f$$

$$\frac{n_s \bar{v}_e}{4} \exp\left(\frac{eV_f}{kT_e}\right) = n_s u_B$$

Bohm Speed:

$$u_s = \left(\frac{kT_e}{M}\right)^{1/2}$$

$$V_f = \frac{kT_e}{e} \frac{1}{2} \ln\left(\frac{2\pi m}{M}\right)$$

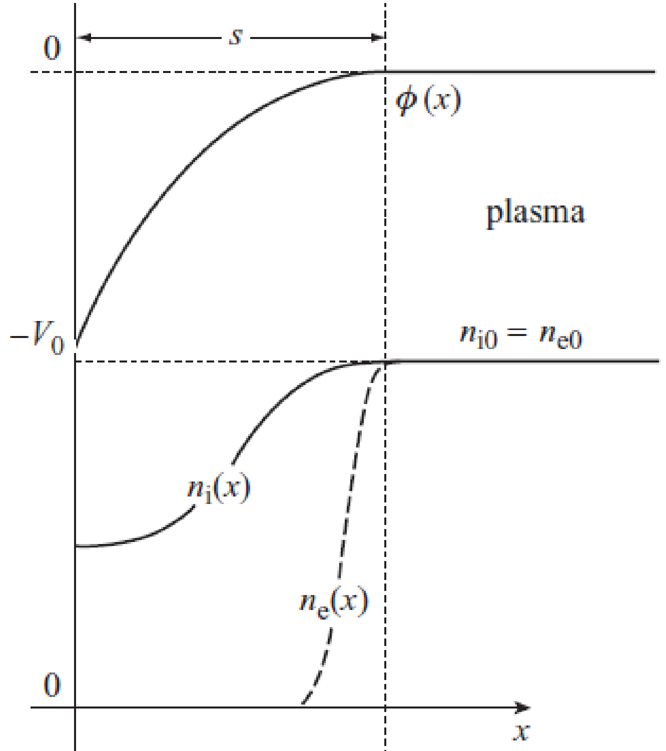
Ion Matrix Model

$$\frac{d^2\phi}{dx^2} = -\frac{e\,n_{i0}}{\varepsilon_0}.$$

$$\phi(x) = -\frac{e\,n_{i0}}{\varepsilon_0}\left(\frac{x^2}{2} + C_1 x + C_2\right).$$

$$\phi(x) = -\frac{e\,n_{i0}}{2\varepsilon_0}(x-s)^2.$$

$$V_0 = \frac{e\,n_{i0}}{2\varepsilon_0}s^2;$$



Two boundary conditions must be supplied to determine the constants C_1 and C_2. Since the plasma is a conductor, it is reasonable from a sheath point of view to set the electric field, $-d\varphi/dx$, to zero at the boundary with the plasma $x = s$: that requires $C_1 = -s$. The second condition is simply that the potential at $x = s$ is zero; that is, the plasma boundary is taken as the reference for the potential. That requires $C_2 = s^2/2$. Calculate the sheath width when the sheath potential is 200 Volt, the electron temperature is 2 eV, and the plasma density is 10^16 m^{-3}.

Geometrically Asymmetric

- **The RF current is constant.**
- **But the ground electroge**

Area is greater then the powered electrode area.

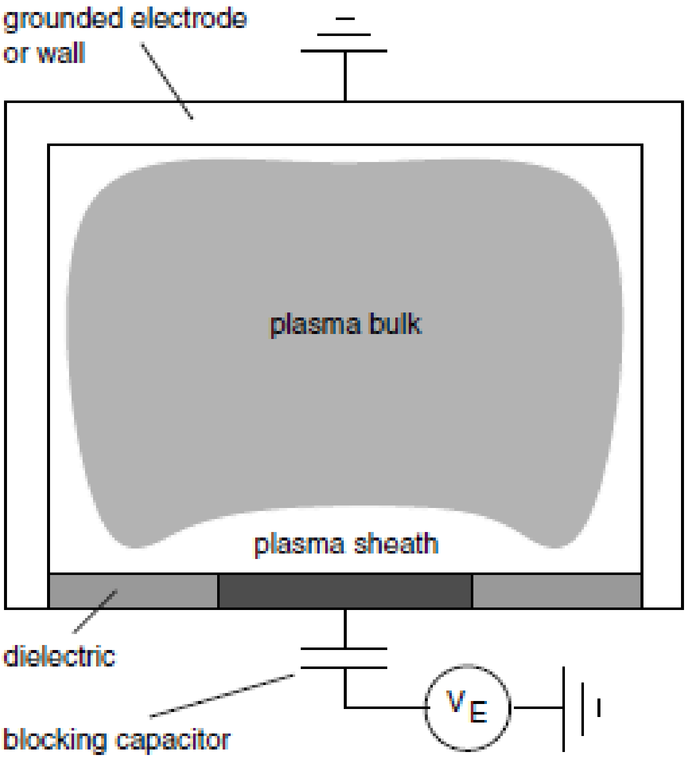
$$J_{\mathrm{g}} = I_{\mathrm{rf}}/A_g$$

$$J_{\mathrm{p}} = I_{\mathrm{rf}}/A_p$$

$$J_{\mathrm{p}} \gg J_{\mathrm{g}}$$

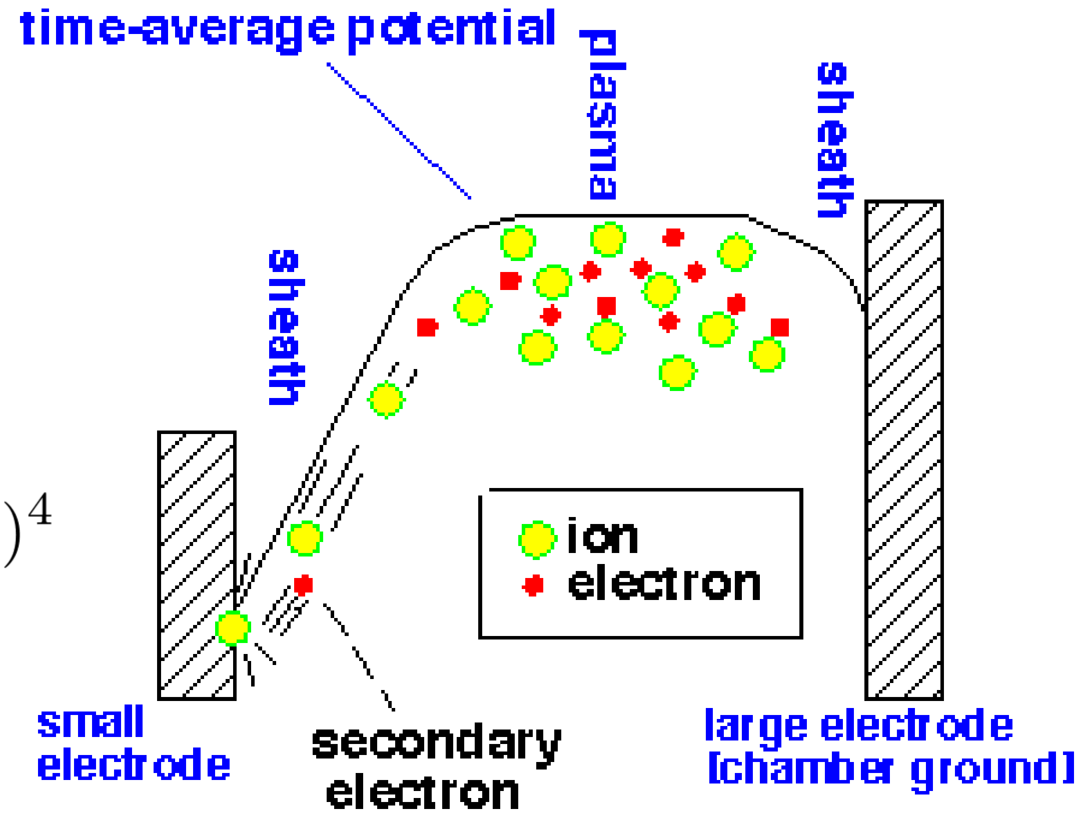
- The blocking capacitor blocks DC currents:

$$\frac{V_{\mathrm{p}}}{V_{\mathrm{g}}} = \left(\frac{A_{\mathrm{g}}}{A_{\mathrm{p}}}\right)^4$$



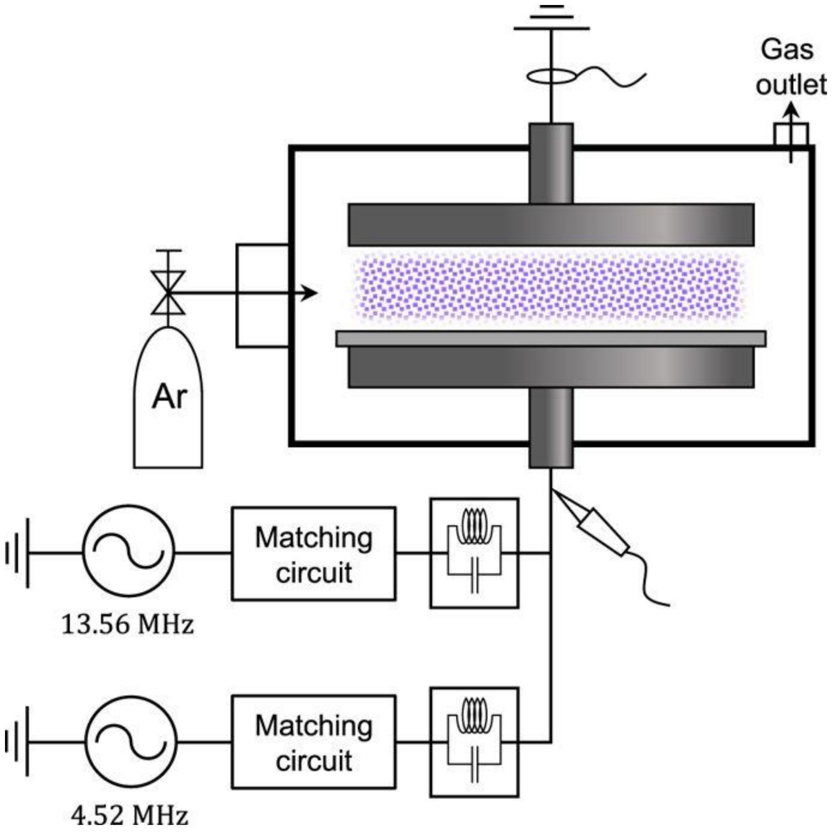
Particle and Potential distribution

$$\frac{V_p}{V_g} = \left(\frac{A_g}{A_p}\right)^4$$



Electrically Asymmetric

- The high frequency controls the ion plasma bulk (ion flux).
- The lower frequency controls the plasma sheath.
- The phase shift between the two sources controls also the sheath potential.
- The independent control is not always perfect.



Plasma Chemistry I

- **Dissociation of feedstock gas into active neutral free radicals:**

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

$$e^- + CF_4 \rightarrow CF_2 + 2F + e^-$$

$$e^- + CF_4 \rightarrow CF + F_2 + F + e^-$$

- **Dissociation of the free radicals**

$$e^- + CF_3 \rightarrow CF_2 + F + e^-$$

$$e^- + CF_2 \rightarrow CF + F + e^-$$

Plasma Chemistry II

- **Dissociative ionization and attachment:**

$$e^- + CF_4 \rightarrow CF_3^+ + F + 2e^-$$

$$e^- + CF_4 \rightarrow CF_3^- + F$$

$$e^- + CF_4 \rightarrow CF_3 + F^-$$

- **Chlorine discharge**

$$e^- + Cl_2 \rightarrow Cl_2^+ + 2e^-$$

$$e^- + Cl_2 \rightarrow Cl^+ + Cl + 2e^-$$

Plasma Chemistry III

- **Chemical reactions between neutrals in the presence of a third body**

$$CF_3 + F + M \rightarrow CF_4 + M$$
$$CF_2 + F + M \rightarrow CF_3 + M$$
$$CF + F + M \rightarrow CF_2 + M$$

- **At the substrate**
- **Removing**

$$Cl(g) + Cl(ads) \rightarrow Cl_2(g)$$

- **Etching**

$$Cl(g) + SiCl_3(s) \rightarrow SiCl_4(g)\uparrow$$

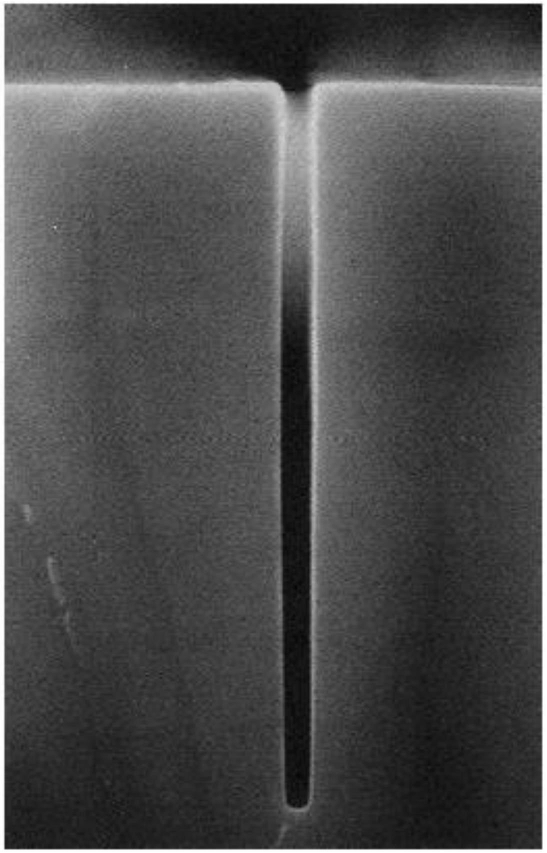
- **Deposition or growth**

$$SiH(g) \rightarrow Si(s)\downarrow + H(g)\uparrow$$

Plasma Etching

- An etched profile with
  - 0.5 micrometer (500 Nanometer) wide
  - 4 micrometer (4000 nanometer)
- Such profiles are used for device isolation and charge storage capacitores.

- Human hair is 50-100 micrometer in diameter.



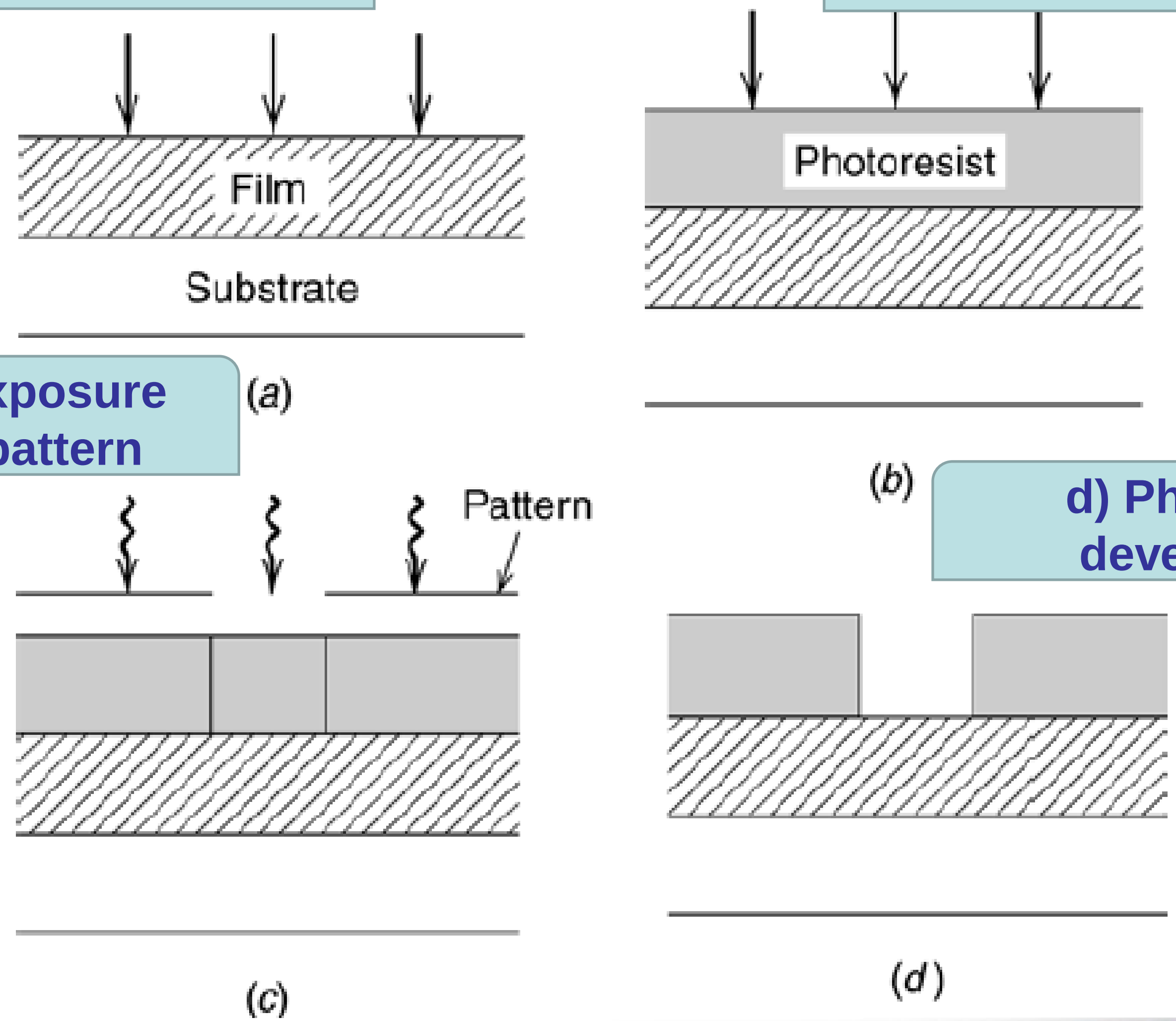
Plasma Etching steps I

a) Metal Deposition

b) Photoresist deposition

c) Optical exposure through a pattern

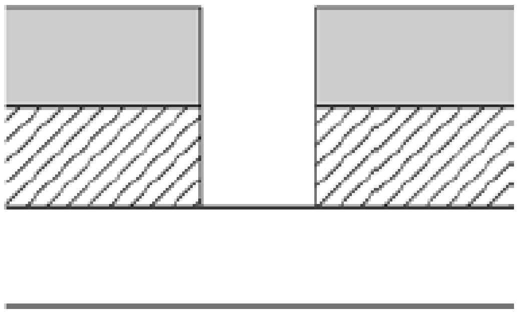
d) Photoresist development



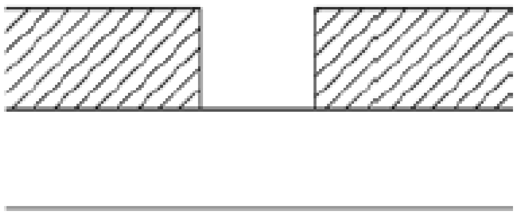
Plasma Etching steps II

e) Anisotropic etching

f) Photoresist removal



(e)



(f)

- **Process Selectivity:**
  - **Depends on the plasma species**
  - **Energy threshold & energy activation**

Wet and Dry etching

- **Carbon Floride (CF4) does not react with Silicin (Si).**

- **Dissociative ionization and attachment:**

$$e^- + CF_4 \rightarrow CF_3^+ + F + 2e^-$$

$$e^- + CF_4 \rightarrow CF_3^- + F$$

$$e^- + CF_3 \rightarrow CF_3 + F^-$$

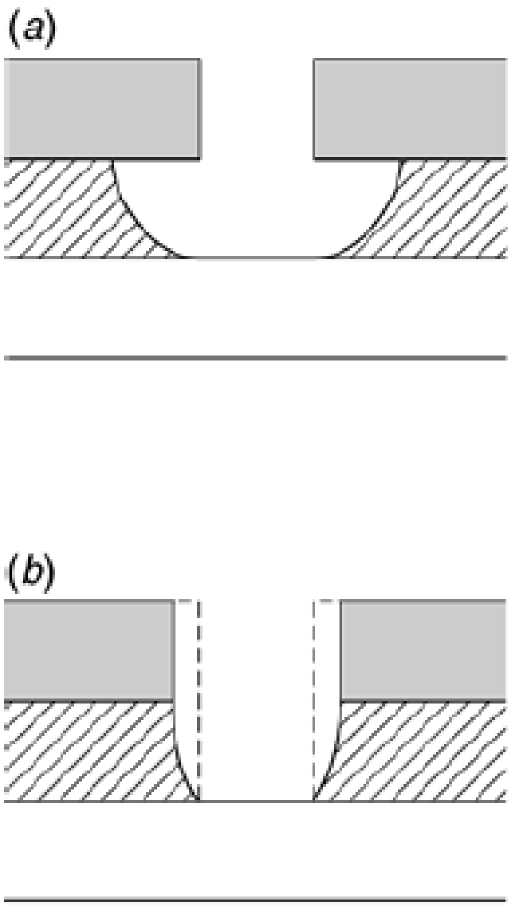
- **Wet etching**

$$\mathrm{Si}(s) + 4\mathrm{F}(g) \rightarrow \mathrm{SiF}_4(g) \uparrow$$

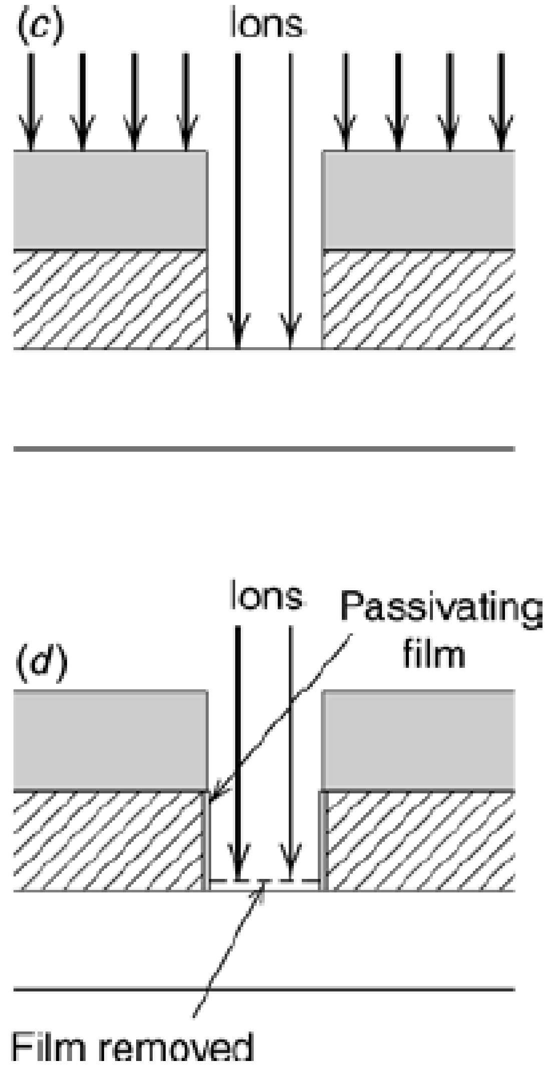
- **Dry etching: Accelerate CF_3^+ toward the Silicon substrate**

Plasma Etching steps II

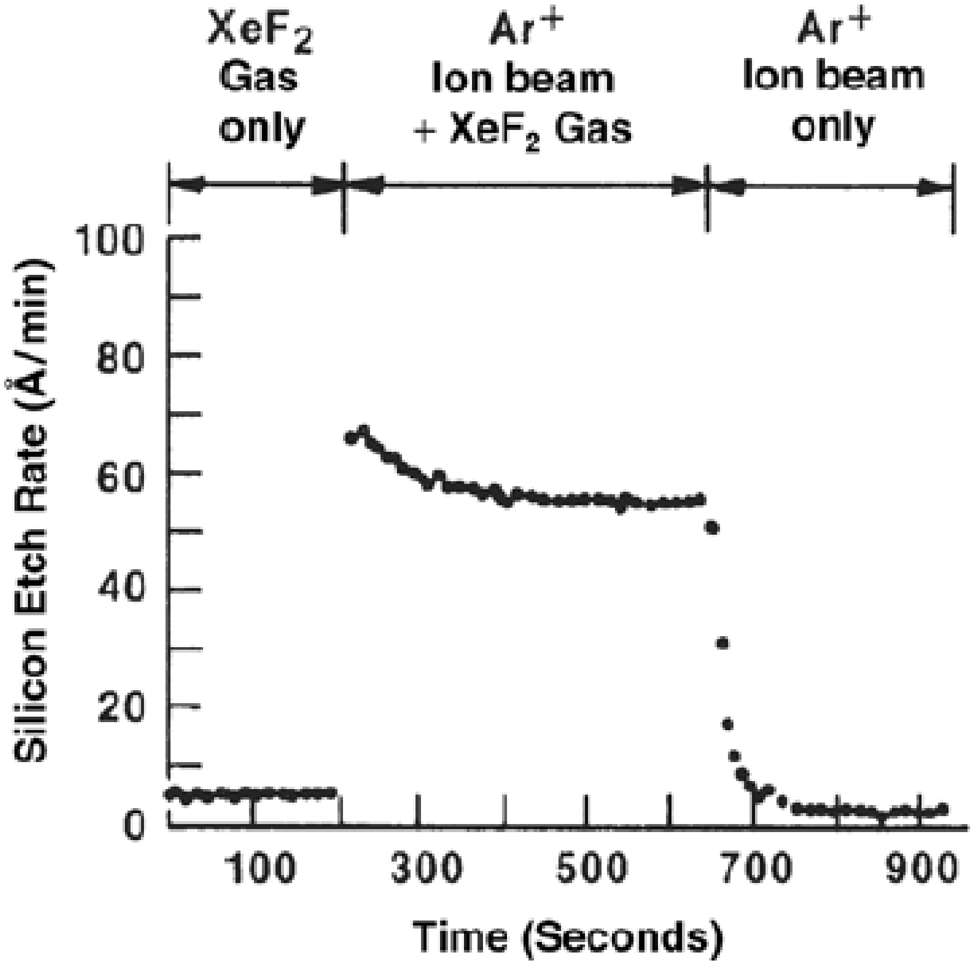
Wet etching
Chemical etching



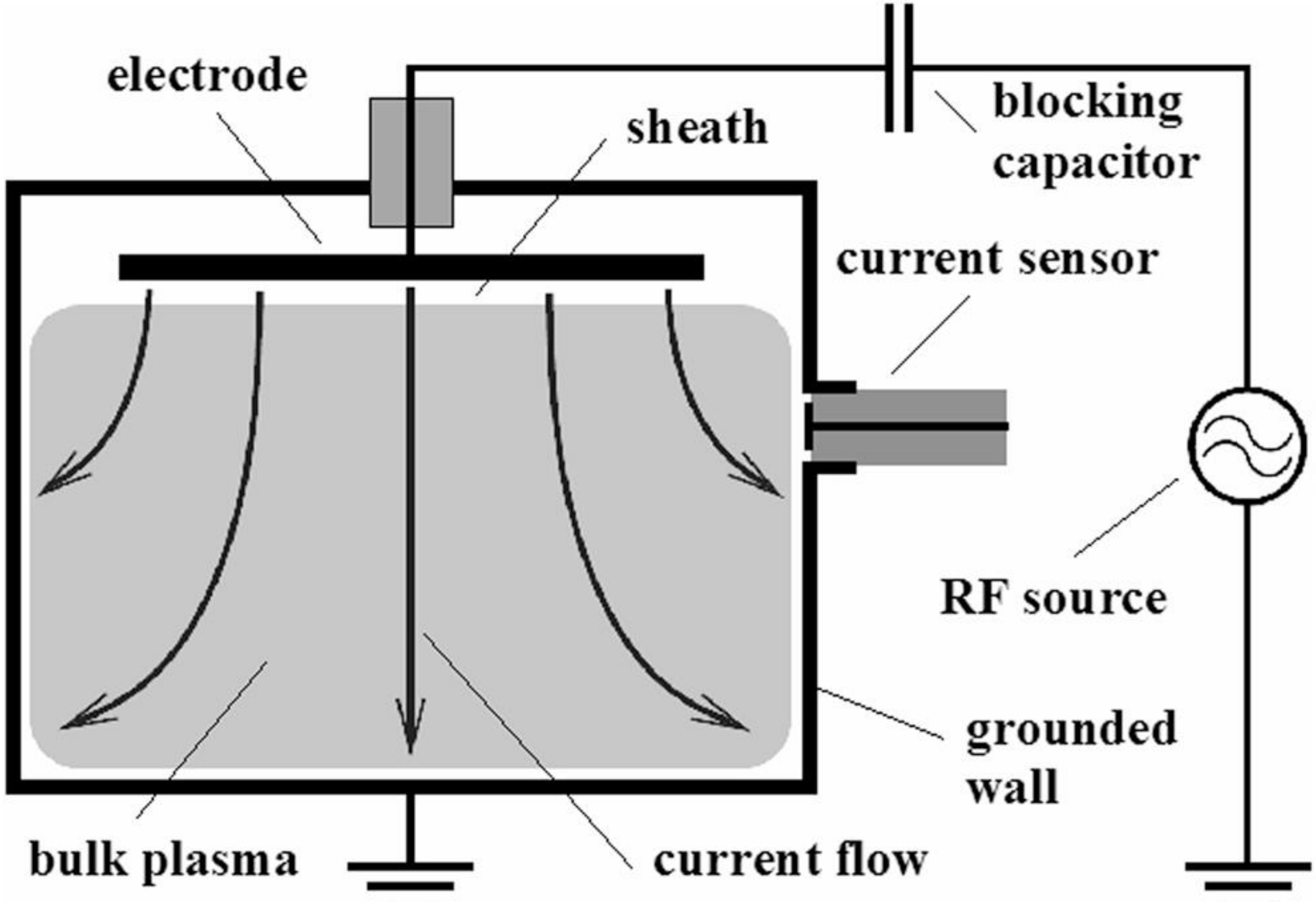
Dry etching



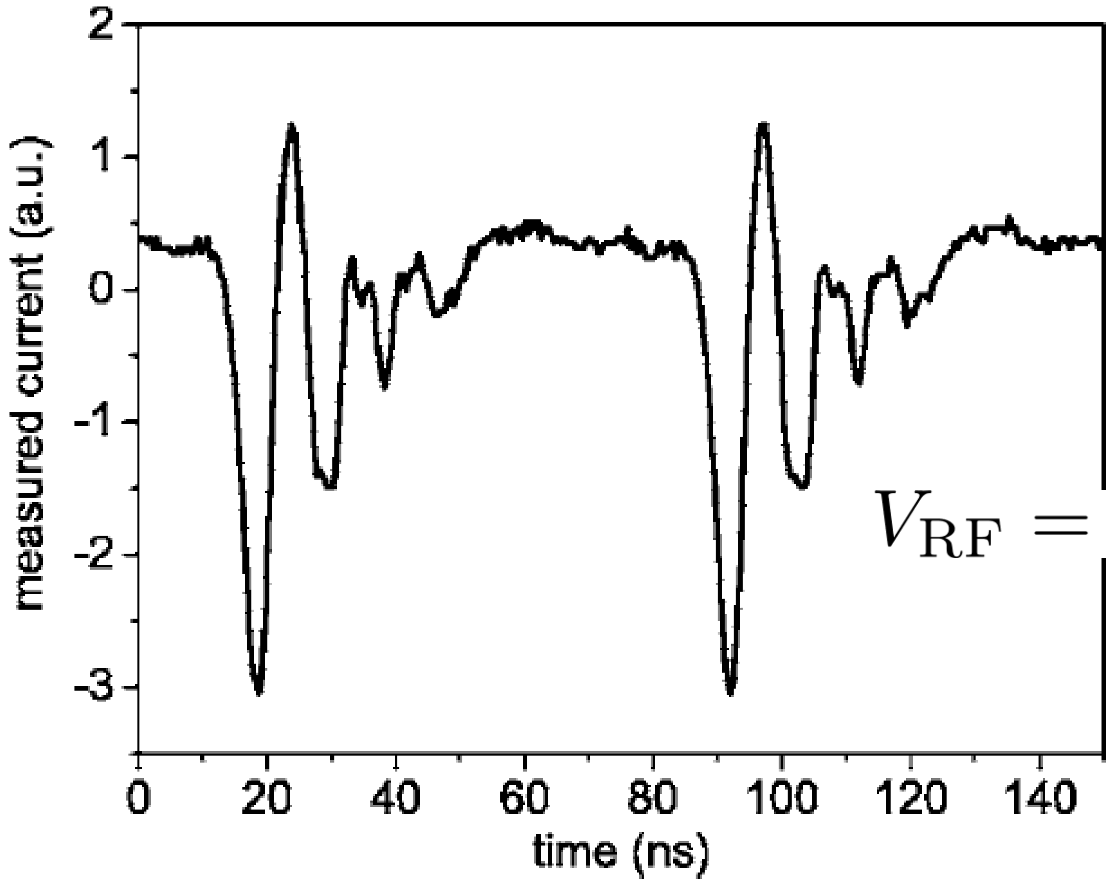
Ion enhanced plasma etching



Why do we need an electrical model?



Measured Current

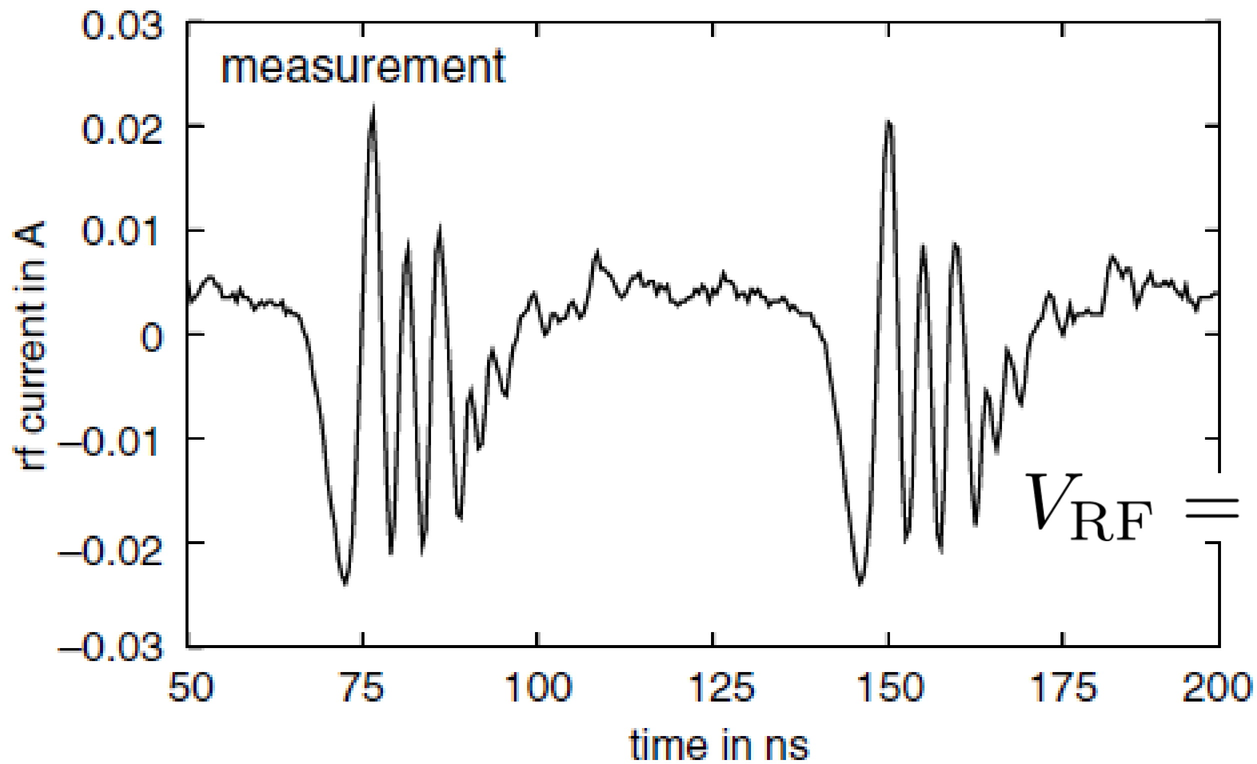


$$V_{\mathrm{RF}} = 13.56\mathrm{MHz}$$

123503-2 Czarnetzki, Mussenbrock, and Brinkmann Phys. Plasmas **13**, 123503 (2006)

[21] E. Semmler and P. Awakowicz, private communication (2006).

Measured Current



$$V_{\mathrm{RF}} = 13.56\mathrm{MHz}$$

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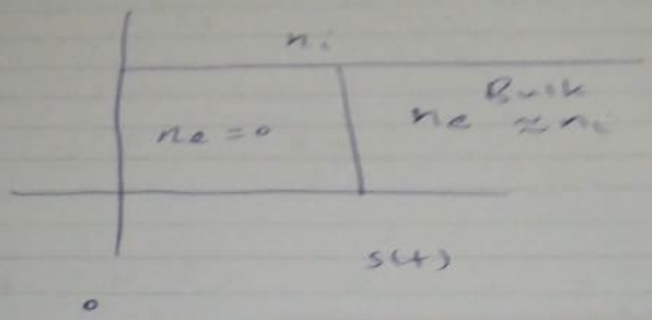
[14] Semmler E and Awakowicz P 2006 private communication

Sheath Model

Title:

sheath model



$$\frac{d^2\phi}{dx^2} = \frac{-e}{\varepsilon_0} n_i \longrightarrow (1)$$

let $\alpha = e \int n_i \, dx \longrightarrow (2)$

then from (1)

$$\frac{d\phi}{dx} = \frac{-e}{\varepsilon_0} n_i \, dx$$

$$\therefore \frac{d\phi}{dx} = \frac{-\alpha}{\varepsilon_0} \longrightarrow (3)$$

Sheath Model

Title:

$$\therefore \sigma = e \int n_i \, dx$$

$$\therefore \frac{d\sigma}{dx} = e n_i$$

then from (3)

$$\frac{d\phi}{d\sigma} \cdot \frac{d\sigma}{dx} = -\frac{\sigma}{\varepsilon_0}$$

$$\therefore \frac{d\phi}{d\sigma} \cdot e n_i = \frac{-\sigma}{\varepsilon_0}$$

$$\therefore \frac{d\phi}{d\sigma} = \frac{-\sigma}{e \varepsilon_0 n_i}$$

$$\therefore \phi_{sheath} = \frac{-\sigma^2}{2 \varepsilon_0 n_i}$$

σ is charge density

$$\therefore \phi_{sheath} = \frac{-Q^2}{2 \varepsilon_0 n_i A^2}$$

Bulk Model

Title:

Bulk model

start from momentum equation

$$m \frac{\partial v}{\partial t} + m_e v_e \frac{\partial v_e}{\partial x} = -eE - m_e v_e \nu_e$$

the plasma bulk is homogeneous

$$\therefore \frac{\partial v_e}{\partial x} = 0$$

$$\therefore m \frac{\partial v}{\partial t} = -eE - m_e v_e \nu_e$$

$$E = -\frac{\partial \phi}{\partial x}$$

$$m_e \frac{\partial v}{\partial t} = e \frac{\partial \phi}{\partial x} - m_e v_e \nu_e$$

$$\therefore m_e \frac{\partial v}{\partial t} + m_e v_e \nu_e = e \frac{\partial \phi}{\partial x}$$

from definition $\Rightarrow J = e n_e v_e$

Bulk Model

Title:

$\therefore\ I(t) = e\, n_e\, v_e\, A \Rightarrow v_e = \frac{I(t)}{e\, n_e\, A}$

$\therefore\ v_e = \frac{I(t)}{e\, n_e\, A}$

$$m_e \frac{\partial v}{\partial t} + m_e\, v_e\, \nu_e = e \frac{d\varphi}{dx}$$

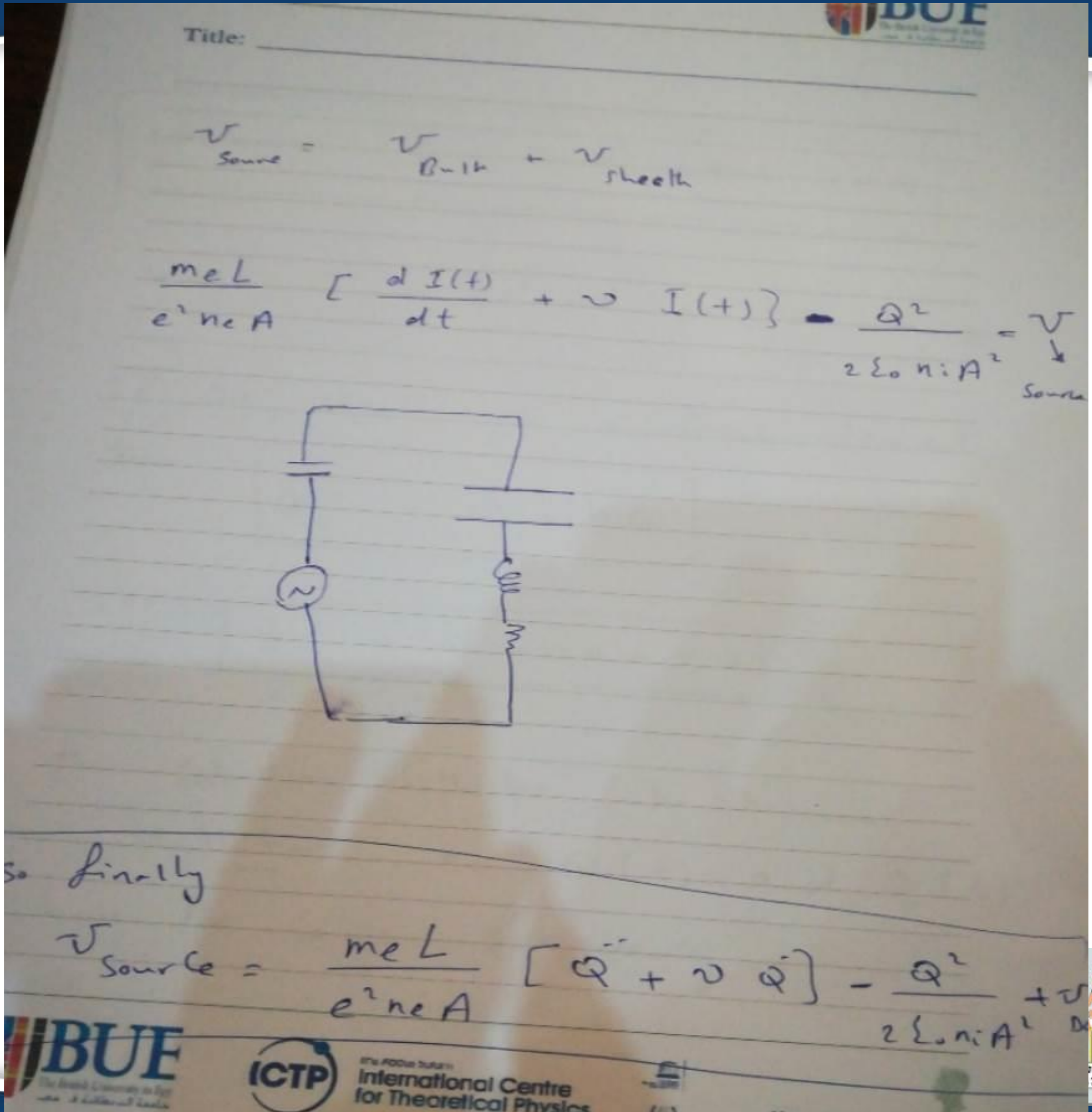
$$\left(m_e \frac{\partial}{\partial t} + m\nu\right) v = e \frac{d\varphi}{dx}$$

$$\int_{x_1}^{x_2} \frac{m_e}{e} \left[\frac{\partial}{\partial t} + \nu\right) v\, dx = \varphi_{21}$$

$$\frac{m_e}{e} \left[\frac{\partial}{\partial t} + \nu\right)\Big] \int \frac{I(t)}{e\, n_e\, A}\, dx = \varphi_{21}$$

$$\therefore\ \frac{m_e L}{e^2 n_e A} \left[\frac{\partial}{\partial t} + \nu\right) I(t) = \varphi_{21}$$

Bulk Model



Title:
$V_{Source} = V_{Bulk} + V_{sheath}$
$\frac{m_e L}{e^2 n_e A}\left[\frac{dI(t)}{dt} + \nu I(t)\right] - \frac{Q^2}{2\varepsilon_0 n_i A^2} = V_{Source}$
So finally
$V_{Source} = \frac{m_e L}{e^2 n_e A}\left[\ddot{Q} + \nu \dot{Q}\right] - \frac{Q^2}{2\varepsilon_0 n_i A^2} + V$
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Bulk Model

Title:

which is $\Phi = a\ddot{Q} + b\dot{Q} + cQ^2$

where Q is the net positive charge.

If the sheath is a linear element then

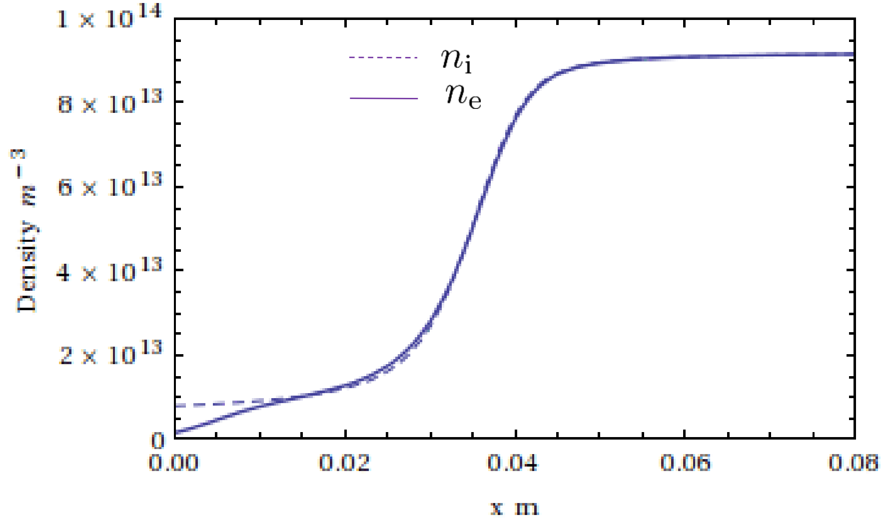
$$\Phi = a\ddot{Q} + b\dot{Q}$$

or

$$\Phi = a\ddot{Q} + b\dot{Q} + cQ$$

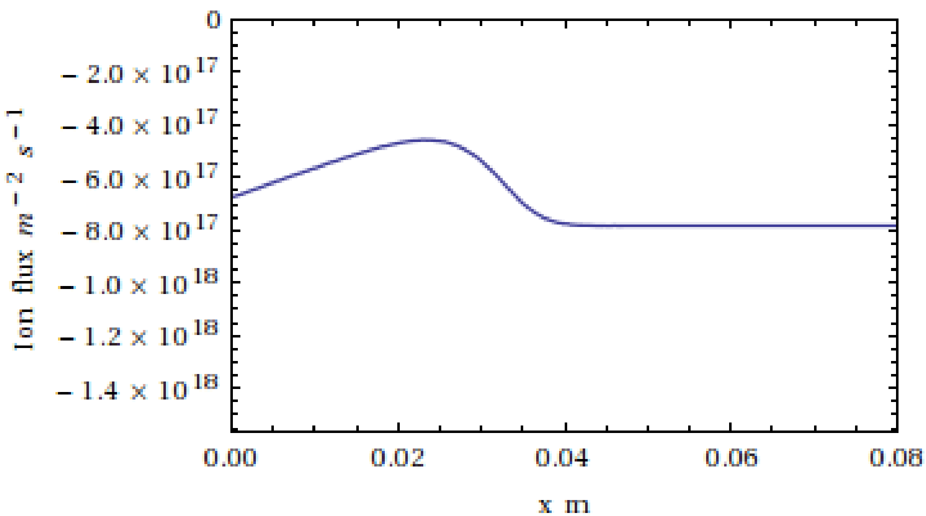
the solution will be like harmonic oscillator. so $Q(t)$ and $\Phi(t)$ have the same frequency.

Ion Dynamics

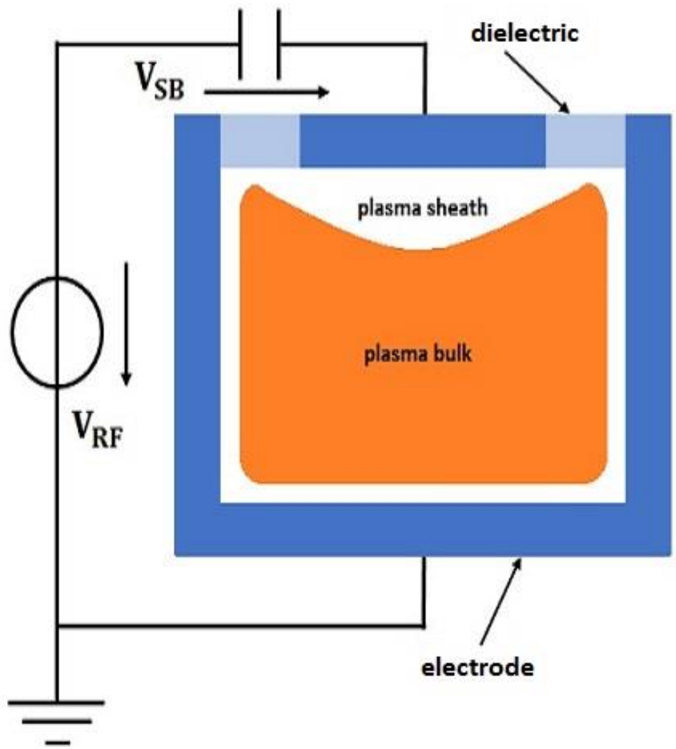


- The intermediate regime

$$\omega_{\mathrm{RF}} \approx \omega_{\mathrm{pi}}$$



lumped model circuit of CCPs at the intermediate radio-frequencies



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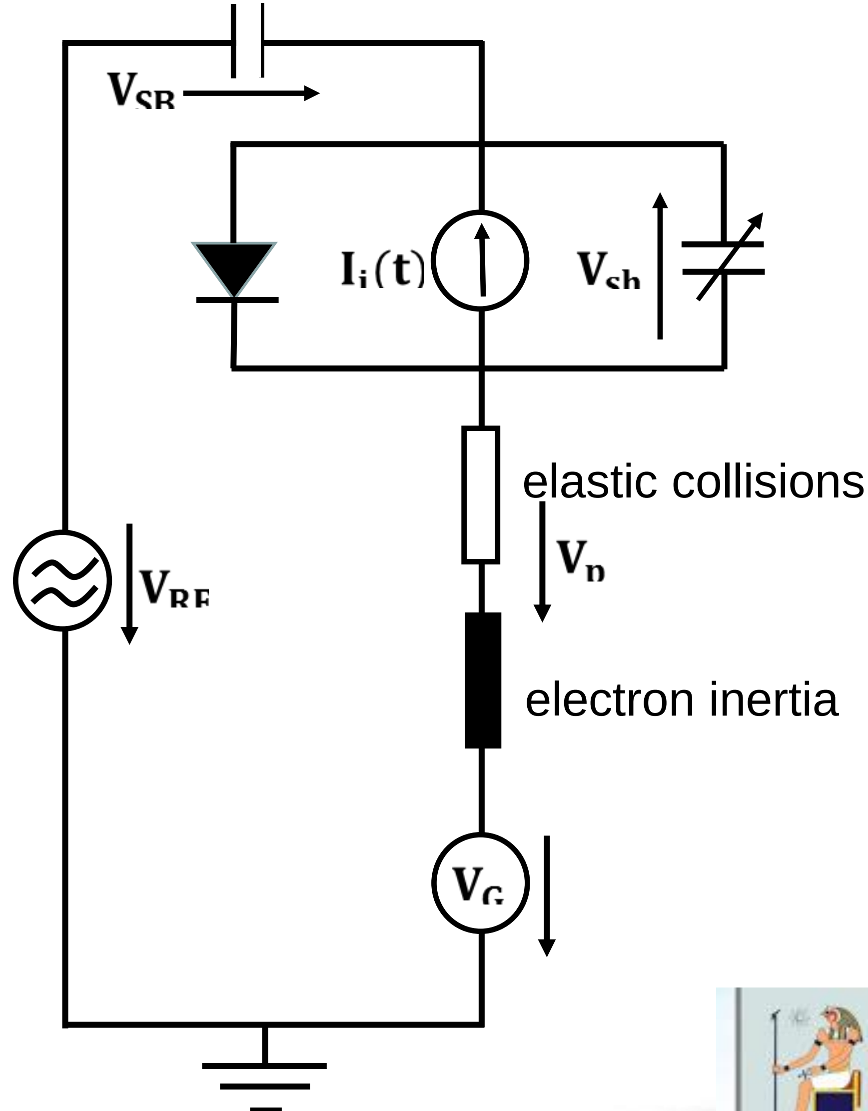
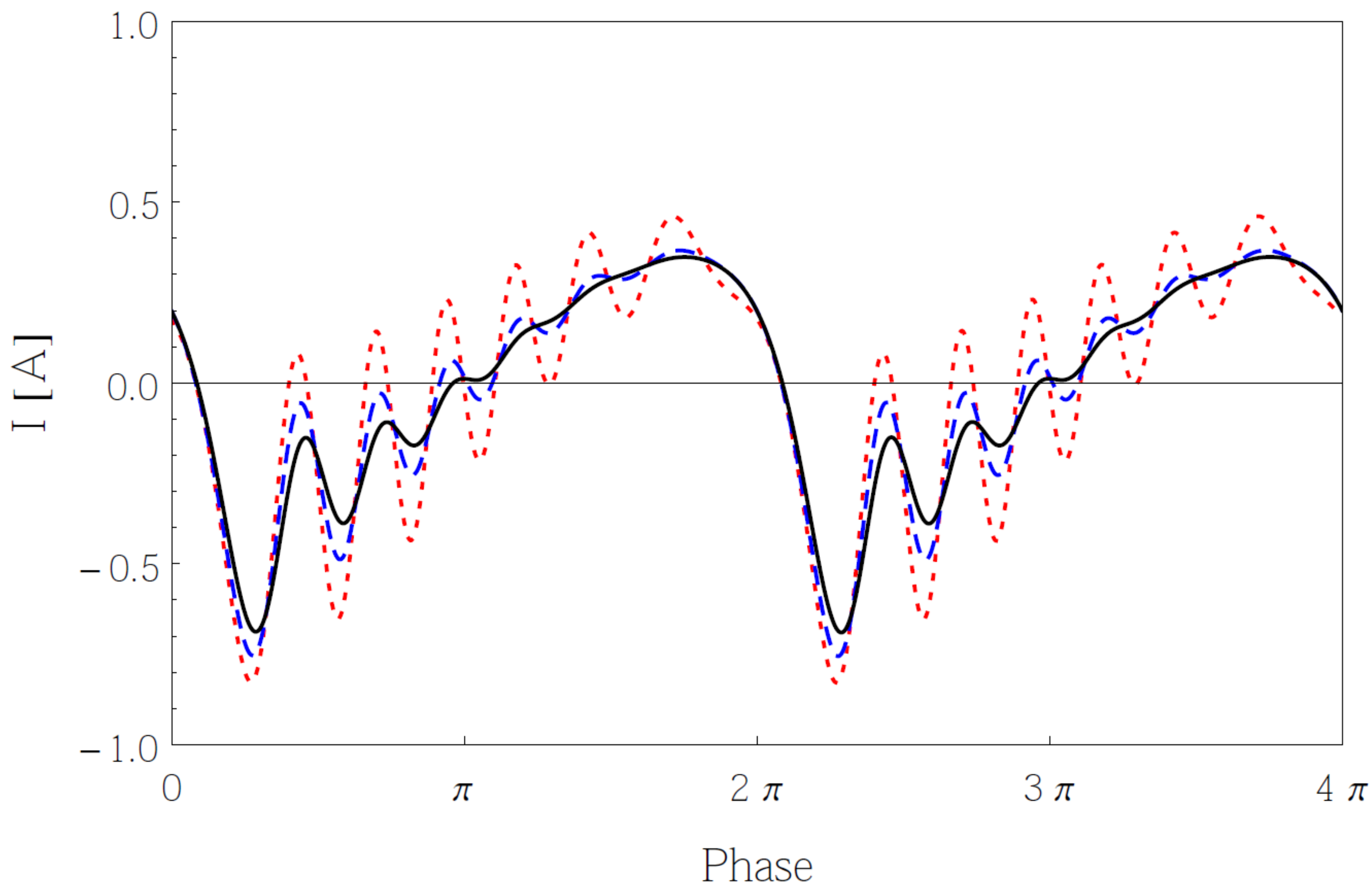
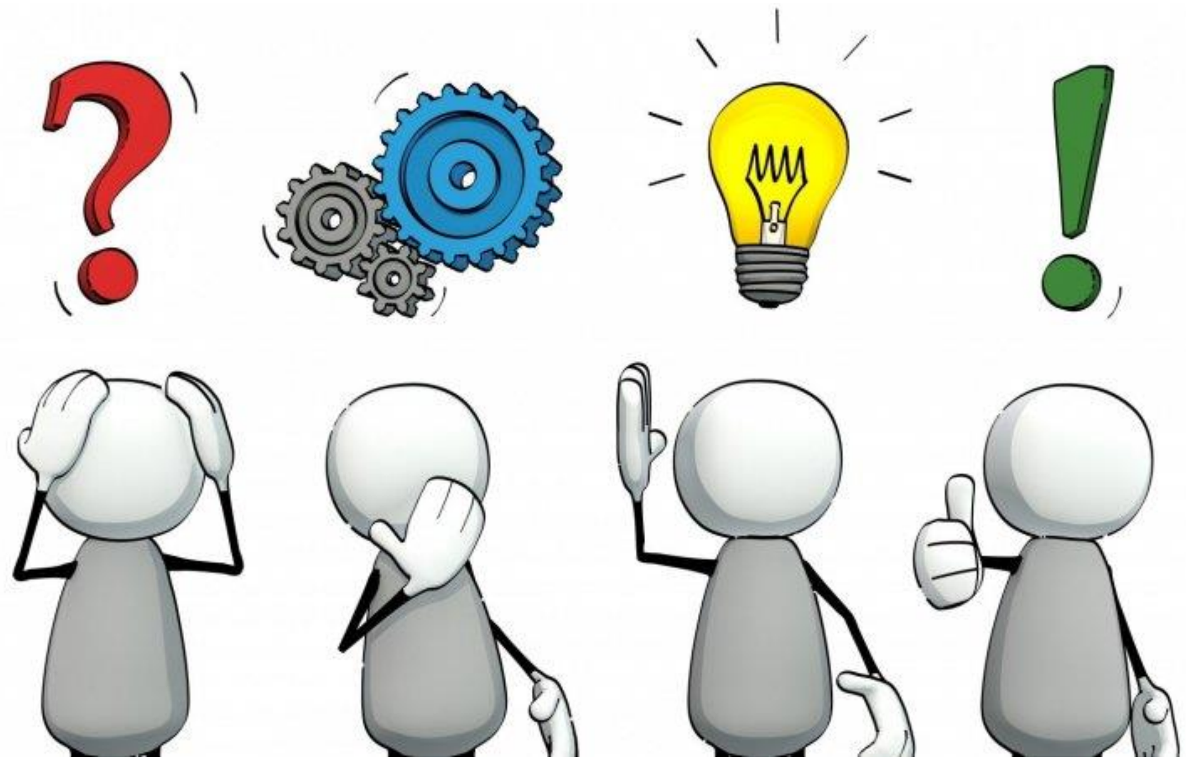




- **50 mTorr Black, 30 mTorr Blue, 10 mTorr Red**
- **13.56 MHz**



Thanks!