A MINI-COURSE ON THE PRINCIPLES OF LOW-PRESSURE DISCHARGES AND MATERIALS PROCESSING

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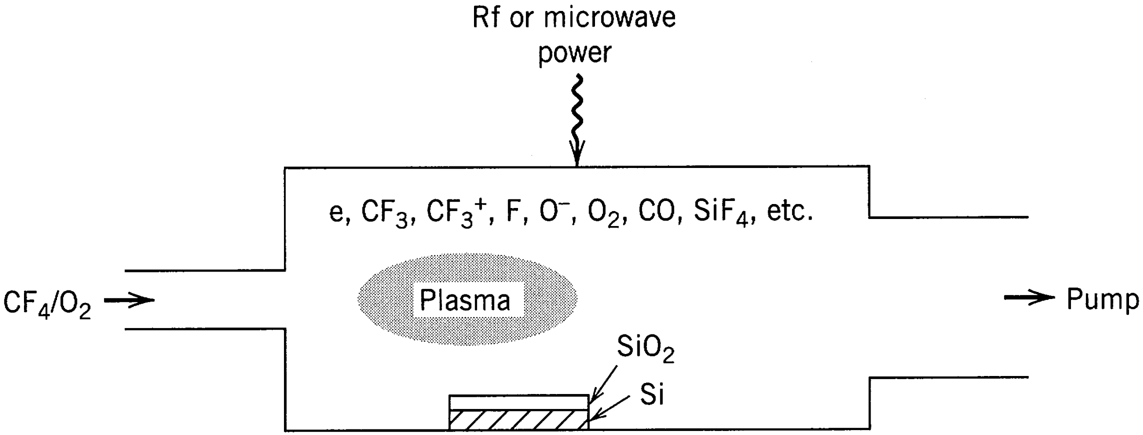


OUTLINE

- Introduction
- Summary of Plasma and Discharge Fundamentals
- Global Model of Discharge Equilibrium

— Break —

- Inductive Discharges
- Reactive Neutral Balance in Discharges
- Adsorption and Desorption Kinetics
- Plasma-Assisted Etch Kinetics

INTRODUCTION TO PLASMA DISCHARGES AND PROCESSING

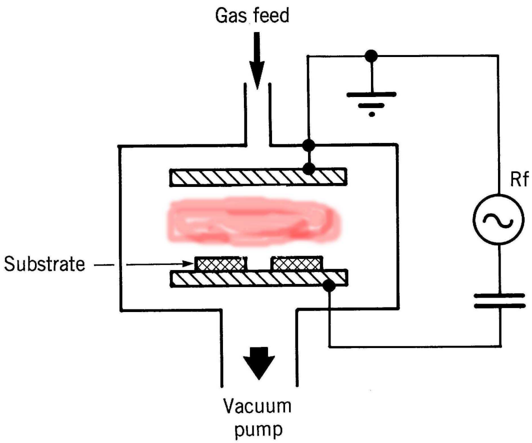
THE NANOELECTRONICS REVOLUTION

- Transistors/chip doubling every $1\frac{1}{2}$–2 years since 1959
- 1,000,000-fold decrease in cost for the same performance

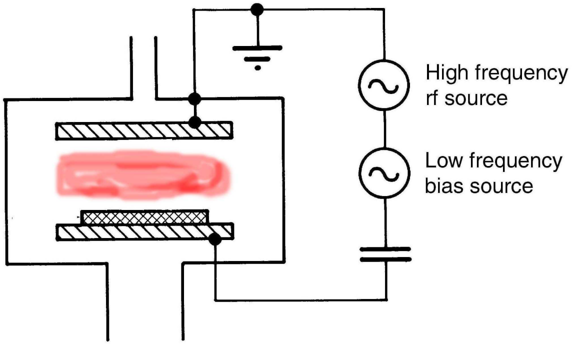
EQUIVALENT AUTOMOTIVE ADVANCE

- 4 million km/hr
- 1 million km/liter
- Never break down
- Throw away rather than pay parking fees
- 3 cm long × 1 cm wide
- Crash 3× a day

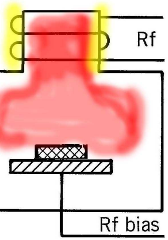
EVOLUTION OF ETCHING DISCHARGES



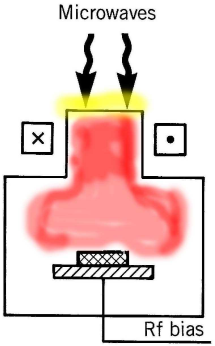
Capacitive
(Anisotropic etch)



Dual frequency
capacitive discharge



Inductive



ECR

ISOTROPIC PLASMA ETCHING

1. Start with inert molecular gas CF_4
2. Make discharge to create reactive species:

$$CF_4 \longrightarrow CF_3 + F$$

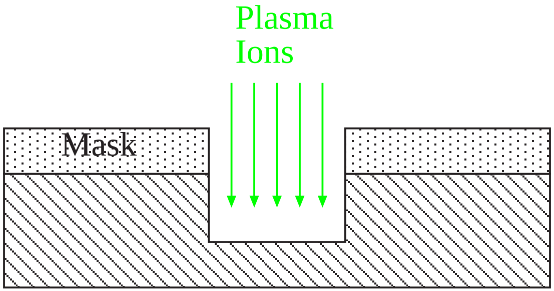
3. Species reacts with material, yielding volatile product:

$$Si + 4F \longrightarrow SiF_4 \uparrow$$

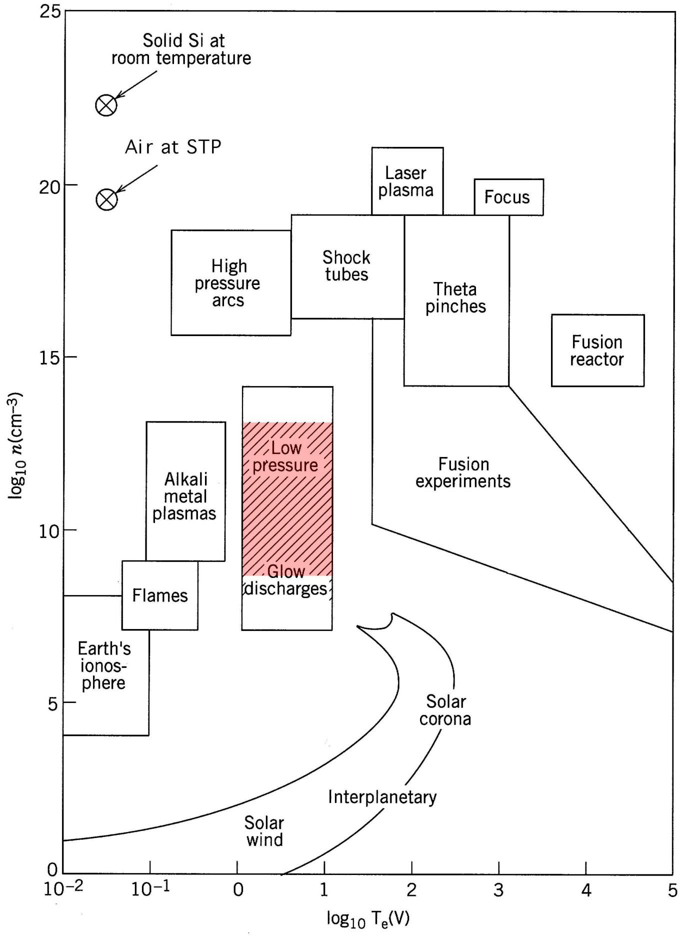
4. Pump away product

ANISOTROPIC PLASMA ETCHING

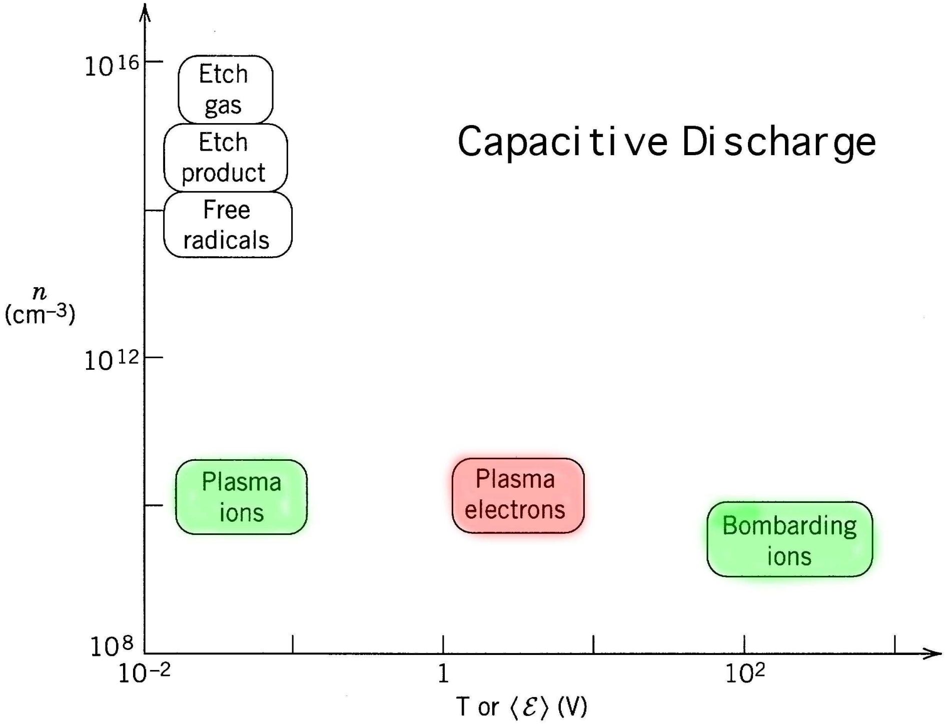
5. Energetic ions bombard trench bottom, but not sidewalls:
   (a) Increase etching reaction rate at trench bottom
   (b) Clear passivating films from trench bottom



PLASMA DENSITY VERSUS TEMPERATURE



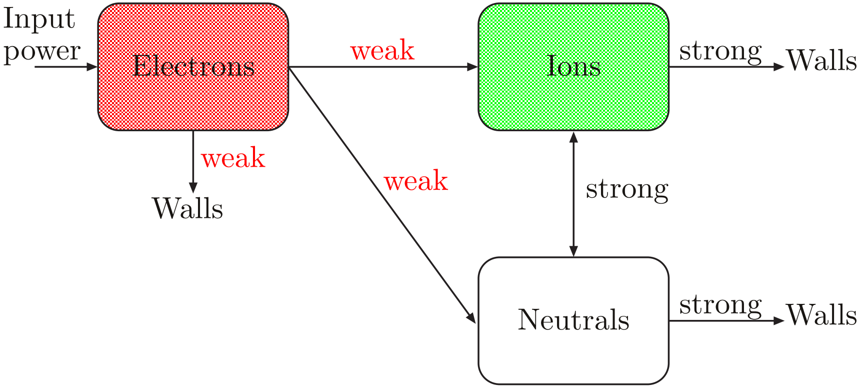
RELATIVE DENSITIES AND ENERGIES



Charged particle densities $\ll$ neutral particle densities

NON-EQUILIBRIUM

- Energy coupling between electrons and heavy particles is weak



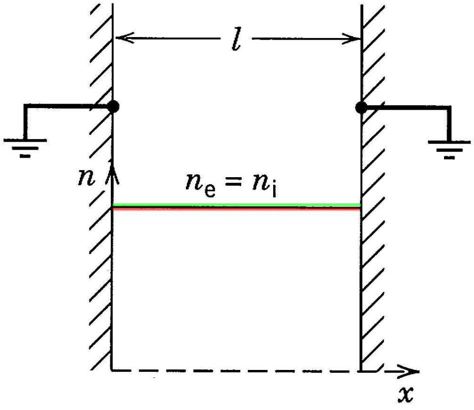
- Electrons are *not* in thermal equilibrium with ions or neutrals

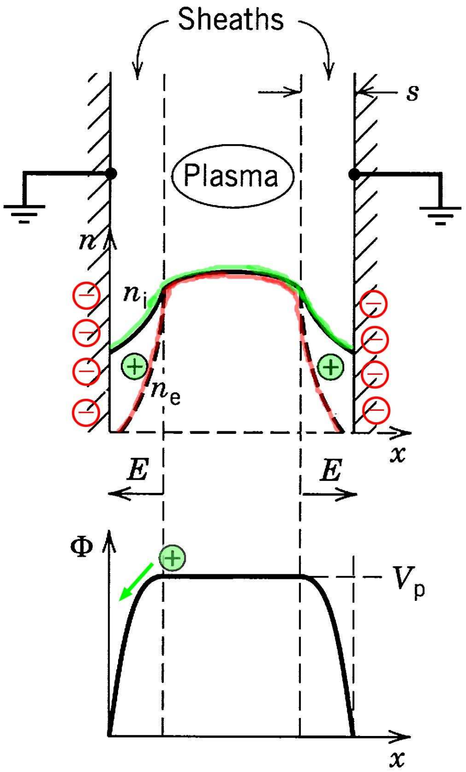
$$\boxed{\begin{array}{c} T_e \gg T_i \quad \text{in plasma bulk} \\ \text{Bombarding } \mathcal{E}_i \gg \mathcal{E}_e \quad \text{at wafer surface} \end{array}}$$

- “High temperature processing at low temperatures”
  1. Wafer can be near room temperature
  2. Electrons produce free radicals $\Longrightarrow$ chemistry
  3. Electrons produce electron-ion pairs $\Longrightarrow$ ion bombardment

ELEMENTARY DISCHARGE BEHAVIOR

- Uniform density of electrons and ions n_e and n_i at time $t = 0$
- Low mass warm electrons quickly drain to the wall, forming sheaths





- Ion bombarding energy $\mathcal{E}_i$
  $= \text{plasma-wall potential } V_p$

- Separation into bulk plasma and sheaths occurs for ALL discharges

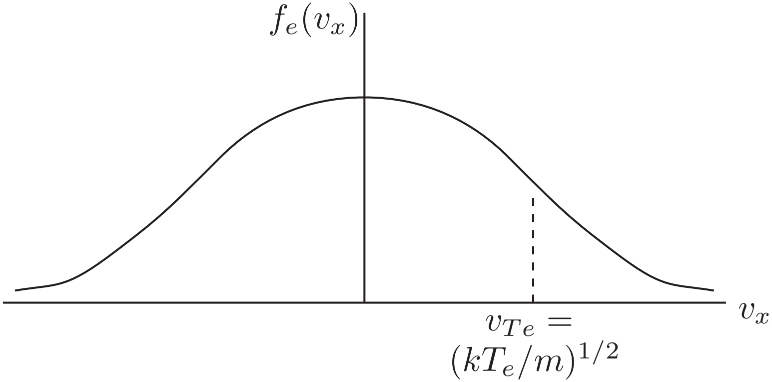
SUMMARY OF PLASMA FUNDAMENTALS

THERMAL EQUILIBRIUM PROPERTIES

- Electrons generally near thermal equilibrium
  Ions generally *not* in thermal equilibrium
- Maxwellian distribution of electrons

$$f_e(v) = n_e \left(\frac{m}{2\pi kT_e}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT_e}\right)$$

where $v^2 = v_x^2 + v_y^2 + v_z^2$



- Pressure $p = nkT$
  For neutral gas at room temperature (300 K)

$$\boxed{n_g[\mathrm{cm}^{-3}] \approx 3.3 \times 10^{16}\, p[\mathrm{Torr}]}$$

AVERAGES OVER MAXWELLIAN DISTRIBUTION

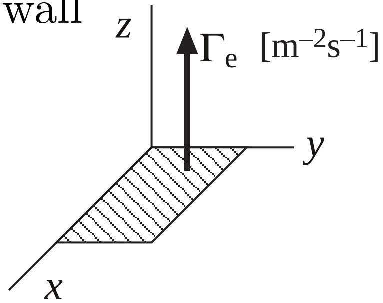
- Average energy

$$\langle \tfrac{1}{2}mv^2 \rangle = \tfrac{1}{n_e}\int d^3v\, \tfrac{1}{2}mv^2 f_e(v) = \tfrac{3}{2}kT_e$$

- Average speed

$$\bar{v}_e = \frac{1}{n_e}\int d^3v\, v\, f_e(v) = \boxed{\left(\frac{8kT_e}{\pi m}\right)^{1/2}}$$

- Average electron flux lost to a wall



$$\Gamma_e = \int_{-\infty}^{\infty} dv_x \int_{-\infty}^{\infty} dv_y \int_{0}^{\infty} dv_z v_z f_e(v) = \boxed{\frac{1}{4}n_e\bar{v}_e} \quad [\mathrm{m}^{-2}\text{-}\mathrm{s}^{-1}]$$

- Average kinetic energy lost per electron lost to a wall

$$\boxed{\mathcal{E}_e = 2\,\mathrm{T}_e}$$

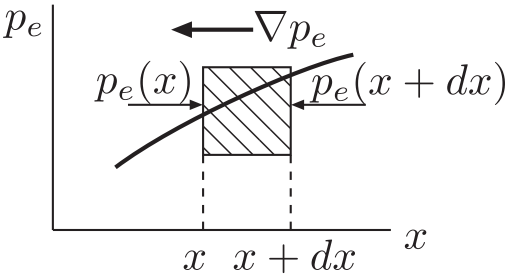
FORCES ON PARTICLES

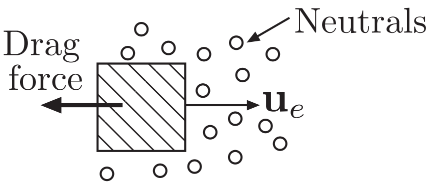
- For a unit volume of electrons (or ions)

$$\boxed{mn_e\frac{d\mathbf{u}_e}{dt} = qn_e\mathbf{E} - \nabla p_e - mn_e\nu_m\mathbf{u}_e}$$

mass × acceleration = electric field force +
+ pressure gradient force + friction (gas drag) force

- m = electron mass
  n_e = electron density
  $\mathbf{u}_e$ = electron flow velocity
  $q = -e$ for electrons ($+e$ for ions)
  $\mathbf{E}$ = electric field
  $p_e = n_e kT_e$ = electron pressure
  ν_m = collision frequency of electrons with neutrals





BOLTZMANN FACTOR FOR ELECTRONS

- If electric field and pressure gradient forces almost balance

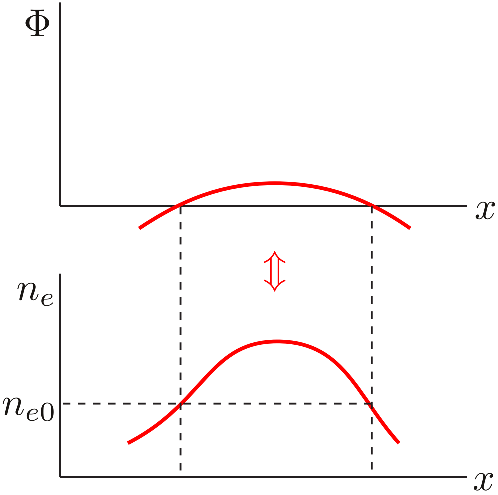
$$0 \approx -en_e\mathbf{E} - \nabla p_e$$

- Let $\mathbf{E} = -\nabla\Phi$ and $p_e = n_e kT_e$

$$\nabla\Phi = \frac{kT_e}{e}\frac{\nabla n_e}{n_e}$$

- Put $kT_e/e = \mathrm{T}_e$ (volts) and integrate to obtain

$$\boxed{n_e(\mathbf{r}) = n_{e0}\,\mathrm{e}^{\Phi(\mathbf{r})/\mathrm{T}_e}}$$



PLASMA DIELECTRIC CONSTANT ϵ_{p}

- RF discharges are driven at a frequency ω

$$E(t) = \mathrm{Re}\,(\widetilde{E}\,\mathrm{e}^{j\omega t}), \quad \text{etc.}$$

- Define ϵ_p from the total current in Maxwell's equations

$$\nabla \times \tilde{H} = \underbrace{\tilde{J}_c + j\omega\epsilon_0\widetilde{E}}_{\text{Total current } \tilde{J}} \equiv j\omega\epsilon_p\widetilde{E}$$

- Conduction current is $\tilde{J}_c = -en_e\tilde{u}_e$

  Newton's law is $j\omega m\tilde{u}_e = -e\widetilde{E} - m\nu_m\tilde{u}_e$

  Solve for $\tilde{u}_e$ and evaluate $\tilde{J}_c$ to obtain

$$\boxed{\epsilon_p \equiv \epsilon_0\kappa_p = \epsilon_0\left[1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_m)}\right]}$$

  with $\omega_{pe} = (e^2n_e/\epsilon_0 m)^{1/2}$ the electron plasma frequency

- For $\omega \gg \nu_m$, ϵ_p is mainly real (nearly lossless dielectric)

PLASMA CONDUCTIVITY $\sigma_\mathbf{p}$

- It is useful to introduce rf plasma conductivity $\tilde{J}_c \equiv \sigma_p \widetilde{E}$
- Since $\tilde{J}_c$ is a linear function of $\widetilde{E}$ [p. 16]

$$\sigma_p = \frac{e^2 n_e}{m(\nu_m + j\omega)}$$

- DC plasma conductivity ($\omega \ll \nu_m$)

$$\boxed{\sigma_{\mathrm{dc}} = \frac{e^2 n_e}{m\nu_m}}$$

- RF current flowing through the plasma heats electrons (just like a resistor)

SUMMARY OF DISCHARGE FUNDAMENTALS

ELECTRON COLLISIONS WITH ARGON

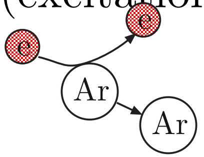
- Maxwellian electrons collide with Ar atoms (density n_g)

$$\frac{\#\ \text{collisions of a particular kind}}{\text{s-m}^3} = \nu n_e = K n_g \, n_e$$

ν = collision frequency [s^{-1}], $K(T_e)$ = rate coefficient [m^3/s]

- Electron-Ar collision processes

$\text{e} + \text{Ar} \longrightarrow \text{Ar}^+ + 2\text{e}$ (ionization)
$\text{e} + \text{Ar} \longrightarrow \text{e} + \text{Ar}^* \longrightarrow \text{e} + \text{Ar} +$ photon (excitation)
$\text{e} + \text{Ar} \longrightarrow \text{e} + \text{Ar}$ (elastic scattering)

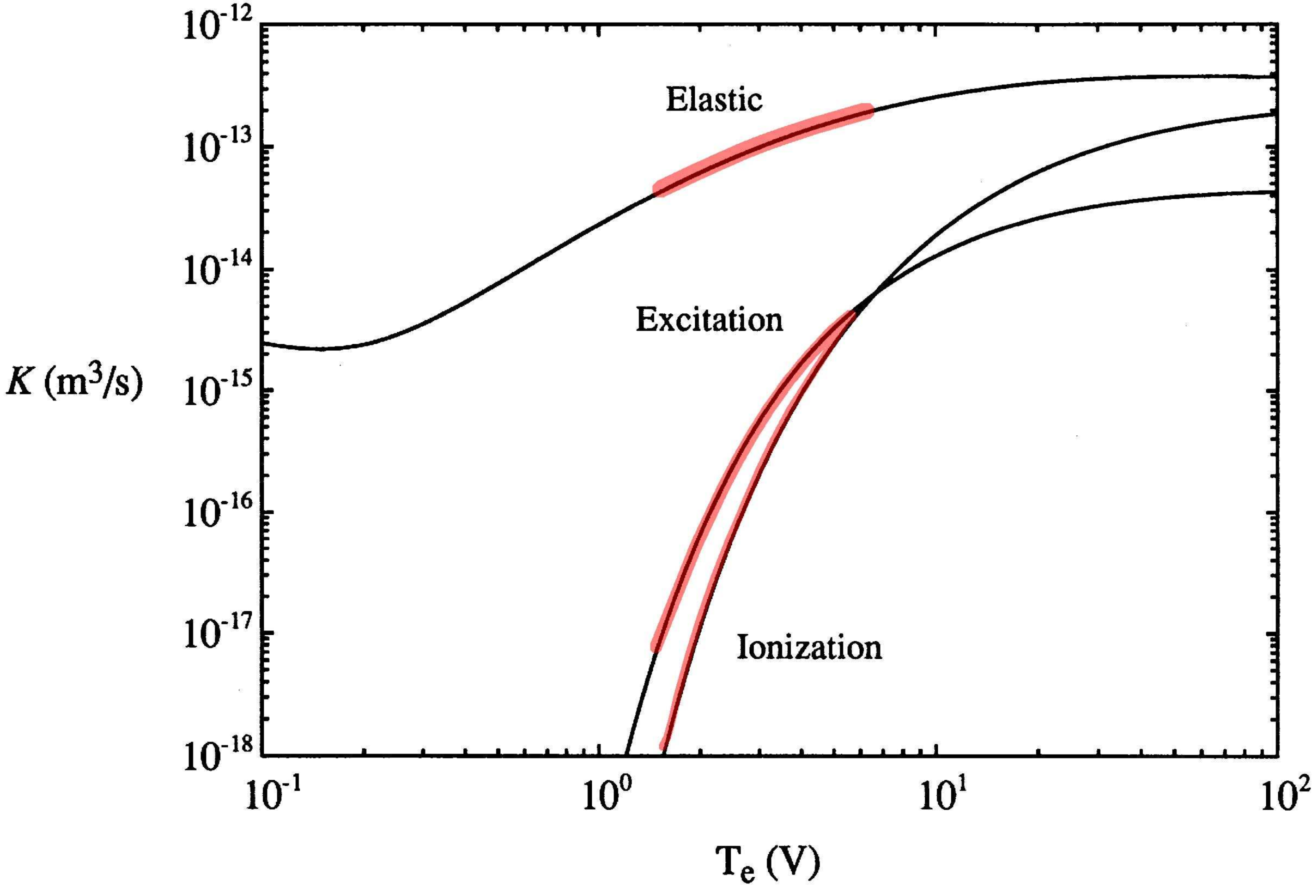


- Rate coefficient $K(T_e)$ is average of cross section $\sigma(v_R)$ [m^2] over Maxwellian distribution

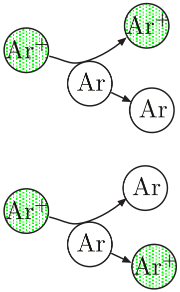
$$K(T_e) = \langle \sigma \, v_R \rangle_{\text{Maxwellian}}$$

v_R = relative velocity of colliding particles

ELECTRON-ARGON RATE COEFFICIENTS



ION COLLISIONS WITH ARGON



- Argon ions collide with Ar atoms
  $\mathrm{Ar}^+ + \mathrm{Ar} \longrightarrow \mathrm{Ar}^+ + \mathrm{Ar}$ (elastic scattering)
  $\mathrm{Ar}^+ + \mathrm{Ar} \longrightarrow \mathrm{Ar} + \mathrm{Ar}^+$ (charge transfer)
- Total cross section for room temperature ions $\sigma_i \approx 10^{-14}\ \mathrm{cm}^2$
- Ion-neutral mean free path (distance ion travels before colliding)

$$\boxed{\lambda_i = \frac{1}{n_g \sigma_i}}$$

- Practical formula

$$\boxed{\lambda_i(\mathrm{cm}) = \frac{1}{330\,p}, \qquad p \text{ in Torr}}$$

THREE ENERGY LOSS PROCESSES

1. Collisional energy $\mathcal{E}_c$ lost per electron-ion pair created

$$K_{\rm iz}\mathcal{E}_c = K_{\rm iz}\mathcal{E}_{\rm iz} + K_{\rm ex}\mathcal{E}_{\rm ex} + K_{\rm el}(2m/M)(3{\rm T}_e/2)$$

$$\Longrightarrow \mathcal{E}_c({\rm T}_e) \qquad \text{(voltage units)}$$

$\mathcal{E}_{\rm iz}$, $\mathcal{E}_{\rm ex}$, and $(3m/M){\rm T}_e$ are energies lost by an electron due to an ionization, excitation, and elastic scattering collision

2. Electron kinetic energy lost to walls

$$\mathcal{E}_e = 2\,{\rm T}_e$$

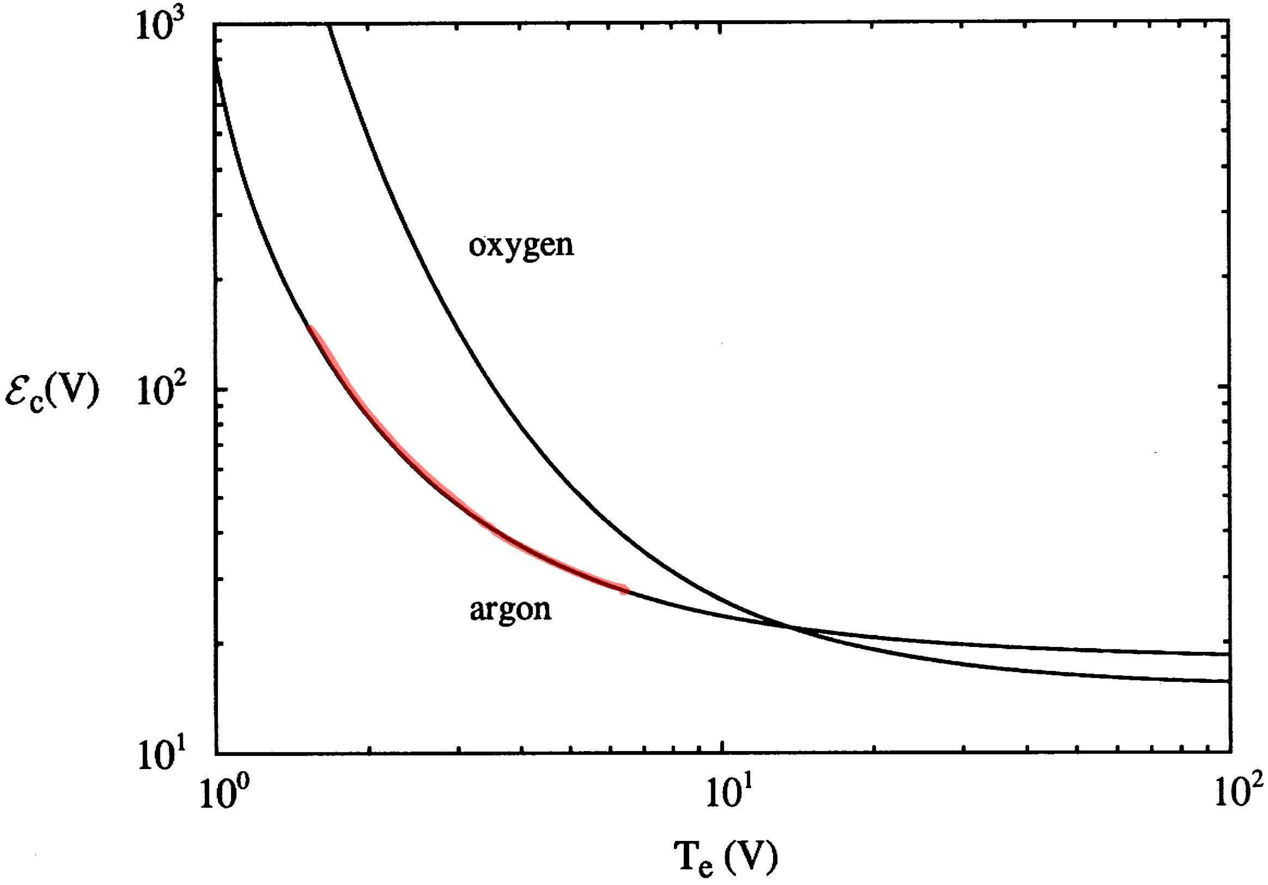
3. Ion kinetic energy lost to walls is mainly due to the dc potential $\bar{V}_s$ across the sheath

$$\mathcal{E}_i \approx \bar{V}_s$$

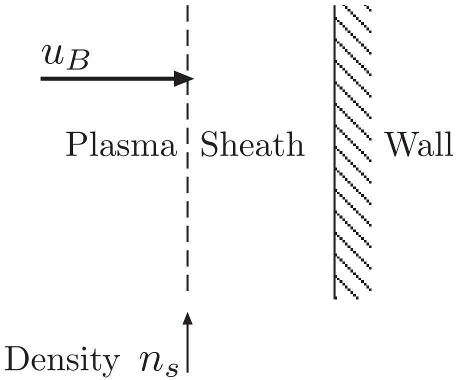
- Total energy lost per electron-ion pair lost to walls

$$\boxed{\mathcal{E}_T = \mathcal{E}_c + \mathcal{E}_e + \mathcal{E}_i}$$

COLLISIONAL ENERGY LOSSES



BOHM (ION LOSS) VELOCITY $\mathbf{u_B}$



- Due to formation of a “presheath”, ions arrive at the plasma-sheath edge with directed energy $kT_e/2$

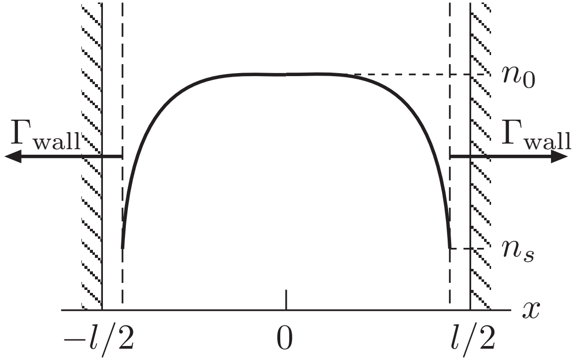
$$\frac{1}{2}Mu_i^2 = \frac{kT_e}{2}$$

- Electron-ion pairs are lost at the Bohm velocity at the plasma-sheath edge (density n_s)

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

PLASMA DIFFUSION AT LOW PRESSURES

- Plasma density profile is relatively flat in the center and falls sharply near the sheath edge



- Ion and electron loss flux to the wall is

$$\Gamma_{\text{wall}} = n_s u_B \equiv h_l n_0 u_B$$

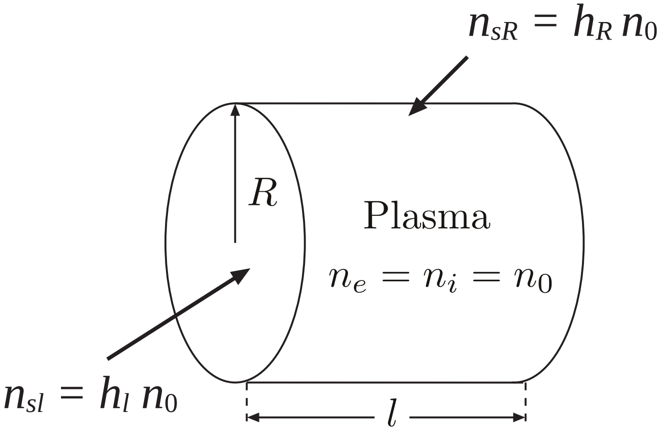
- The edge-to-center density ratio is

$$\boxed{h_l \equiv \frac{n_s}{n_0} \approx \frac{0.86}{(3 + l/2\lambda_i)^{1/2}}}$$

where λ_i = ion-neutral mean free path [p. 21]

- Applies for pressures < 100 mTorr in argon

PLASMA DIFFUSION IN LOW PRESSURE CYLINDRICAL DISCHARGE



- For a cylindrical plasma of length l and radius R, loss fluxes to axial and radial walls are

$$\boxed{\Gamma_{\text{axial}} = h_l n_0 u_B, \qquad \Gamma_{\text{radial}} = h_R n_0 u_B}$$

where the edge-to-center density ratios are

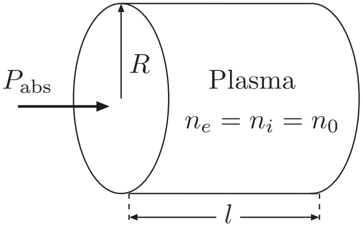
$$\boxed{h_l \approx \frac{0.86}{(3 + l/2\lambda_i)^{1/2}}, \qquad h_R \approx \frac{0.8}{(4 + R/\lambda_i)^{1/2}}}$$

- Applies for pressures $<$ 100 mTorr in argon

GLOBAL MODEL OF DISCHARGE EQUILIBRIUM

PARTICLE BALANCE AND $\mathbf{T_e}$

- Assume uniform cylindrical plasma absorbing power P_{abs}



- Particle balance

Production due to ionization = loss to the walls

$$\boxed{K_{\text{iz}} n_g \cancel{n}_0 \pi R^2 l = (2\pi R^2 h_l \cancel{n}_0 + 2\pi R l h_R \cancel{n}_0) u_B}$$

- Solve to obtain

$$\boxed{\frac{K_{\text{iz}}(T_e)}{u_B(T_e)} = \frac{1}{n_g d_{\text{eff}}}}$$

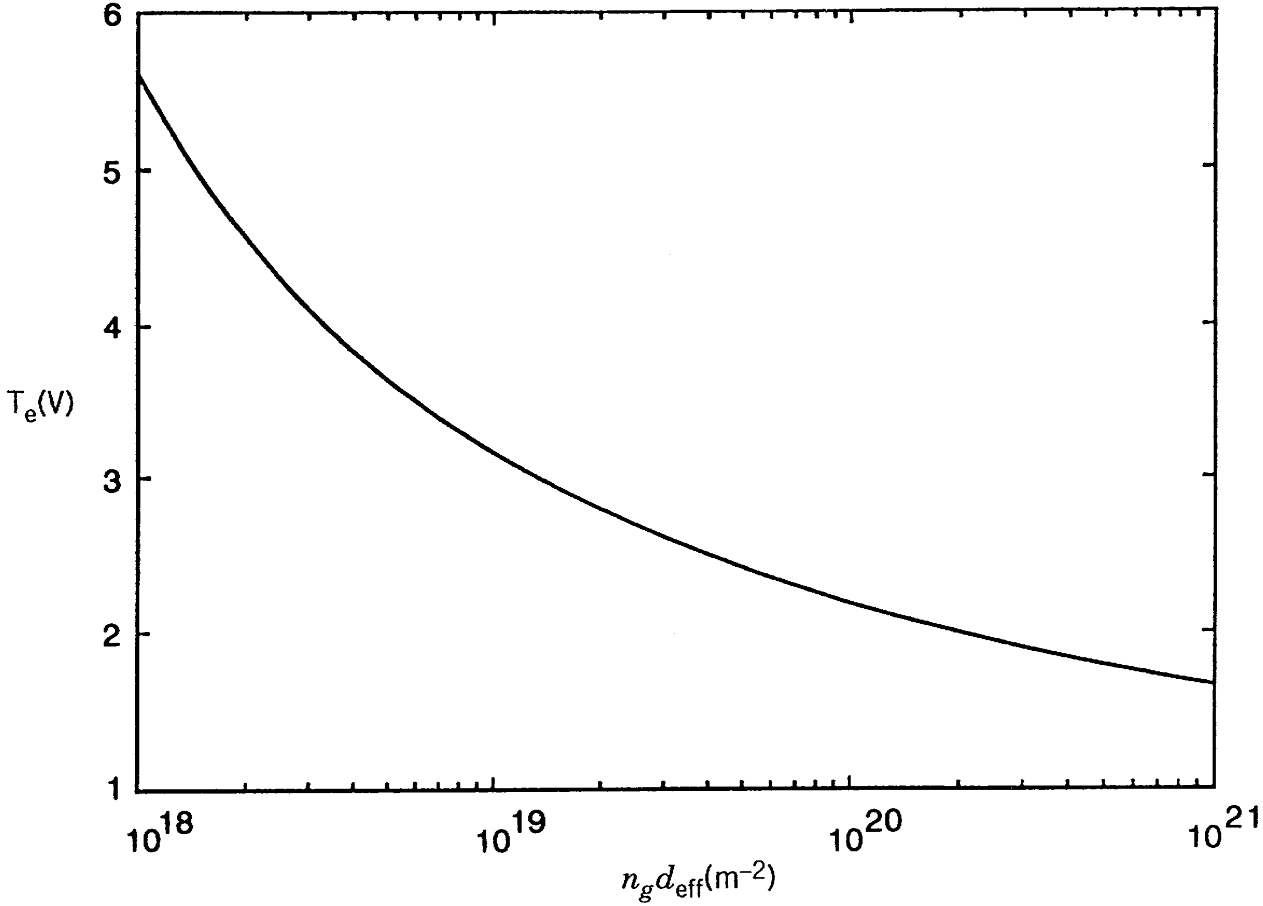
where

$$d_{\text{eff}} = \frac{1}{2} \frac{Rl}{Rh_l + lh_R}$$

is an effective plasma size

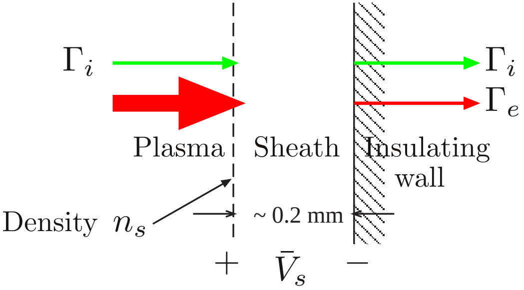
- Given n_g and d_{eff} $\Longrightarrow$ electron temperature T_e
- T_e varies over a narrow range of 2–5 volts

ELECTRON TEMPERATURE IN ARGON DISCHARGE



ION ENERGY FOR LOW VOLTAGE SHEATHS

- $\mathcal{E}_i$ = energy entering sheath + energy gained traversing sheath
- Ion energy entering sheath = $\mathrm{T}_e/2$ (voltage units)
- Sheath voltage determined from particle conservation



$$\Gamma_i = n_s u_B, \qquad \Gamma_e = \underbrace{\tfrac{1}{4} n_s \bar{v}_e}_{\text{Random flux at sheath edge}} \, \mathrm{e}^{-\overline{V}_s/\mathrm{T}_e}$$

with $\bar{v}_e = (8e\mathrm{T}_e/\pi m)^{1/2}$

- The ion and electron fluxes at the wall must balance

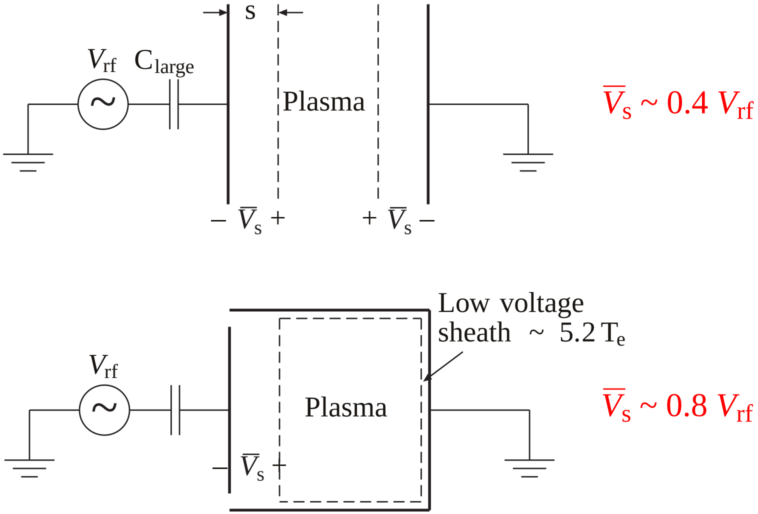
$$\boxed{\overline{V}_s = \frac{\mathrm{T}_e}{2} \ln\left(\frac{M}{2\pi m}\right)}$$

or $\overline{V}_s \approx 4.7\,\mathrm{T}_e$ for argon

- Accounting for the initial ion energy, $\mathcal{E}_i \approx 5.2\,\mathrm{T}_e$

ION ENERGY FOR HIGH VOLTAGE SHEATHS

- Large ion bombarding energies can be gained near rf-driven electrodes



- The sheath thickness s is given by the Child law

$$\bar{J}_i = e n_s u_B = \frac{4}{9}\epsilon_0 \left(\frac{2e}{M}\right)^{1/2} \frac{\bar{V}_s^{3/2}}{s^2}$$

- Estimating ion energy is not simple as it depends on the type of discharge and the application of rf or dc bias voltages

POWER BALANCE AND $\mathbf{n_0}$

- Assume low voltage sheaths at all surfaces

$$\mathcal{E}_T(\mathrm{T}_e) = \underbrace{\mathcal{E}_c(\mathrm{T}_e)}_{\text{Collisional}} + \underbrace{2\,\mathrm{T}_e}_{\text{Electron}} + \underbrace{5.2\,\mathrm{T}_e}_{\text{Ion}}$$

- Power balance

$$\text{Power in} = \text{power out}$$

$$\boxed{P_{\text{abs}} = (h_l n_0 2\pi R^2 + h_R n_0 2\pi R l)\, u_B\, e\mathcal{E}_T}$$

- Solve to obtain

$$\boxed{n_0 = \frac{P_{\text{abs}}}{A_{\text{eff}} u_B e \mathcal{E}_T}}$$

where

$$A_{\text{eff}} = 2\pi R^2 h_l + 2\pi R l h_R$$

is an effective area for particle loss

- Density n_0 is proportional to the absorbed power P_{abs}
- Density n_0 depends on pressure p through h_l, h_R, and T_e

PARTICLE AND POWER BALANCE

- Particle balance $\Longrightarrow$ electron temperature T_e
  (independent of plasma density)

- Power balance $\Longrightarrow$ plasma density n_0
  (once electron temperature T_e is known)

EXAMPLE 1

- Let $R = 0.15$ m, $l = 0.3$ m, $n_g = 3.3 \times 10^{19}$ m^{-3} ($p = 1$ mTorr at 300 K), and $P_{\text{abs}} = 800$ W
- Assume low voltage sheaths at all surfaces
- Find $\lambda_i = 0.03$ m. Then $h_l \approx h_R \approx 0.3$ and $d_{\text{eff}} \approx 0.17$ m [pp. 21, 26, 28]
- From the T_e versus $n_g d_{\text{eff}}$ figure, $\mathrm{T}_e \approx 3.5$ V [p. 29]
- From the $\mathcal{E}_c$ versus T_e figure, $\mathcal{E}_c \approx 42$ V [p. 23].
  Adding $\mathcal{E}_e = 2\mathrm{T}_e \approx 7$ V and $\mathcal{E}_i \approx 5.2\mathrm{T}_e \approx 18$ V yields
  $\mathcal{E}_T = 67$ V [p. 22]
- Find $u_B \approx 2.9 \times 10^3$ m/s and find $A_{\text{eff}} \approx 0.13$ m^2 [pp. 24, 32]
- Power balance yields $n_0 \approx 2.0 \times 10^{17}$ m^{-3} [p. 32]
- Ion current density $J_{il} = e h_l n_0 u_B \approx 2.9$ mA/cm^2
- Ion bombarding energy $\mathcal{E}_i \approx 18$ V [p. 30]

EXAMPLE 2

- Apply a strong dc magnetic field along the cylinder axis
  $\Longrightarrow$ particle loss to radial wall is inhibited
- Assume no radial losses, then $d_{\text{eff}} = l/2h_l \approx 0.5$ m
- From the T_e versus $n_g d_{\text{eff}}$ figure, $\mathrm{T}_e \approx 3.3$ V (was 3.5 V)
- From the $\mathcal{E}_c$ versus T_e figure, $\mathcal{E}_c \approx 46$ V. Adding $\mathcal{E}_e = 2\mathrm{T}_e \approx 6.6$ V and $\mathcal{E}_i \approx 5.2\mathrm{T}_e \approx 17$ V yields $\mathcal{E}_T = 70$ V
- Find $u_B \approx 2.8 \times 10^3$ m/s and find $A_{\text{eff}} = 2\pi R^2 h_l \approx 0.043$ m^2
- Power balance yields $n_0 \approx 5.8 \times 10^{17}$ m^{-3} (was 2×10^{17} m^{-3})

- Ion current density $J_{il} = e h_l n_0 u_B \approx 7.8$ mA/cm^2
- Ion bombarding energy $\mathcal{E}_i \approx 17$ V

$\Longrightarrow$ Slight decrease in electron temperature T_e

$\Longrightarrow$ Significant increase in plasma density n_0

EXPLAIN WHY!

- What happens to T_e and n_0 if there is a sheath voltage $V_s = 500$ V at each end plate?

ELECTRON HEATING MECHANISMS

- Discharges can be distinguished by electron heating mechanisms
  - (a) Ohmic (collisional) heating (capacitive, inductive discharges)
  - (b) Stochastic (collisionless) heating (capacitive, inductive discharges)
  - (c) Resonant wave-particle interaction heating (Electron cyclotron resonance and helicon discharges)
- Although the heated electrons provide the ionization required to sustain the discharge, the electrons tend to short out the applied heating fields within the bulk plasma
- Achieving adequate electron heating is a key issue

INDUCTIVE DISCHARGES

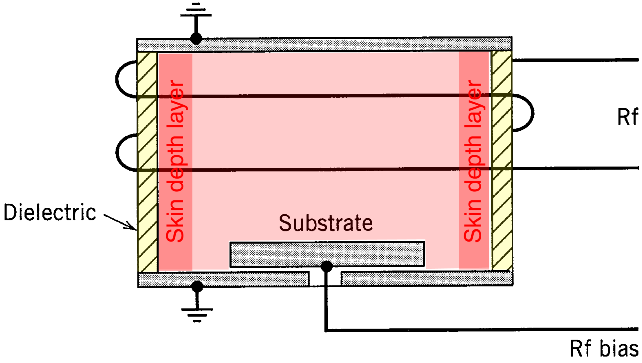
DESCRIPTION AND MODEL

MOTIVATION

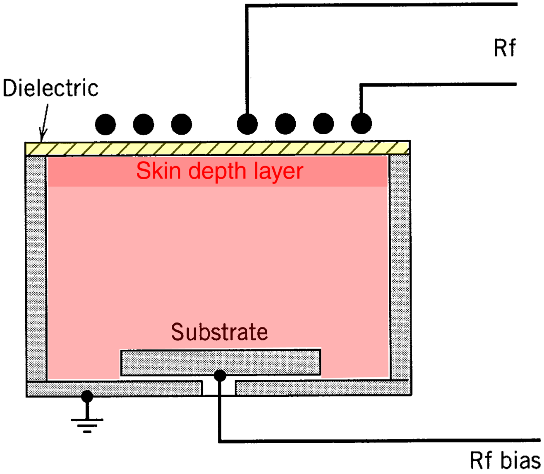
- High density (compared to capacitive discharge)
- Independent control of plasma density and ion energy
- Simplicity of concept
- RF rather than microwave powered
- No source magnetic fields

CYLINDRICAL AND PLANAR CONFIGURATIONS

- Cylindrical coil

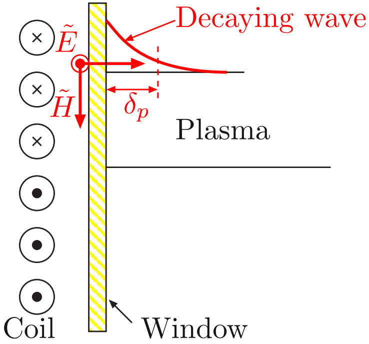


- Planar coil



HIGH DENSITY REGIME

- Inductive coil launches decaying wave into plasma



- Wave decays exponentially into plasma

$$\widetilde{E} = \widetilde{E}_0\, \mathrm{e}^{-z/\delta_p}, \qquad \delta_p = \frac{c}{\omega}\frac{1}{\mathrm{Im}(\kappa_p^{1/2})}$$

where κ_p = plasma dielectric constant [p. 16]

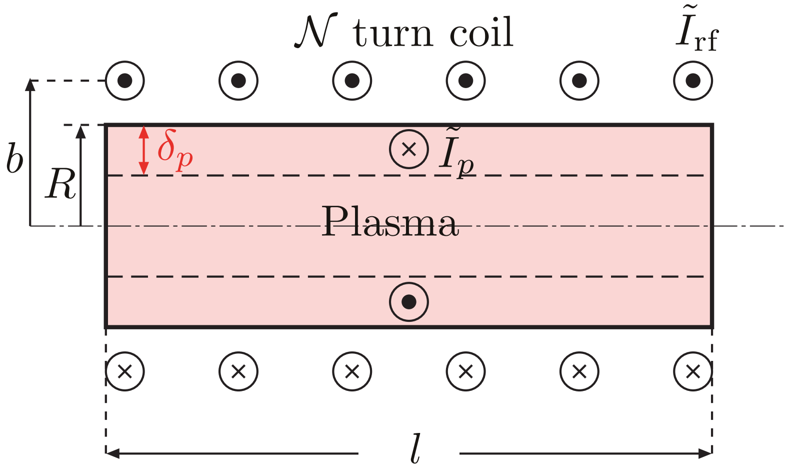
$$\kappa_p = 1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_m)}$$

For typical high density, low pressure ($\nu_m \ll \omega$) discharge

$$\boxed{\delta_p \approx \frac{c}{\omega_{pe}} \sim \ 1\text{–}2 \text{ cm}}$$

TRANSFORMER MODEL

- For simplicity consider a long cylindrical discharge



- Current $\tilde{I}_{\mathrm{rf}}$ in $\mathcal{N}$ turn coil induces current $\tilde{I}_p$ in 1-turn plasma skin

$$\boxed{\Longrightarrow \text{A transformer}}$$

PLASMA RESISTANCE AND INDUCTANCE

- Plasma resistance R_p

$$R_p = \frac{1}{\sigma_{\rm dc}} \frac{\text{circumference of plasma loop}}{\text{average cross sectional area of loop}}$$

where [p. 17]

$$\sigma_{\rm dc} = \frac{e^2 n_{es}}{m\nu_m}$$

with n_{es} = density at plasma-sheath edge

$$\boxed{\Longrightarrow R_p = \frac{\pi R}{\sigma_{\rm dc} l \delta_p}}$$

- Plasma inductance L_p

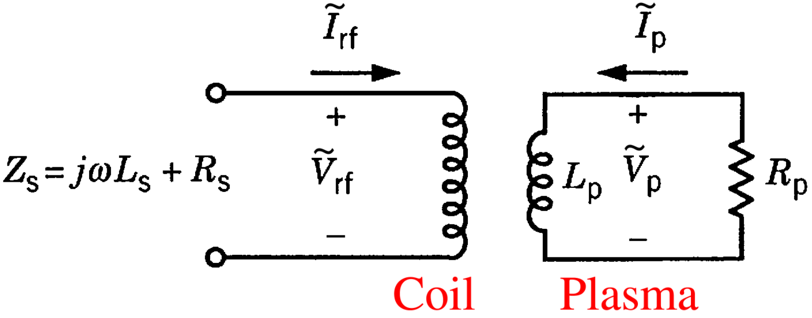
$$L_p = \frac{\text{magnetic flux produced by plasma current}}{\text{plasma current}}$$

- Using magnetic flux $= \pi R^2 \mu_0 \tilde{I}_p / l$

$$\boxed{\Longrightarrow L_p = \frac{\mu_0 \pi R^2}{l}}$$

COUPLING OF COIL TO PLASMA

- Model the source as a transformer



$$\tilde{V}_{\mathrm{rf}} = j\omega L_{11}\tilde{I}_{\mathrm{rf}} + j\omega L_{12}\tilde{I}_p$$

$$\tilde{V}_p = j\omega L_{21}\tilde{I}_{\mathrm{rf}} + j\omega L_{22}\tilde{I}_p$$

- Transformer inductances

$$L_{11} = \frac{\text{magnetic flux linking coil}}{\text{coil current}} = \frac{\mu_0 \pi b^2 \mathcal{N}^2}{l}$$

$$L_{12} = L_{21} = \frac{\text{magnetic flux linking plasma}}{\text{coil current}} = \frac{\mu_0 \pi R^2 \mathcal{N}}{l}$$

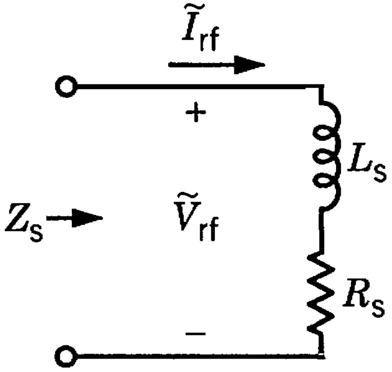
$$L_{22} = L_p = \frac{\mu_0 \pi R^2}{l}$$

SOURCE CURRENT AND VOLTAGE

- Put $\widetilde{V}_p = -\tilde{I}_p R_p$ in transformer equations and solve for the impedance $Z_s = \widetilde{V}_{\rm rf}/\tilde{I}_{\rm rf}$ seen at coil terminals

$$Z_s = j\omega L_{11} + \frac{\omega^2 L_{12}^2}{R_p + j\omega L_p} \equiv R_s + j\omega L_s$$

- Equivalent circuit at coil terminals



$$R_s = \mathcal{N}^2 \frac{\pi R}{\sigma_{\rm dc} l \delta_p}$$

$$L_s = \frac{\mu_0 \pi R^2 \mathcal{N}^2}{l} \left(\frac{b^2}{R^2} - 1 \right)$$

- Power balance $\Longrightarrow \tilde{I}_{\rm rf}$

$$\boxed{P_{\rm abs} = \frac{1}{2} \tilde{I}_{\rm rf}^2 R_s}$$

- From source impedance $\Longrightarrow V_{\rm rf}$

$$\boxed{\widetilde{V}_{\rm rf} = \tilde{I}_{\rm rf} Z_s}$$

EXAMPLE

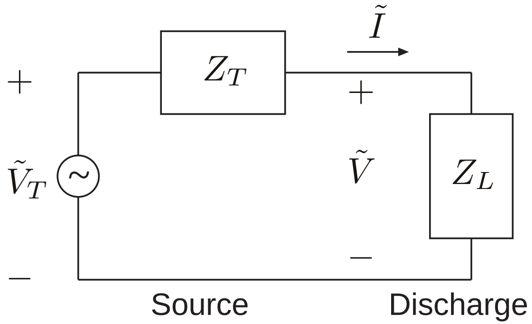
- Assume plasma radius $R = 10$ cm, coil radius $b = 15$ cm, length $l = 20$ cm, $\mathcal{N} = 3$ turns, gas density $n_g = 6.6\times10^{14}$ cm^{-3} (20 mTorr argon at 300 K), $\omega = 85 \times 10^6$ s^{-1} (13.56 MHz), absorbed power $P_{\text{abs}} = 600$ W, and low voltage sheaths

- At 20 mTorr, $\lambda_i \approx 0.15$ cm, $h_l \approx h_R \approx 0.1$, $d_{\text{eff}} \approx 34$ cm [pp. 21, 26, 28]
- Particle balance (T_e versus $n_g d_{\text{eff}}$ figure [p. 29]) yields $\mathrm{T}_e \approx 2.1$ V
- Collisional energy losses ($\mathcal{E}_c$ versus T_e figure [p. 23]) are $\mathcal{E}_c \approx 110$ V. Adding $\mathcal{E}_e + \mathcal{E}_i = 7.2\,\mathrm{T}_e$ yields total energy losses $\mathcal{E}_T \approx 126$ V [p. 22]
- $u_B \approx 2.3 \times 10^5$ cm/s [p. 24] and $A_{\text{eff}} \approx 185$ cm^2 [p. 32]
- Power balance yields $n_e \approx 7.1 \times 10^{11}$ cm^{-3} and $n_{se} \approx 7.4 \times 10^{10}$ cm^{-3} [p. 32]

- Use n_{se} to find skin depth $\delta_p \approx 2.0$ cm [p. 40]; estimate $\nu_m = K_{\text{el}} n_g$ (K_{el} versus T_e figure [p. 20]) to find $\nu_m \approx 3.4 \times 10^7$ s^{-1}
- Use ν_m and n_{se} to find $\sigma_{\text{dc}} \approx 61\ \Omega^{-1}$-m^{-1} [p. 17]
- Evaluate impedance elements $R_s \approx 23.5\ \Omega$ and $L_s \approx 2.2\ \mu$H; $|Z_s| \approx \omega L_s \approx 190\ \Omega$ [p. 44]
- Power balance yields $\tilde{I}_{\text{rf}} \approx 7.1$A; from source impedance $|Z_s| = 190\ \Omega$, $\widetilde{V}_{\text{rf}} \approx 1360$ V [p. 44]

MATCHING DISCHARGE TO POWER SOURCE

- Consider an rf power source connected to a discharge

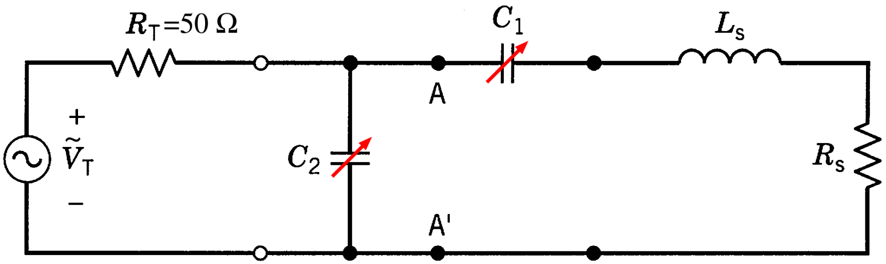


- Source impedance $Z_T = R_T + jX_T$ is given
  Discharge impedance $Z_L = R_L + jX_L$
- Time-average power delivered to discharge $P_{\text{abs}} = \frac{1}{2}\text{Re}\,(\widetilde{V}\tilde{I}^*)$
- For fixed source $\widetilde{V}_T$ and Z_T, maximize power delivered to discharge

$$\boxed{\begin{aligned} X_L &= -X_T \\ R_L &= R_T \end{aligned}}$$

MATCHING NETWORK

- Insert lossless matching network between power source and coil



Power source Matching network Discharge coil

- Continue EXAMPLE [p. 45] with $R_s = 23.5\ \Omega$ and $\omega L_s = 190\ \Omega$; assume $R_T = 50\ \Omega$ (corresponds to a conductance $1/R_T = 1/50$ S)
- Choose C_1 such that the conductance seen looking to the right at terminals AA′ is 1/50 S

$$\boxed{\Longrightarrow C_1 = 71 \text{ pF}}$$

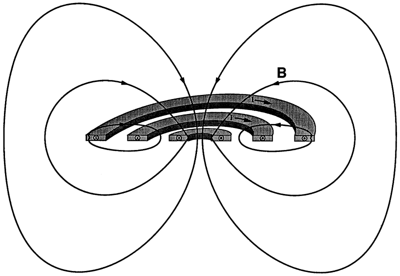
- Choose C_2 to cancel the reactive part of the impedance seen at AA′

$$\boxed{\Longrightarrow C_2 = 249 \text{ pF}}$$

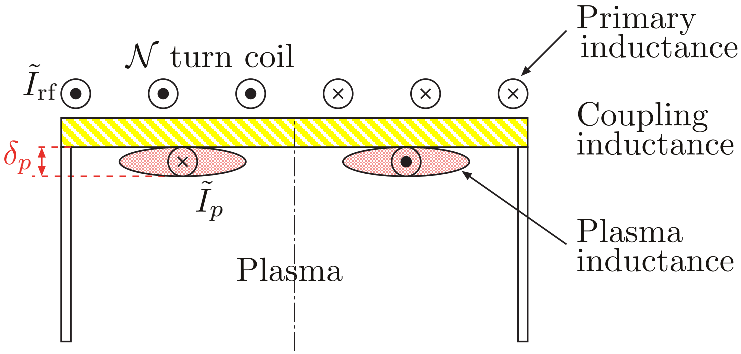
- For $P_{\text{abs}} = 600$ W, the 50 Ω source supplies $\tilde{I}_{\text{rf}} = 4.9$ A
- Voltage at source terminals (AA′) $= \tilde{I}_{\text{rf}} R_T = 245$ V

PLANAR COIL DISCHARGE

- Magnetic field produced by planar coil



- RF power is deposited in a ring-shaped plasma volume



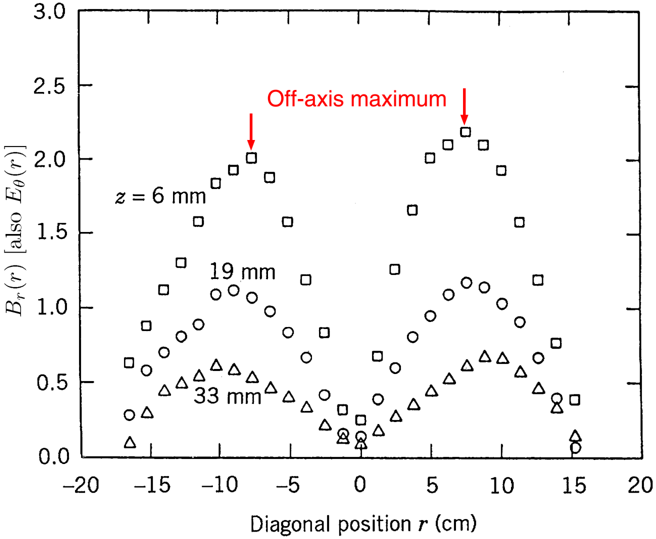
- As for a cylindrical discharge, there is a primary (L_{11}), coupling ($L_{12} = L_{21}$) and secondary ($L_p = L_{22}$) inductance

PLANAR COIL FIELDS

- A ring-shaped plasma forms because

$$\text{Induced electric field} = \begin{cases} 0, & \text{on axis} \\ \text{max}, & \text{at } r \approx \frac{1}{2}R_{\text{wall}} \\ 0, & \text{at } r = R_{\text{wall}} \end{cases}$$

- Measured radial variation of B_r (and E_θ) at three distances below the window (5 mTorr argon, 500 W, Hopwood et al, 1993)



INDUCTIVE DISCHARGES

POWER BALANCE

RESISTANCE AT HIGH AND LOW DENSITIES

- Plasma resistance seen by the coil [p. 44]

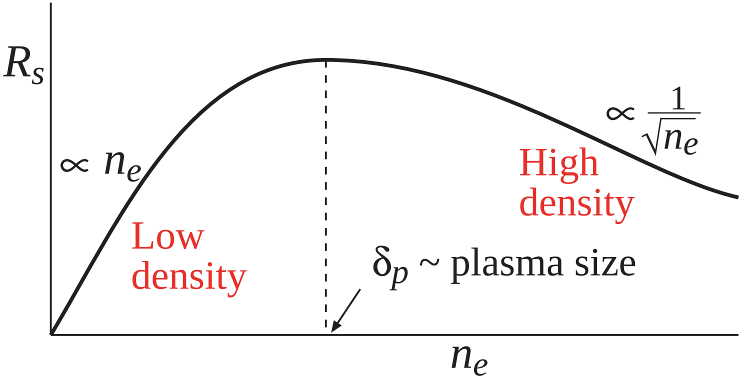
$$R_s = R_p \frac{\omega^2 L_{12}^2}{R_p^2 + \omega^2 L_p^2}$$

- High density (normal inductive operation) [p. 44]

$$R_s \propto R_p \propto \frac{1}{\sigma_{\rm dc}\delta_p} \propto \frac{1}{\sqrt{n_e}}$$

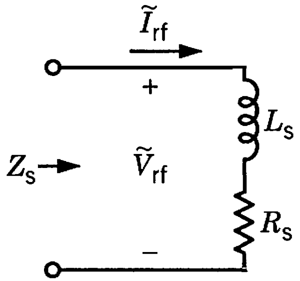
- Low density (skin depth > plasma size)

$$R_s \propto \text{ number of electrons in the heating volume} \propto n_e$$

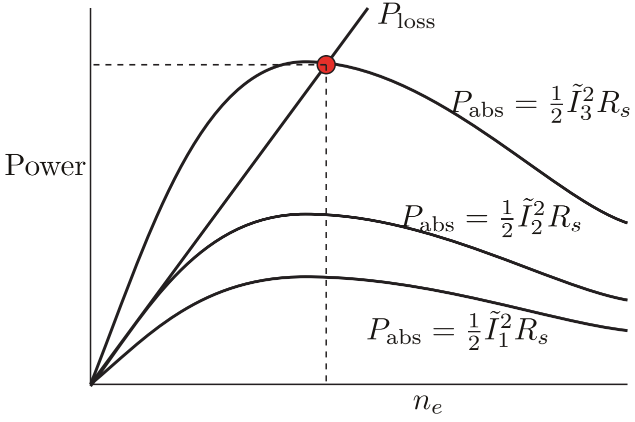


POWER BALANCE

- Drive discharge with rf current



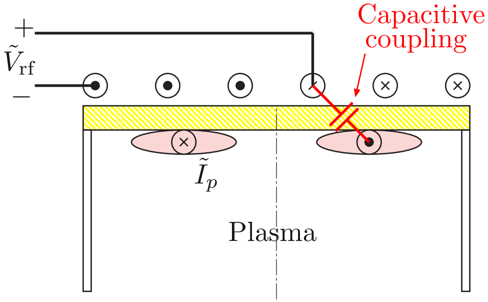
- Power absorbed by discharge is $P_{\rm abs} = \frac{1}{2}|\tilde{I}_{\rm rf}|^2 R_s(n_e)$ [p. 44]
  Power lost by discharge $P_{\rm loss} \propto n_e$ [p. 32]
- Intersection (red dot) gives operating point; let $\tilde{I}_1 < \tilde{I}_2 < \tilde{I}_3$



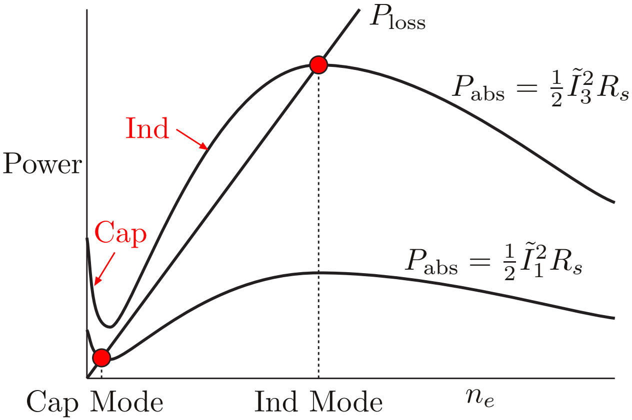
- Inductive operation impossible for $\tilde{I}_{\rm rf} \leq \tilde{I}_2$

CAPACITIVE COUPLING OF COIL TO PLASMA

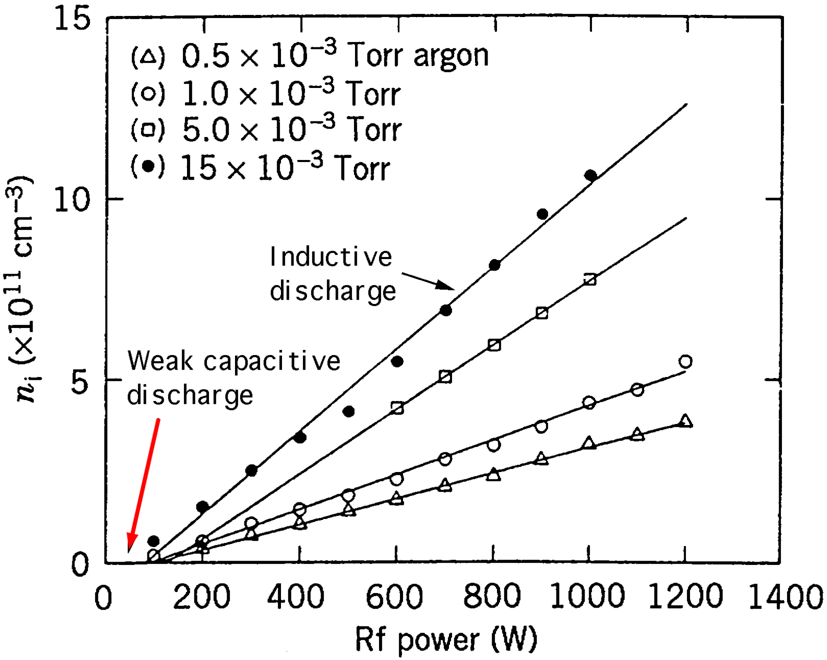
- For $\tilde{I}_{\mathrm{rf}}$ below the minimum current $\tilde{I}_2$, there is only a weak capacitive coupling of the coil to the plasma



- A small capacitive power is absorbed
  $\Longrightarrow$ low density capacitive discharge



MEASURMENTS OF ARGON ION DENSITY

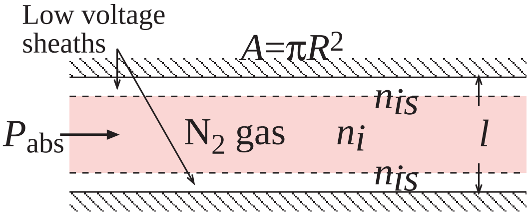


- Above 100 W, discharge is inductive and $n_e \propto P_{\rm abs}$
- Below 100 W, a weak capacitive discharge is present

REACTIVE NEUTRAL BALANCE IN DISCHARGES

PLANE-PARALLEL DISCHARGE

- Example of $\mathrm{N_2}$ discharge with low fractional ionization ($n_g \approx n_{\mathrm{N_2}}$) and planar 1D geometry ($l \ll R$)



- Determine T_e

  Ion particle balance is [p. 28]

$$K_{\mathrm{iz}} n_g n_i l A \approx 2 n_{is} u_B A$$

where $n_{is} = h_l n_i$ with $h_l = 0.86/(3 + l/2\lambda_i)^{1/2}$ [p. 25]

$$\boxed{\frac{K_{\mathrm{iz}}(\mathrm{T}_e)}{u_B(\mathrm{T}_e)} \approx \frac{2h_l}{n_g l} \Longrightarrow \mathrm{T}_e}$$

PLANE-PARALLEL DISCHARGE (CONT'D)

- Determine edge plasma density n_{is}
  Overall discharge power balance [p. 32] gives the plasma density at the sheath edge

$$\boxed{n_{is} \approx \frac{P_{\rm abs}}{2e\mathcal{E}_T u_B A}}$$

- Determine central plasma density [p. 25]

$$\boxed{n_i = \frac{n_{is}}{h_l}}$$

- Determine ion flux to the surface [p. 25]

$$\boxed{\Gamma_{is} \approx n_{is} u_B}$$

- Determine ion bombarding energy [p. 30]

$$\boxed{\mathcal{E}_i = 5.2\,\mathrm{T}_e}$$

REACTIVE NEUTRAL BALANCE

- For nitrogen atoms

$$\boxed{\mathrm{e} + \mathrm{N}_2 \xrightarrow{K_{\mathrm{diss}}} 2\mathrm{N} + \mathrm{e}}$$

- Assume low fractional dissociation and loss of N atoms only due to a vacuum pump S_p (m^3/s)

$$Al\frac{dn_{\mathrm{N}}}{dt} = Al\,2K_{\mathrm{diss}}n_g n_i - S_p n_{\mathrm{N}S} = 0$$

- Solve for reactive neutral density at the surface

$$\boxed{n_{\mathrm{N}S} = K_{\mathrm{diss}}\frac{2Aln_g}{S_p}n_i}$$

- Flux of N atoms to the surface

$$\boxed{\Gamma_{\mathrm{N}S} = \frac{1}{4}n_{\mathrm{N}S}\bar{v}_{\mathrm{N}}}$$

where $\bar{v}_{\mathrm{N}} = (8kT_{\mathrm{N}}/\pi M_{\mathrm{N}})^{1/2}$

LOADING EFFECT

- Consider recombination and/or reaction of N atoms on surfaces

$$\mathrm{N} + \text{wall} \xrightarrow{\gamma_{\text{rec}}} \tfrac{1}{2}\mathrm{N}_2$$

$$\mathrm{N} + \text{substrate} \xrightarrow{\gamma_{\text{reac}}} \text{product}$$

- Pumping speed S_p in the expression for n_{NS} [p. 58] is replaced by

$$S_p \longrightarrow S_p + \gamma_{\text{rec}} \frac{1}{4} \bar{v}_{\mathrm{N}} (2A - A_{\text{subs}}) + \gamma_{\text{reac}} \frac{1}{4} \bar{v}_{\mathrm{N}} A_{\text{subs}}$$

  A_{subs} is the part of the substrate area reacting with N atoms

- $n_{\mathrm{N}S}$ is reduced due to recombination and reaction losses

- $n_{\mathrm{N}S}$, and therefore etch and deposition rates, now depend on the part of the substrate area A_{subs} exposed to the reactive neutrals, a *loading effect*

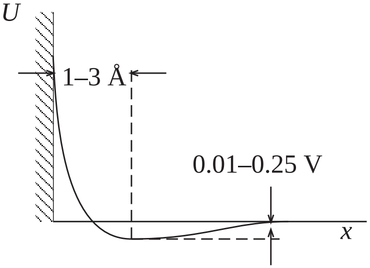
ADSORPTION AND DESORPTION KINETICS

ADSORPTION

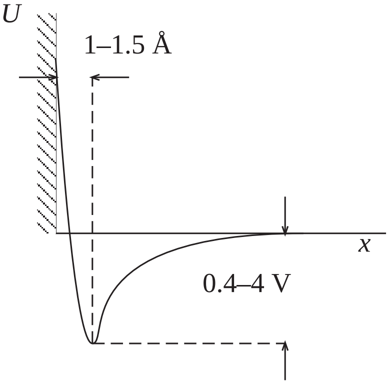
- Reaction of a molecule with the surface

$$\mathrm{A} + \mathrm{S} \underset{K_d}{\overset{K_a}{\rightleftarrows}} \mathrm{A{:}S}$$

- Physisorption (due to weak van der Waals forces)



- Chemisorption (due to formation of chemical bonds)



STICKING COEFFICIENT

- Adsorbed flux [p. 13]

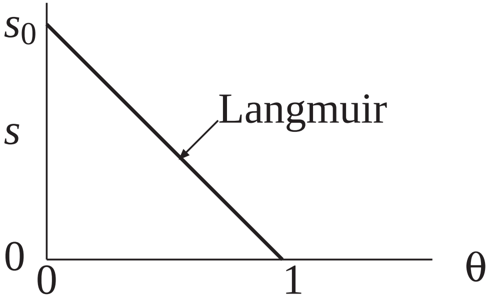
$$\boxed{\Gamma_{\mathrm{ads}} = s\Gamma_A = s\cdot\frac{1}{4}n_{AS}\bar{v}_A}$$

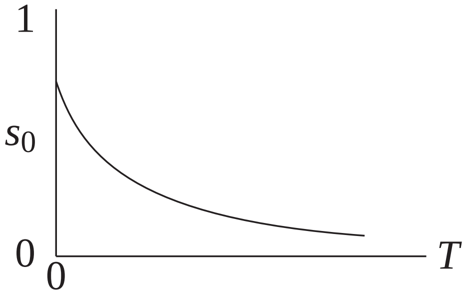
$s(\theta, T) =$ sticking coefficient
$\theta =$ fraction of surface sites covered with absorbate
$n_{AS} =$ gas phase density of A near the surface
$\bar{v}_A = (8kT_A/\pi M_A)^{1/2} =$ mean thermal speed of A

- Langmuir kinetics

$$\boxed{s(\theta, \mathrm{T}) = s_0(1-\theta)}$$

$s_0 =$ zero-coverage sticking coefficient ($s_0 \sim 10^{-6}$–1)





DESORPTION

$$\boxed{\mathrm{A\!:S} \xrightarrow{K_d} \mathrm{A} + \mathrm{S}}$$

- Rate coefficient has “Arrhenius” form

$$\boxed{K_d = K_{d0}\, \mathrm{e}^{-\mathcal{E}_{\mathrm{desor}}/\mathrm{T}}}$$

where $\mathcal{E}_{\mathrm{desor}} = \mathcal{E}_{\mathrm{chemi}}$ or $\mathcal{E}_{\mathrm{physi}}$

- Pre-exponential factors are typically

$$\begin{aligned} K_{d0} &\sim 10^{14}\text{–}10^{16}\ \mathrm{s}^{-1} \quad \text{physisorption} \\ &\sim 10^{13}\text{–}10^{15}\ \mathrm{s}^{-1} \quad \text{chemisorption} \end{aligned}$$

ADSORPTION-DESORPTION KINETICS

- Consider the reactions

$$\boxed{\mathrm{A} + \mathrm{S} \underset{K_d}{\overset{K_a}{\rightleftarrows}} \mathrm{A{:}\,S}}$$

- Adsorbed flux is [p. 62]

$$\Gamma_{\text{ads}} = K_a n_{AS} n_0' (1 - \theta)$$

$n_0' =$ area density (m^{-2}) of adsorption sites

$n_{AS} =$ the gas phase density at the surface

$$K_a = s_0 \frac{1}{4} \bar{v}_A / n_0' \qquad [\mathrm{m}^3/\mathrm{s}] \qquad \text{(adsorption rate coef)}$$

- Desorbed flux ∝ area density $n_0'\theta$ of covered sites [p. 63]

$$\Gamma_{\text{desor}} = K_d n_0' \theta$$

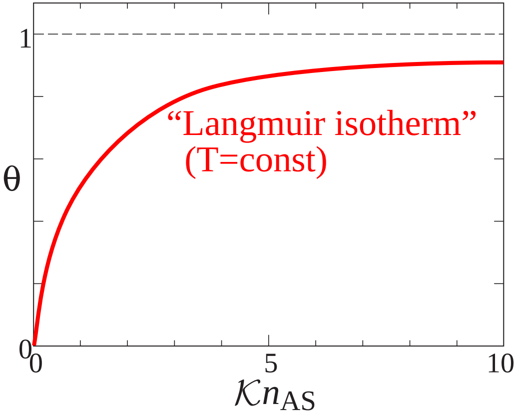
ADSORPTION-DESORPTION KINETICS (CONT'D)

- Equate adsorption and desorption fluxes ($\Gamma_{\mathrm{ads}} = \Gamma_{\mathrm{desor}}$)

$$\boxed{\Longrightarrow \theta = \frac{\mathcal{K} n_{AS}}{1 + \mathcal{K} n_{AS}}}$$

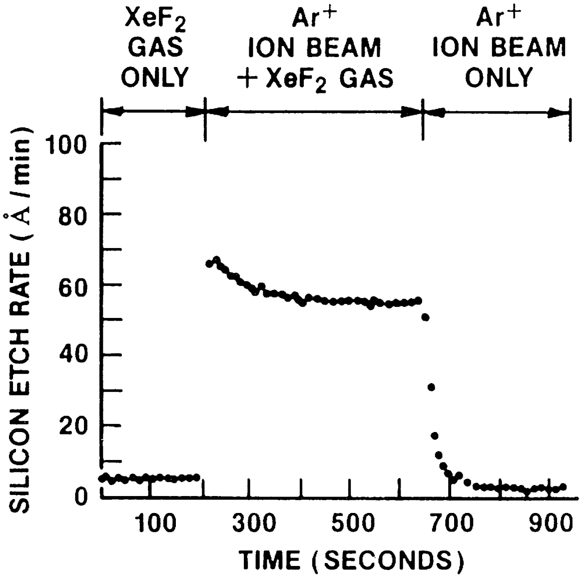
  where $\mathcal{K} = K_a/K_d$

- Note that $T \uparrow$ $\Rightarrow \quad \mathcal{K} \downarrow \quad \Rightarrow \quad \theta \downarrow$



PLASMA-ASSISTED ETCH KINETICS

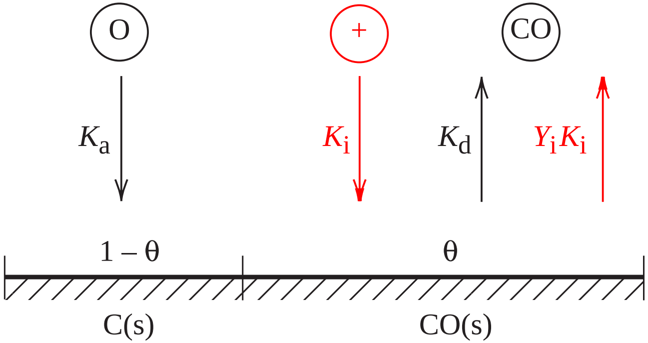
ION-ENHANCED PLASMA ETCHING



1. Low chemical etch rate of silicon substrate in XeF_2 etchant gas
2. Tenfold increase in etch rate with XeF_2 + 500 V argon ions, simulating ion-enhanced plasma etching
3. Very low “etch rate” due to the physical sputtering of silicon by ion bombardment alone

STANDARD MODEL OF ETCH KINETICS

- O atom etching of a carbon substrate



- Let n'_0 = active surface sites/m^2
- Let θ = fraction of surface sites covered with C : O bonds

$$\mathrm{O(g) + C(s)} \xrightarrow{K_a} \mathrm{C:O} \qquad \text{(O atom adsorption)}$$

$$\mathrm{C:O} \xrightarrow{K_d} \mathrm{CO(g)} \qquad \text{(CO thermal desorption)}$$

$$\mathrm{ion + C:O} \xrightarrow{Y_i K_i} \mathrm{CO(g)} \qquad \text{(CO ion-assisted desorption)}$$

SURFACE COVERAGE

- The steady-state surface coverage is found from [pp. 64–65]

$$\frac{d\theta}{dt} = K_a n_{\rm OS}(1-\theta) - K_d\theta - Y_i K_i n_{\rm is}\theta = 0$$

- $n_{\rm OS}$ is the O-atom density near the surface

  $n_{\rm is}$ is the ion density at the plasma-sheath edge

- K_a is the rate coefficient for O-atom adsorption

  K_d is the rate coefficient for thermal desorption of CO

  $K_i = u_B/n_0'$ is the rate coefficient for ions incident on the surface

- Y_i is the yield of CO molecules desorbed per ion incident on a fully covered surface

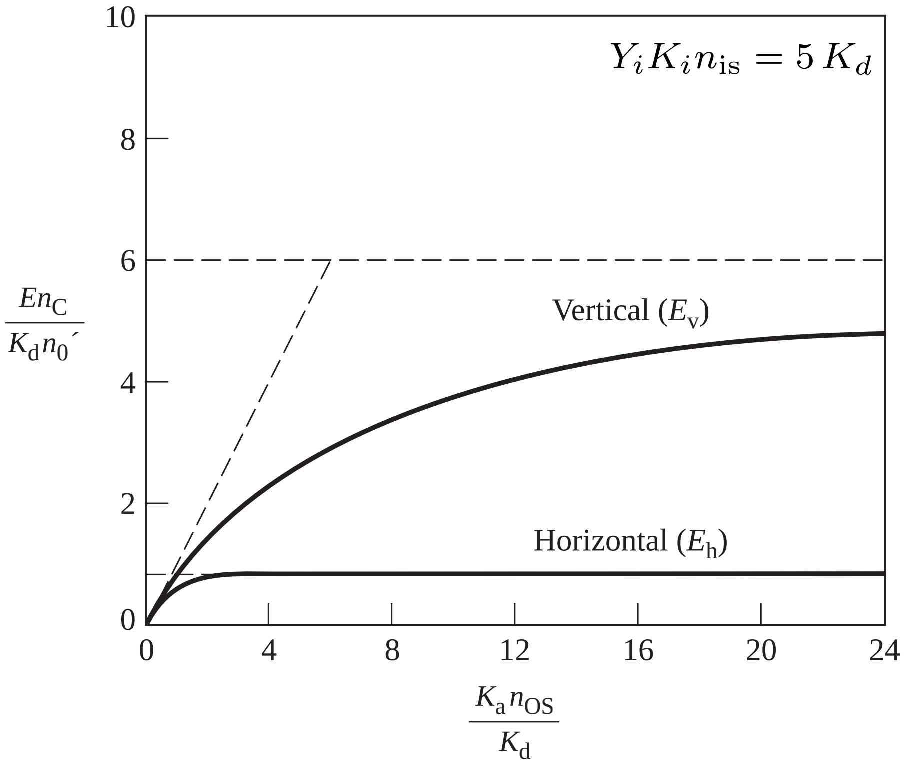
  Typically $Y_i \gg 1$ and $Y_i \approx Y_{i0}\sqrt{\mathcal{E}_i - \mathcal{E}_{\rm thr}}$ (as for sputtering)

$$\Longrightarrow \theta = \frac{K_a n_{\rm OS}}{K_a n_{\rm OS} + K_d + Y_i K_i n_{\rm is}}$$

ETCH RATES

- The flux of CO molecules leaving the surface is
$$\Gamma_{\mathrm{CO}} = (K_d + Y_i K_i n_{\mathrm{is}})\,\theta\, n_0' \qquad [\mathrm{m}^{-2}\text{-}\mathrm{s}^{-1}]$$
with n_0' = number of surface sites/m^2
- The vertical etch rate is
$$E_v = \frac{\Gamma_{\mathrm{CO}}}{n_{\mathrm{C}}} \qquad [\mathrm{m/s}]$$
where n_{C} is the carbon atom density of the substrate
- The vertical (ion-enhanced) etch rate is
$$\boxed{E_v = \frac{n_0'}{n_{\mathrm{C}}}\,\frac{1}{\dfrac{1}{K_d + Y_i K_i n_{\mathrm{is}}} + \dfrac{1}{K_a n_{\mathrm{OS}}}}}$$
- The horizontal (non ion-enhanced) etch rate is
$$\boxed{E_h = \frac{n_0'}{n_{\mathrm{C}}}\,\frac{1}{\dfrac{1}{K_d} + \dfrac{1}{K_a n_{\mathrm{OS}}}}}$$

NORMALIZED ETCH RATES



- High O-atom flux ⇒ highest anisotropy $E_v/E_h = 1 + Y_i K_i n_{\mathrm{is}}/K_d$
- Low O-atom flux ⇒ low etch rates with $E_v/E_h \to 1$

SIMPLEST MODEL OF ION-ENHANCED ETCHING

- In the usual ion-enhanced regime $Y_i K_i n_{\mathrm{is}} \gg K_d$

$$\boxed{\frac{1}{E_v} = n_C \left(\frac{1}{Y_i \underbrace{K_i n_{\mathrm{is}} n_0'}_{\Gamma_{\mathrm{is}}}} + \frac{1}{\underbrace{K_a n_{\mathrm{OS}} n_0'}_{\Gamma_{\mathrm{OS}}}} \right)}$$

- The ion and neutral fluxes and the yield (a function of ion energy) determine the ion-assisted etch rate
- The discharge parameters set the ion and neutral fluxes and the ion bombarding energy

ADDITIONAL CHEMISTRY AND PHYSICS

- Sputtering of carbon

$$\Gamma_{\mathrm{C}} = \gamma_{\mathrm{sput}} K_i n_{\mathrm{is}} n_0'$$

- Associative and normal desorption of O atoms,

$$\mathrm{C:O} \longrightarrow \mathrm{C} + \mathrm{O(g)}$$

$$\mathrm{2C:O} \longrightarrow \mathrm{2C} + \mathrm{O_2(g)}$$

- Ion energy driven desorption of O atoms

$$\mathrm{ions} + \mathrm{C:O} \longrightarrow \mathrm{C} + \mathrm{O(g)}$$

- Formation and desorption of CO_2 as an etch product
- Non-zero ion angular bombardment of sidewall surfaces
- Deposition kinetics (C-atoms, etc)

CONCLUSIONS

- Plasma discharges are widely used for materials processing and are indispensible for microelectronics fabrication
- The charged particle balance determines the electron temperature and ion bombarding energy to the substrate $\Longrightarrow Y_i(\mathcal{E}_i)$
- The energy balance determines the plasma density and the ion flux to the substrate $\Longrightarrow \Gamma_{\mathrm{is}}$
- A transformer model determines the relation among voltage, current, and power for inductive discharges
- The reactive neutral balance determines the flux of reactive neutrals to the surface $\Longrightarrow \Gamma_{\mathrm{OS}}$
- Hence the discharge parameters (power, pressure, geometry, etc) set the ion and neutral fluxes and the ion bombarding energy
- The ion and neutral fluxes and the yield (a function of ion energy) determine the ion-assisted etch rate

THANK YOU FOR ATTENDING THIS COURSE

MIKE LIEBERMAN