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

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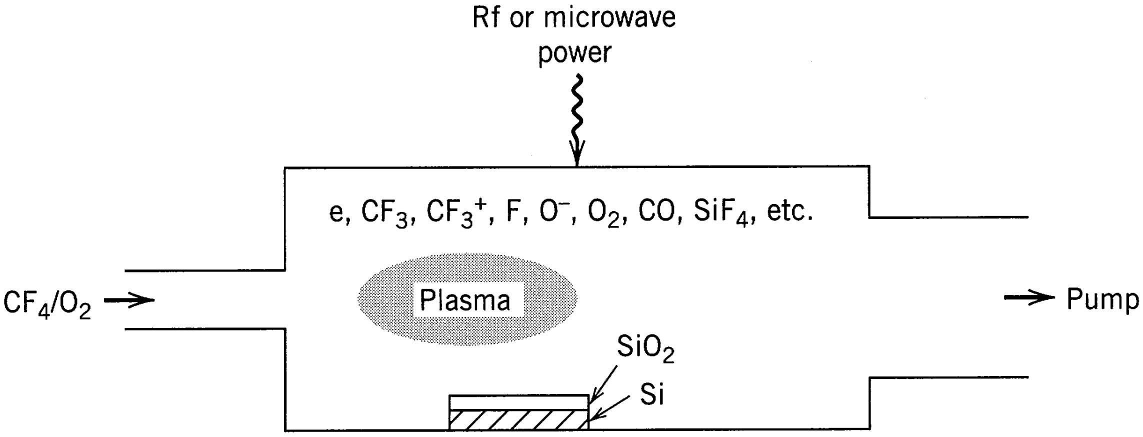


OUTLINE

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

— Break —

- Inductive Discharges
- Free Radical 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
- In 2020: 6 nm gate length, 6×10^9 transistors, 73 GHz on-chip clock, 14–18 wiring levels

EQUIVALENT AUTOMOTIVE ADVANCE

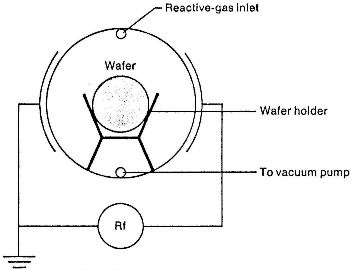
- 4 million km/hr
- 1 million km/liter
- Never break down
- Throw away rather than pay parking fees
- 3 cm long × 1 cm wide
- Crash 3× a day

RANGE OF NANOELECTRONICS APPLICATIONS

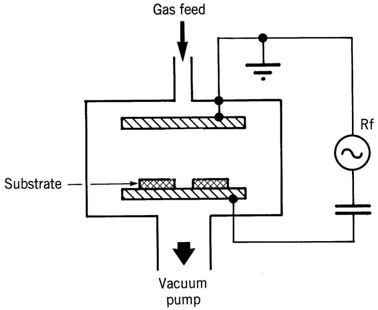
- Etching
  Si, a-Si, oxide, nitride, III-V's
- Ashing
  Photoresist removal
- Deposition (PECVD)
  Oxide, nitride, a-Si
- Oxidation
  Si
- Sputtering
  Al, W, Au, Cu, YBaCuO
- Polymerization
  Various plastics
- Implantation
  H, He, B, P, O, As, Pd

EVOLUTION OF ETCHING DISCHARGES

FIRST GENERATION
(1 source, multi-wafer, low density)

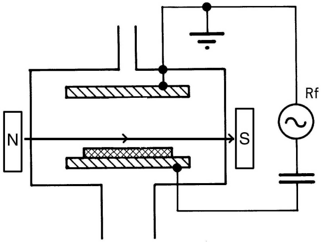


Barrel etcher
(Isotropic etch)

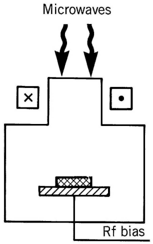


Capacitive
(Anisotropic etch)

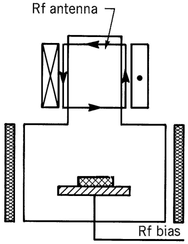
SECOND GENERATION
(2 sources, single wafer, high density)



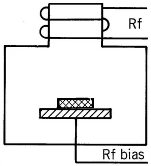
Magnetically enhanced
capacitive discharge



ECR

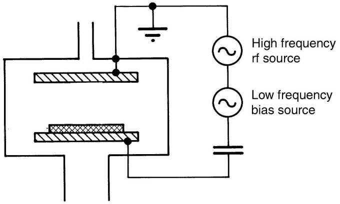


Helicon

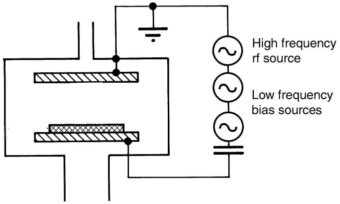


Inductive

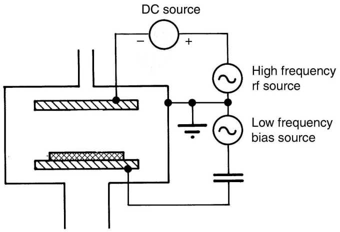
THIRD GENERATION
(multi-source, single wafer, moderate density)



Dual frequency
capacitive discharge



Triple frequency
capacitive discharge



DC/dual frequency
capacitive discharge

ISOTROPIC PLASMA ETCHING

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

$$CF_4 \longrightarrow CF_3 + F$$

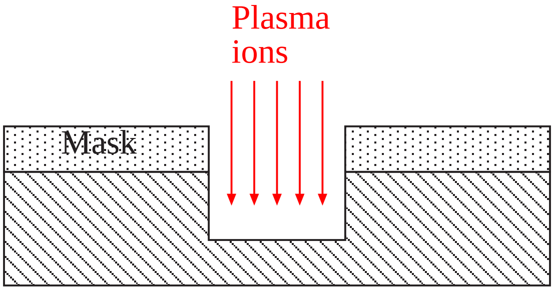
3. Species reacts with material, yielding volatile product:

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

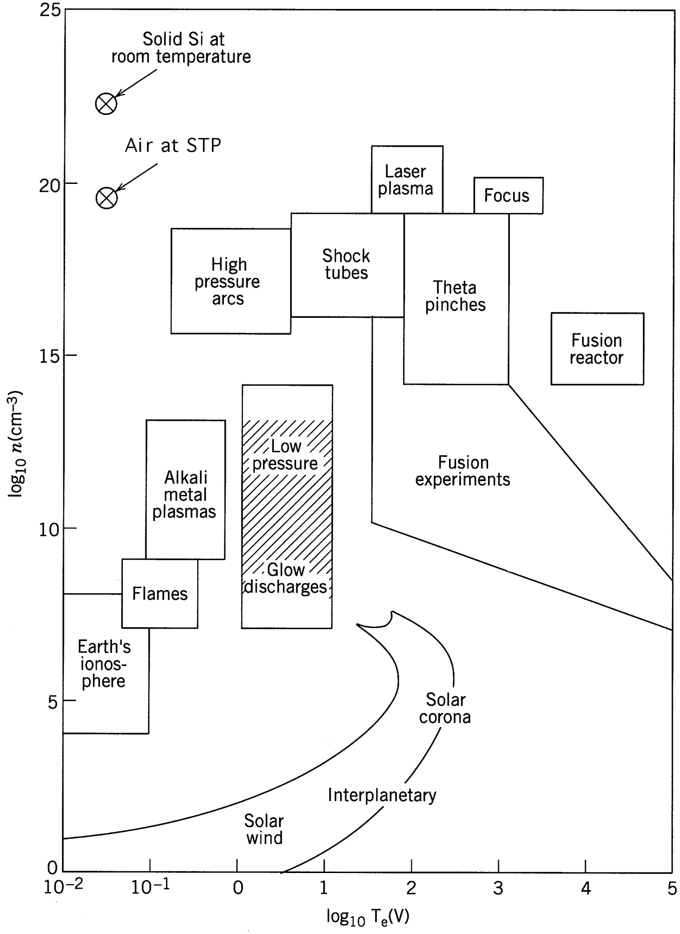
4. Pump away product

ANISOTROPIC PLASMA ETCHING

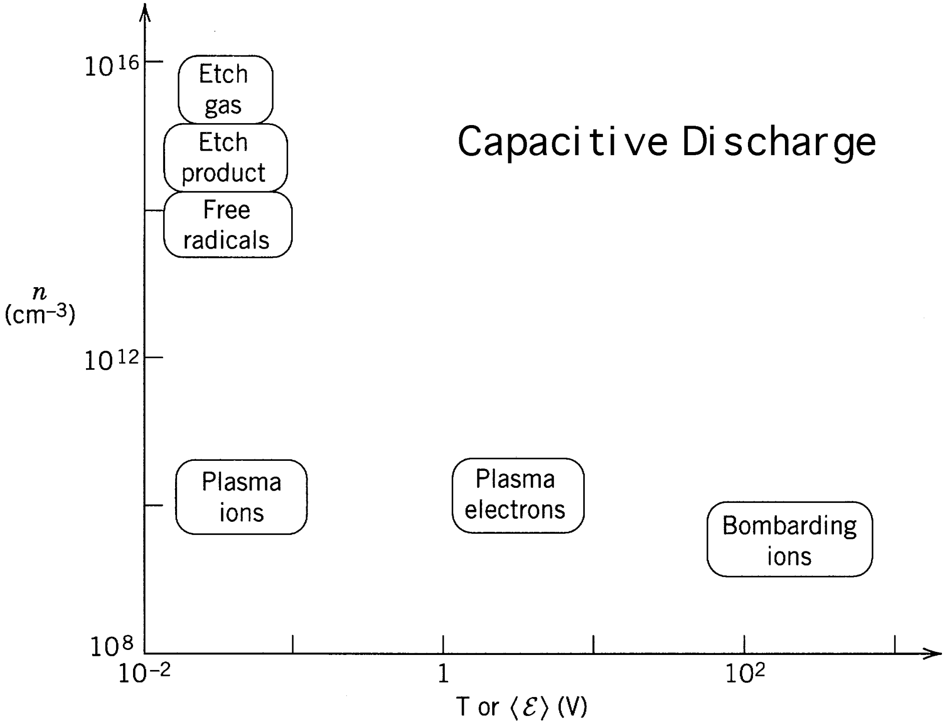
5. Energetic ions bombard trench bottom, but not sidewalls:
   (a) Increase etching reaction rate at trench bottom
   (b) Clear passivating films from trench bottom



PLASMA DENSITY VERSUS TEMPERATURE



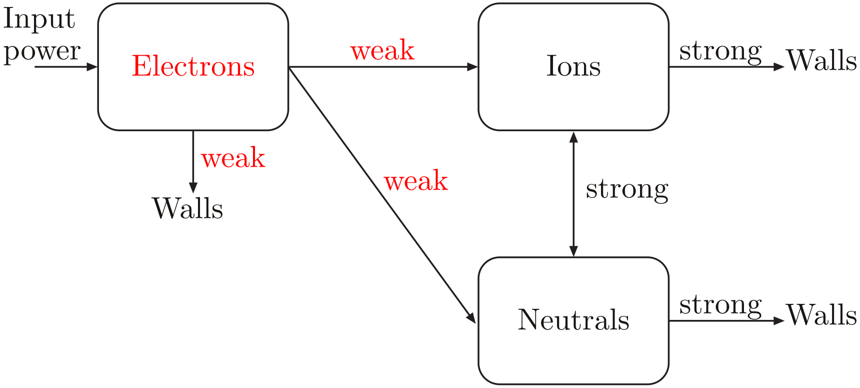
RELATIVE DENSITIES AND ENERGIES



Charged particle densities $\ll$ neutral particle densities

NON-EQUILIBRIUM

- Energy coupling between electrons and heavy particles is weak



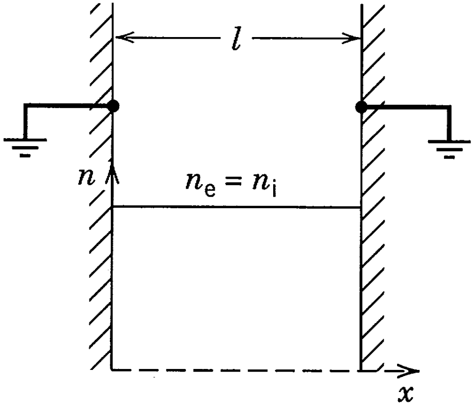
- Electrons are *not* in thermal equilibrium with ions or neutrals

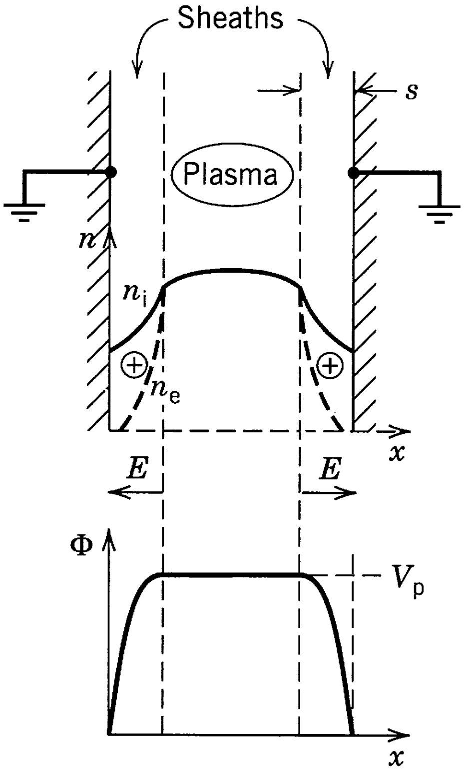
$$\boxed{\begin{array}{c} T_e \gg T_i \quad \text{in plasma bulk} \\ \text{Bombarding } \mathcal{E}_i \gg \mathcal{E}_e \quad \text{at wafer surface} \end{array}}$$

- "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

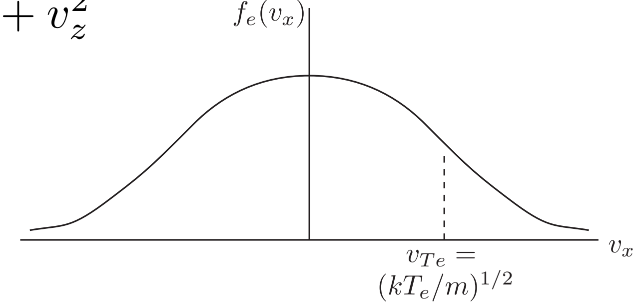
SUMMARY OF PLASMA FUNDAMENTALS

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



- Electron energy distribution function (EEDF)

$$g_e(\mathcal{E}) \propto \mathcal{E}^{1/2} \exp(-\mathcal{E}/\mathrm{T}_e)$$

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

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

AVERAGES OVER MAXWELLIAN DISTRIBUTION

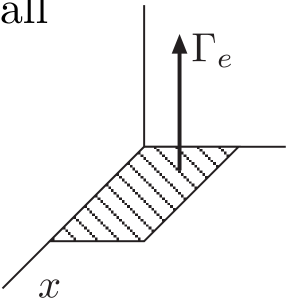
- Average energy

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

- 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



$$\Gamma_e = \int_{-\infty}^{\infty} dv_x \int_{-\infty}^{\infty} dv_y \int_0^{\infty} dv_z v_z f_e(v) = \boxed{\frac{1}{4} n_e \bar{v}_e} \quad [\text{m}^{-2}\text{-s}^{-1}]$$

- Average kinetic energy lost per electron lost to a wall

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

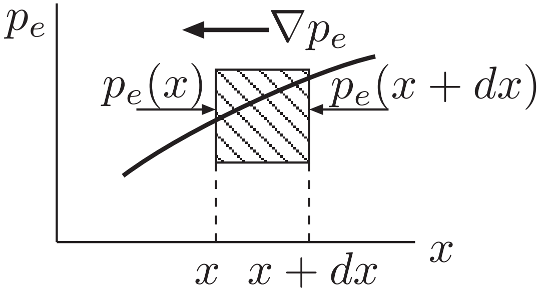
FORCES ON PARTICLES

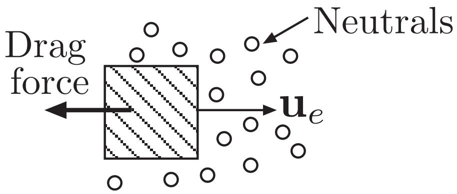
For a unit volume of electrons (or ions)

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

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

- Electric field and pressure gradient forces almost balance

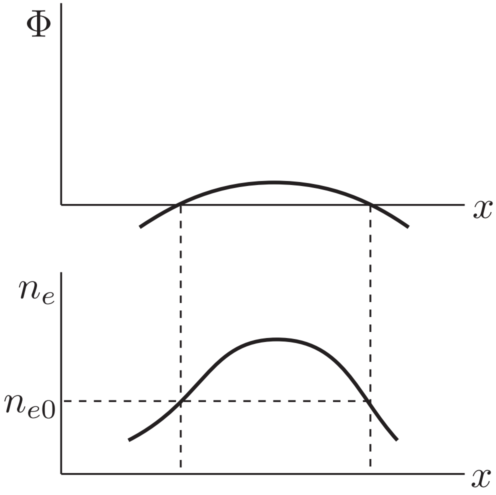
$$0 \approx -en_e\mathbf{E} - \nabla p_e$$

- 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 $\epsilon_{\mathbf{p}}$

- RF discharges are driven at a frequency ω

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

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

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

- Conduction current $\tilde{J}_c = -en_e\tilde{u}_e$ is mainly due to electrons
- Newton's law (electric field and neutral drag) is

$$j\omega m\tilde{u}_e = -e\tilde{E} - m\nu_m\tilde{u}_e$$

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

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

PLASMA CONDUCTIVITY $\sigma_{\mathbf{p}}$

- It is useful to introduce the plasma conductivity $\tilde{J}_c \equiv \sigma_p \tilde{E}$
- RF plasma conductivity

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

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

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

- The plasma dielectric constant and conductivity are related by:

$$j\omega\epsilon_p = \sigma_p + j\omega\epsilon_0$$

- Due to $\mathrm{Re}(\sigma_p)$ [or $\mathrm{Im}(\epsilon_p)$], 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)

$$\frac{dn_e}{dt} = \nu n_e = K n_g \, n_e$$

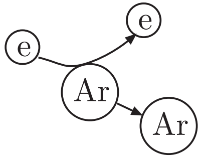
ν = collision frequency [s^{-1}], $K(T_e)$ = rate coefficient [m^3/s]

- Electron-Ar collision processes

$\mathrm{e} + \mathrm{Ar} \longrightarrow \mathrm{Ar}^+ + 2\mathrm{e}$ (ionization)

$\mathrm{e} + \mathrm{Ar} \longrightarrow \mathrm{e} + \mathrm{Ar}^* \longrightarrow \mathrm{e} + \mathrm{Ar} +$ photon (excitation)

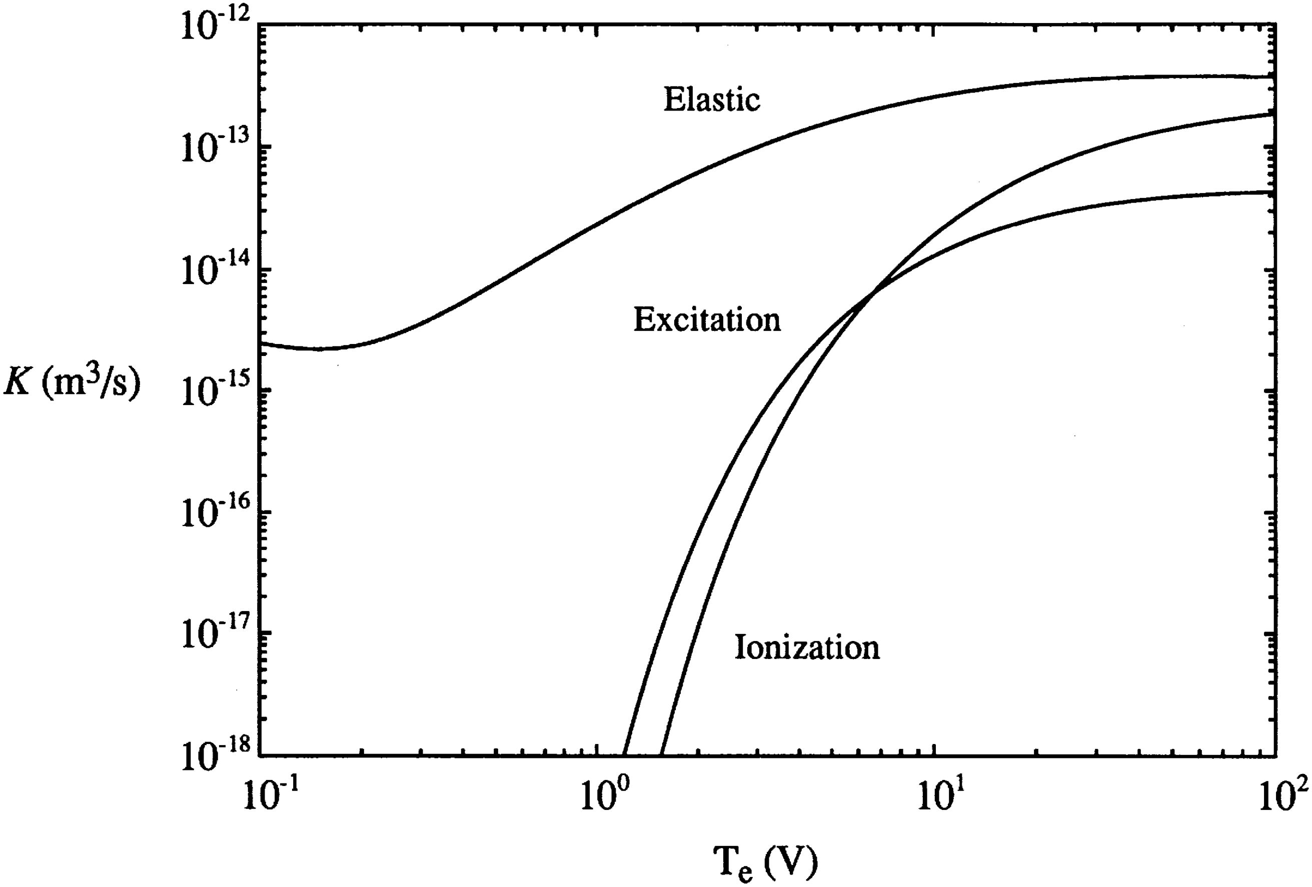
$\mathrm{e} + \mathrm{Ar} \longrightarrow \mathrm{e} + \mathrm{Ar}$ (elastic scattering)



- Rate coefficient $K(T_e)$ is average over Maxwellian distribution of cross section σ [m^2] × relative velocity v for the process

$$K(T_e) = \langle \sigma v \rangle_{\mathrm{Maxwellian}}$$

ELECTRON-ARGON RATE COEFFICIENTS

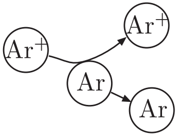


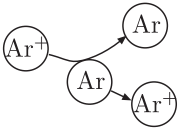
ION COLLISIONS WITH ARGON

- Argon ions collide with Ar atoms

$$\mathrm{Ar}^+ + \mathrm{Ar} \longrightarrow \mathrm{Ar}^+ + \mathrm{Ar} \qquad \text{(elastic scattering)}$$

$$\mathrm{Ar}^+ + \mathrm{Ar} \longrightarrow \mathrm{Ar} + \mathrm{Ar}^+ \qquad \text{(charge transfer)}$$





- Total cross section for room temperature ions $\sigma_i \approx 10^{-14}$ cm^2
- Ion-neutral mean free path

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

- Practical formula

$$\lambda_i[\mathrm{cm}] = \frac{1}{330\,p}, \qquad [p \text{ in Torr}]$$

- Ion-neutral collision frequency

$$\nu_i = n_g \bar{v}_i / \lambda_i$$

with $\bar{v}_i = (8kT_i/\pi M)^{1/2}$

THREE ENERGY LOSS PROCESSES

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

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

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

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

2. Electron kinetic energy lost to walls

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

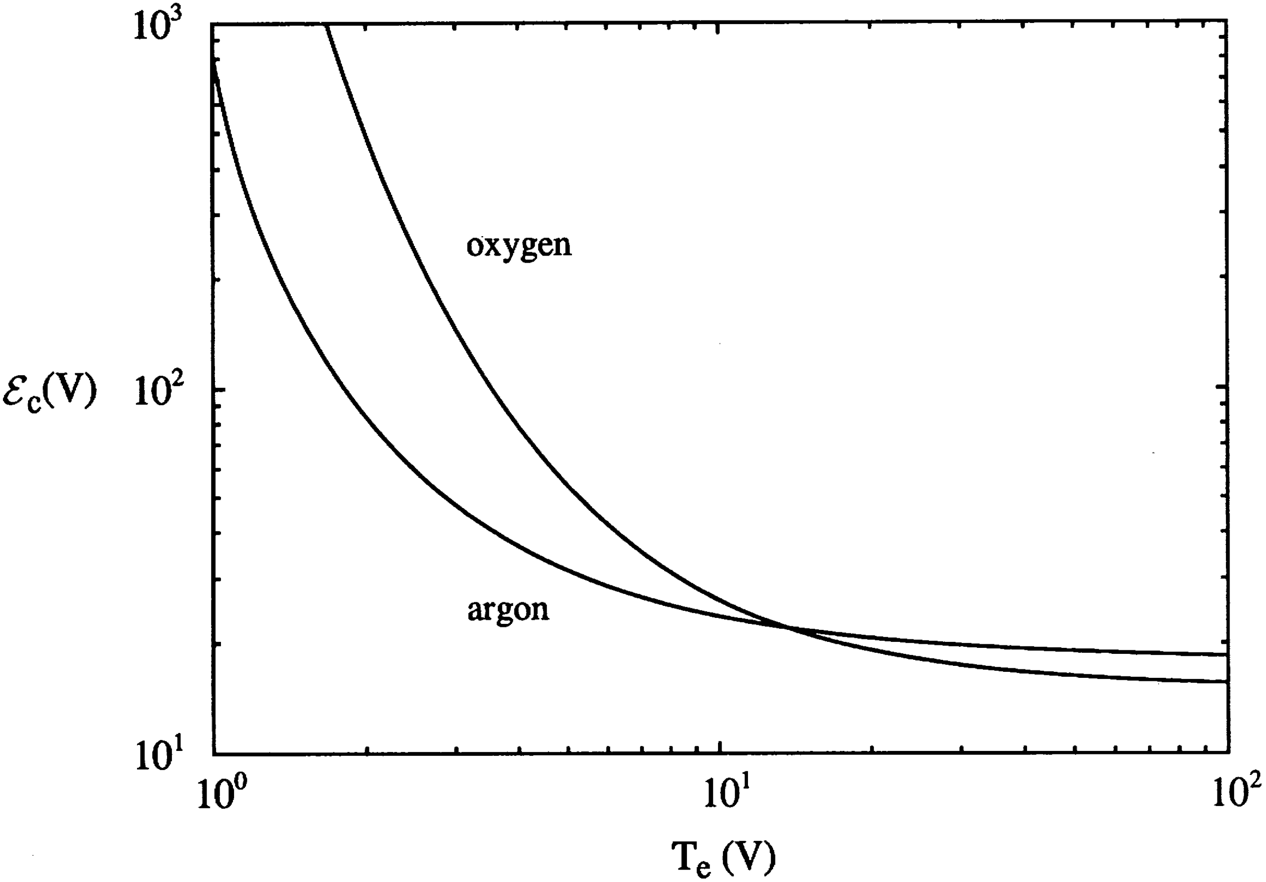
3. Ion kinetic energy lost to walls is mainly due to the dc potential $\bar{V}_s$ across the sheath

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

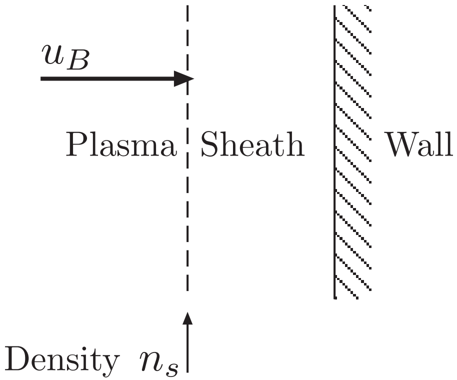
- Total energy lost per electron-ion pair lost to walls

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

COLLISIONAL ENERGY LOSSES



BOHM (ION LOSS) VELOCITY u_B



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

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

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

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

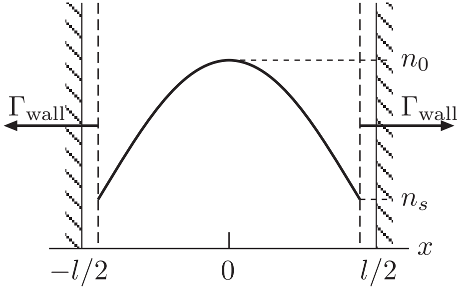
AMBIPOLAR DIFFUSION AT HIGH PRESSURES

- Plasma bulk is quasi-neutral ($n_e \approx n_i = n$) and the electron and ion loss fluxes are equal ($\Gamma_e \approx \Gamma_i \approx \Gamma$)
- Fick's law

$$\Gamma = -D_a \nabla n$$

with ambipolar diffusion coefficient $D_a = kT_e/M\nu_i$

- Density profile is sinusoidal



- Loss flux to the wall is

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

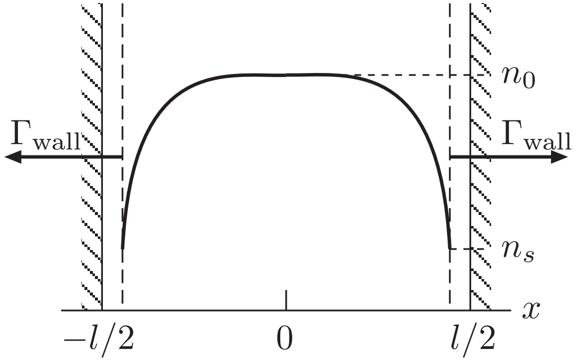
- Edge-to-center density ratio is

$$h_l \equiv \frac{n_s}{n_0} = \frac{\pi}{l} \frac{u_B}{\nu_i}$$

- Applies for pressures > 100 mTorr in argon

AMBIPOLAR DIFFUSION AT LOW PRESSURES

- The diffusion coefficient is not constant
- Density profile is relatively flat in the center and falls sharply near the sheath edge



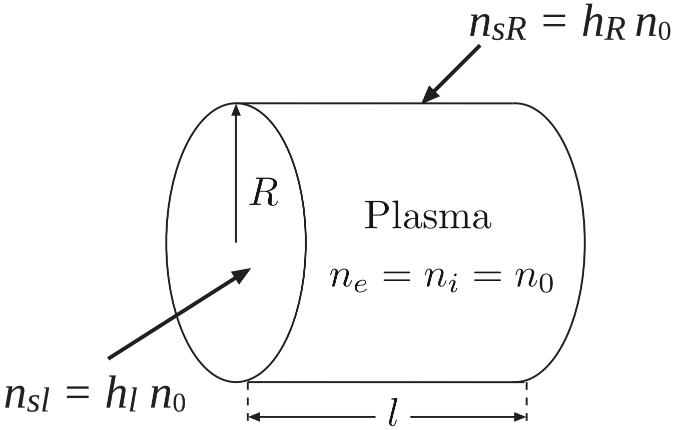
- The edge-to-center density ratio is

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

where λ_i = ion-neutral mean free path [p. 22]

- Applies for pressures $<$ 100 mTorr in argon

AMBIPOLAR 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

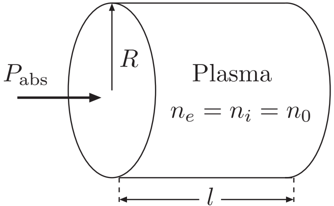
$$\boxed{h_l \approx \frac{0.86}{(3 + l/2\lambda_i)^{1/2}}, \qquad h_R \approx \frac{0.8}{(4 + R/\lambda_i)^{1/2}}}$$

- Applies for pressures $<$ 100 mTorr in argon

GLOBAL MODEL OF DISCHARGE EQUILIBRIUM

PARTICLE BALANCE AND $\mathbf{T_e}$

- Assume uniform cylindrical plasma absorbing power $P_{\rm abs}$



- Particle balance

Production due to ionization = loss to the walls

$$\boxed{K_{\rm iz} n_g n_0 \pi R^2 l = (2\pi R^2 h_l n_0 + 2\pi R l h_R n_0) u_B}$$

- Solve to obtain

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

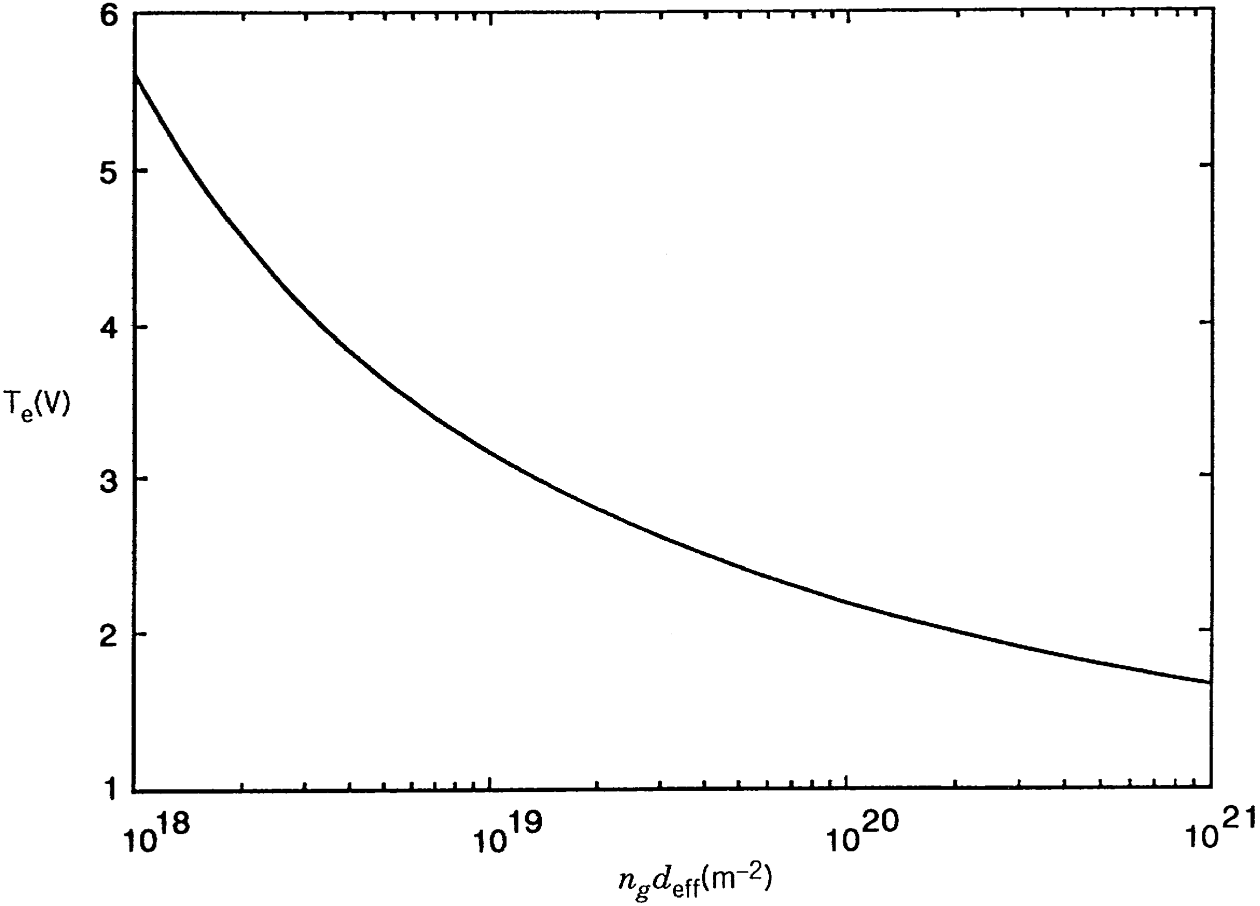
where

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

is an effective plasma size

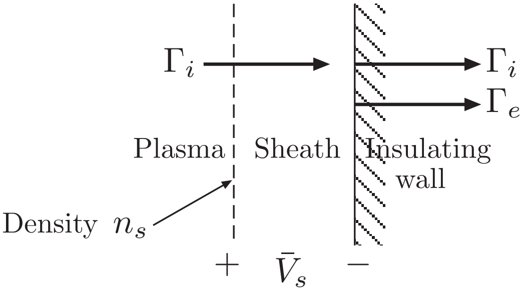
- Given n_g and $d_{\rm eff}$ $\Longrightarrow$ electron temperature T_e
- T_e varies over a narrow range of 2–5 volts

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 in the sheath



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

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

- The ion and electron fluxes must balance

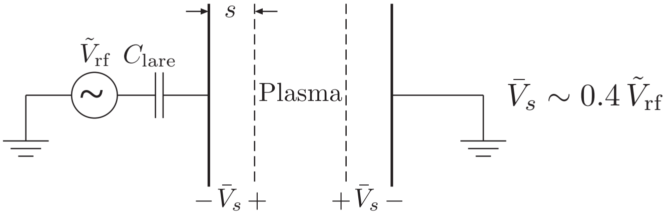
$$\boxed{\bar{V}_s = \frac{\mathrm{T}_e}{2} \ln\left(\frac{M}{2\pi m}\right)}$$

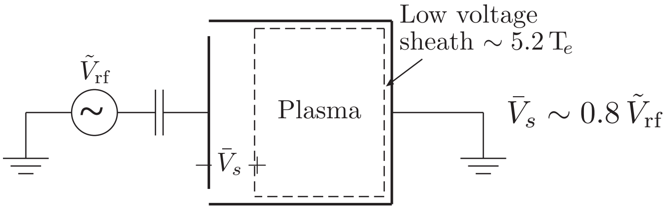
or $\bar{V}_s \approx 4.7\,\mathrm{T}_e$ for argon

- 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- or dc-driven electrodes embedded in the plasma





- 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

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

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

- Solve to obtain

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

where

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

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. 22, 28, 30]
- From the T_e versus $n_g d_{\text{eff}}$ figure, $\mathrm{T}_e \approx 3.5$ V [p. 31]
- From the $\mathcal{E}_c$ versus T_e figure, $\mathcal{E}_c \approx 42$ V [p. 24]. 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. 23]
- Find $u_B \approx 2.9 \times 10^3$ m/s and find $A_{\text{eff}} \approx 0.13$ m^2 [pp. 25, 34]
- Power balance yields $n_0 \approx 2.0 \times 10^{17}$ m^{-3} [p. 34]
- 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. 32]

EXAMPLE 2

- Apply a strong dc magnetic field along the cylinder axis $\Longrightarrow$ particle loss to radial wall is inhibited
- For no radial loss, $d_{\text{eff}} = l/2h_l \approx 0.5$ m
- From the T_e versus $n_g d_{\text{eff}}$ figure, $\mathrm{T}_e \approx 3.3$ V
- 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}
- 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

$\Longrightarrow$ Small drop in T_e and significant increase in n_0

EXPLAIN WHY!

IMPROVEMENTS TO GLOBAL MODEL

NON-MAXWELLIAN ELECTRON DISTRIBUTIONS

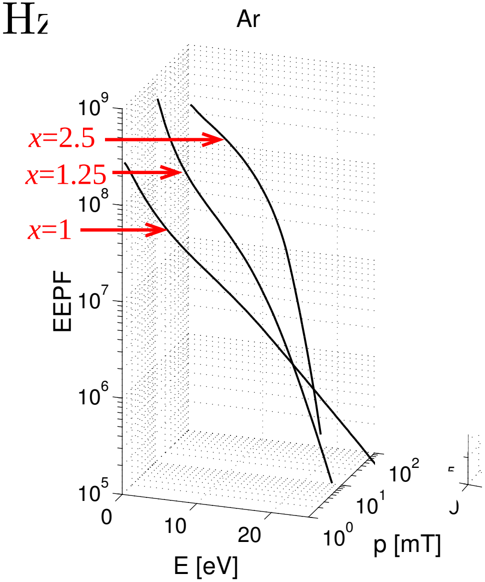
- Global model theory with EEDF [p. 13]

  $$g_e \propto \mathcal{E}^{1/2}\exp(-c\mathcal{E}^x)$$

  $x = 1 \Rightarrow$ Maxwellian; $x = 2 \Rightarrow$ Druyvesteyn

  (J.T. Gudmundsson, *Plasma Sources Sci. Technol.* **10**, 76, 2001)

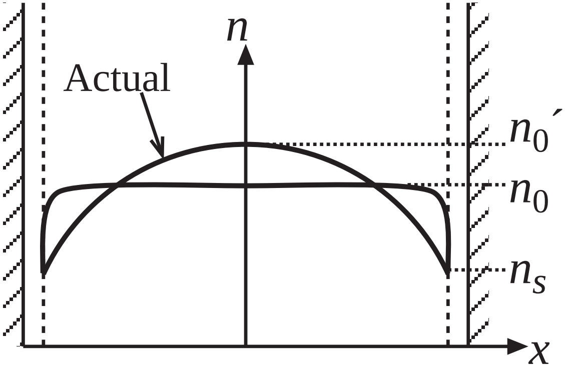
- 1D PIC simulations with "inductive source"-type excitation, 5 cm gap, 13.56 MHz



(D. Monahan, "Modelling the Electronegative Discharge," PhD Thesis submitted to Dublin City University, June 2007; Prof. Miles Turner, supervisor)

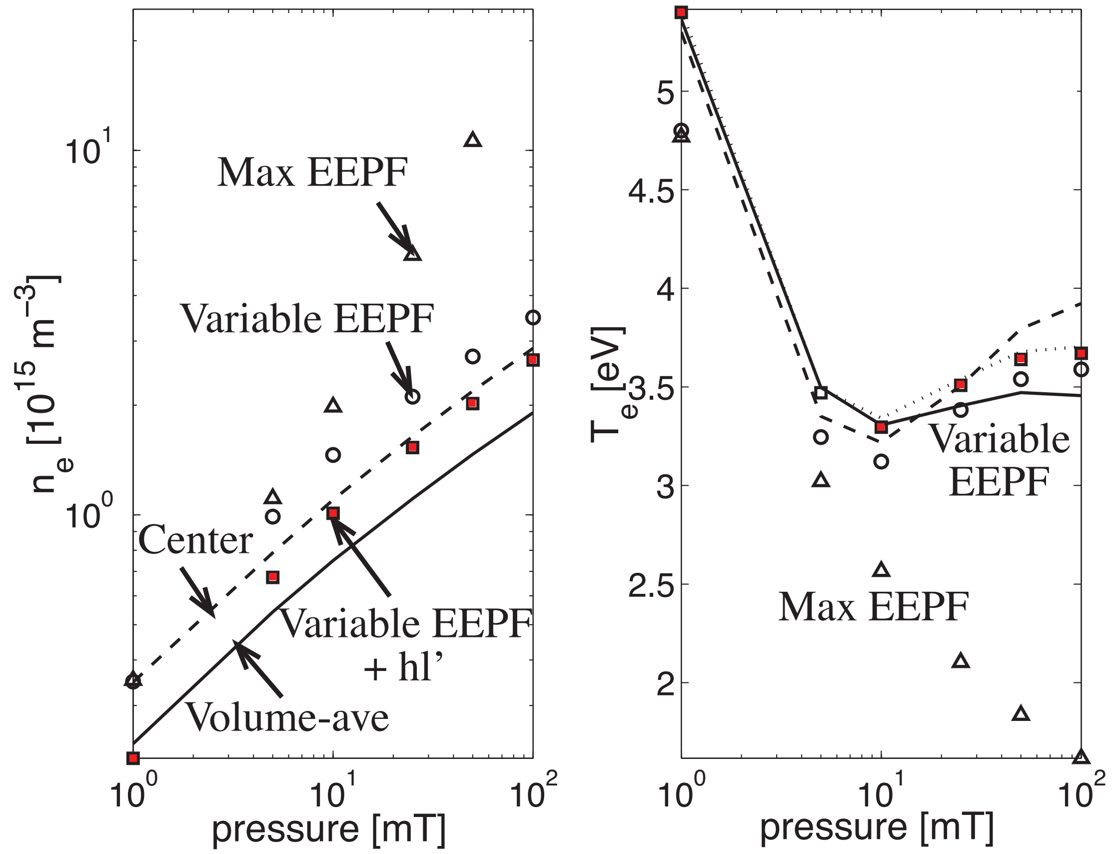
NON-UNIFORM BULK PLASMA

- Global model assumes a uniform bulk plasma (density n_0) dropping sharply to a sheath edge density n_s
- The actual low-pressure profile is more like a piece of a circle



$$\boxed{h_l = \frac{n_s}{n_0} \quad \Longrightarrow \quad h_l' = \frac{n_s}{n_0'}}$$

PIC SIMULATION RESULTS



ELECTRON HEATING

- 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)
- Achieving adequate electron heating is a central issue
- 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

INDUCTIVE DISCHARGES

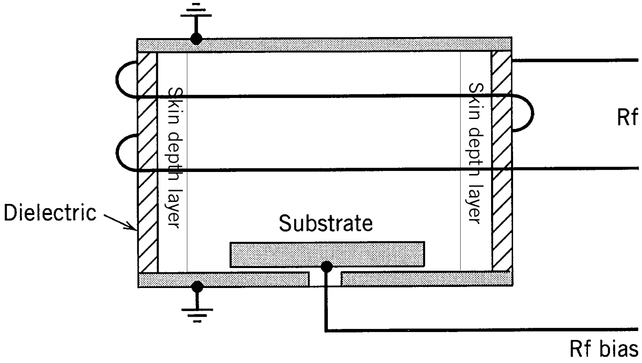
DESCRIPTION AND MODEL

MOTIVATION

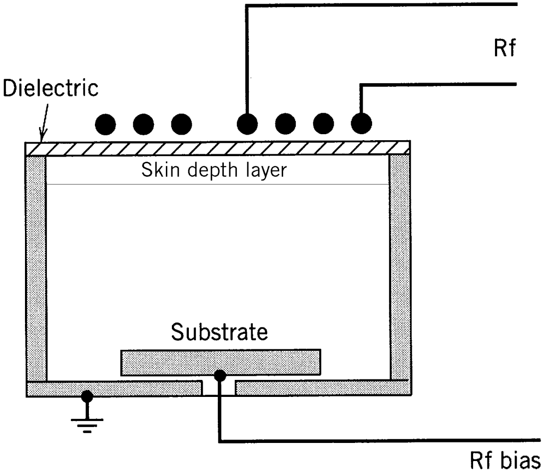
- Independent control of plasma density and ion energy
- Simplicity of concept
- RF rather than microwave powered
- No source magnetic fields

CYLINDRICAL AND PLANAR CONFIGURATIONS

- Cylindrical coil

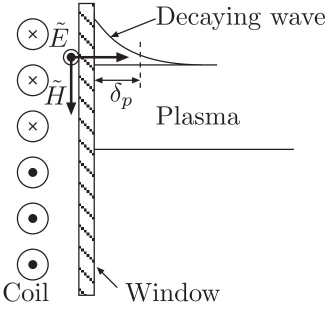


- Planar coil



HIGH DENSITY REGIME

- Inductive coil excites a decaying electromagnetic wave in plasma



- Wave decays exponentially into plasma

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

where κ_p = plasma dielectric constant [p. 17]

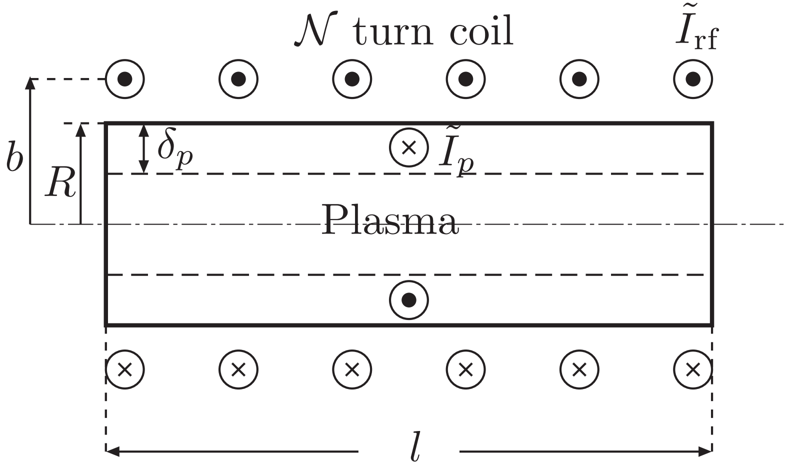
$$\kappa_p = 1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_m)}$$

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

$$\boxed{\delta_p \approx \frac{c}{\omega_{pe}} = \left(\frac{m}{e^2\mu_0 n_e}\right)^{1/2} \sim \ 1\text{–}2\ \mathrm{cm}}$$

TRANSFORMER MODEL

- For simplicity consider long cylindrical discharge



- Current $\tilde{I}_{\rm rf}$ 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

$$\sigma_{\rm dc} = \frac{e^2 n_{es}}{m\nu_m} \qquad \text{[p. 18]}$$

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

- Plasma inductance L_p

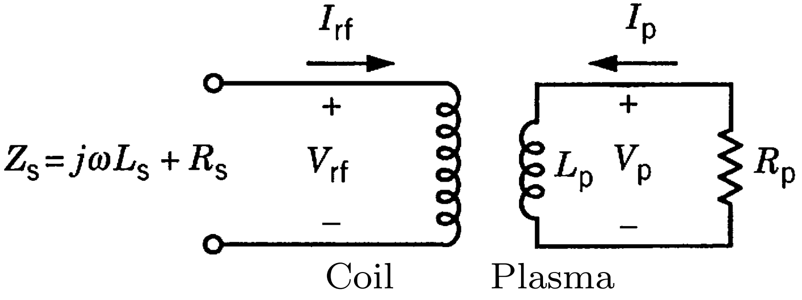
$$L_p = \frac{\text{magnetic flux produced by plasma current}}{\text{plasma current}}$$

- 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



$$\boxed{\begin{aligned}\tilde{V}_{\mathrm{rf}} &= j\omega L_{11}\tilde{I}_{\mathrm{rf}} + j\omega L_{12}\tilde{I}_p \\ \tilde{V}_p &= j\omega L_{21}\tilde{I}_{\mathrm{rf}} + j\omega L_{22}\tilde{I}_p\end{aligned}}$$

- Transformer inductances

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

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

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

- Plasma resistance

$$\boxed{V_p = -I_p R_p}$$

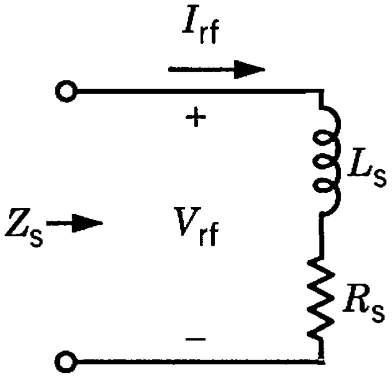
SOURCE CURRENT AND VOLTAGE

- Solve for impedance $Z_s = \tilde{V}_{\text{rf}}/\tilde{I}_{\text{rf}}$ 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

$$\boxed{\begin{aligned} R_s &= \mathcal{N}^2 \frac{\pi R}{\sigma_{\text{dc}} l \delta_p} \\ L_s &= \frac{\mu_0 \pi R^2 \mathcal{N}^2}{l}\left(\frac{b^2}{R^2} - 1\right) \end{aligned}}$$



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

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

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

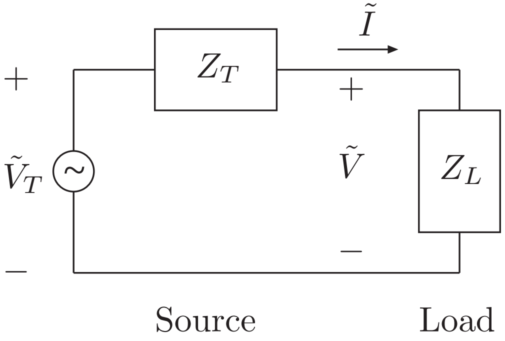
$$\boxed{\tilde{V}_{\text{rf}} = \tilde{I}_{\text{rf}} Z_s}$$

EXAMPLE

- Assume plasma radius $R = 10$ cm, coil radius $b = 15$ cm, length $l = 20$ cm, $\mathcal{N} = 3$ turns, gas density $n_g = 6.6\times 10^{14}$ 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, $h_l \approx h_R \approx 0.1$, and $d_{\text{eff}} \approx 34$ cm [pp. 22, 28, 30]
- Particle balance (T_e versus $n_g d_{\text{eff}}$ figure) yields $\mathrm{T}_e \approx 2.1$ V [p. 31]
- Collisional energy losses ($\mathcal{E}_c$ versus T_e figure) are $\mathcal{E}_c \approx 110$ V [p. 24]. Adding $\mathcal{E}_e + \mathcal{E}_i = 7.2\,\mathrm{T}_e$ yields total energy losses $\mathcal{E}_T \approx 126$ V [p. 23]
- $u_B \approx 2.3 \times 10^5$ cm/s and $A_{\text{eff}} \approx 185$ cm^2 [pp. 25, 34]
- 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. 34]
- Use n_{se} to find skin depth $\delta_p \approx 2.0$ cm [p. 46]; estimate $\nu_m = K_{\text{el}} n_g$ (K_{el} versus T_e figure) to find $\nu_m \approx 3.4 \times 10^7$ s^{-1} [p. 21]
- Use ν_m and n_{se} to find $\sigma_{\text{dc}} \approx 61\ \Omega^{-1}$-m^{-1} [p. 18]
- 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. 50]
- Power balance yields $\tilde{I}_{\text{rf}} \approx 7.1$A; from impedance $\tilde{V}_{\text{rf}} \approx 1360$ V [p. 50]

MATCHING DISCHARGE TO POWER SOURCE

- Consider an rf power source connected to a load

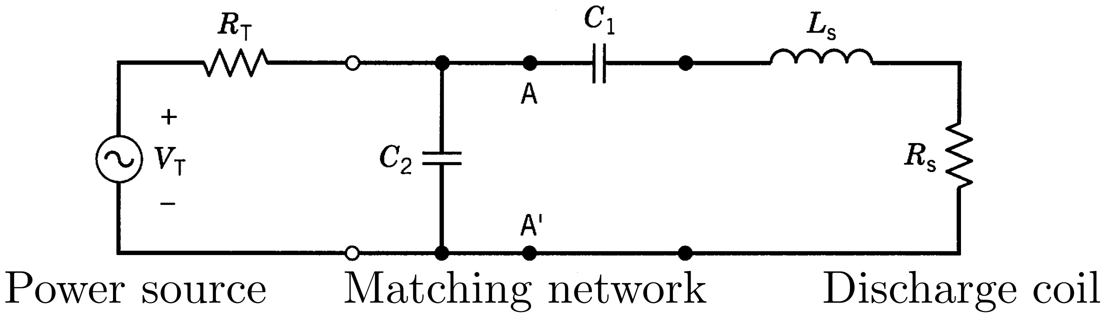


- Source impedance $Z_T = R_T + jX_T$ is given
  Load impedance $Z_L = R_L + jX_L$
- Time-average power delivered to load $P_{\rm abs} = \frac{1}{2}{\rm Re}\,(\tilde V \tilde I^*)$
- For fixed source $\tilde V_T$ and Z_T, to maximize power delivered to load,

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

MATCHING NETWORK

- Insert lossless matching network between power source and coil



- Continue EXAMPLE with $R_s = 23.5\ \Omega$ and $\omega L_s = 190\ \Omega$; assume $R_T = 50\ \Omega$ (corresponds to conductance of $1/50\ \Omega^{-1}$)
- Choose C_1 such that the conductance seen looking to the right at terminals AA' is $1/R_T = 1/50\ \Omega^{-1}$

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

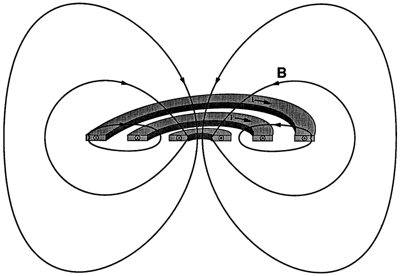
- Choose C_2 to cancel the reactive part of the impedance seen at AA'

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

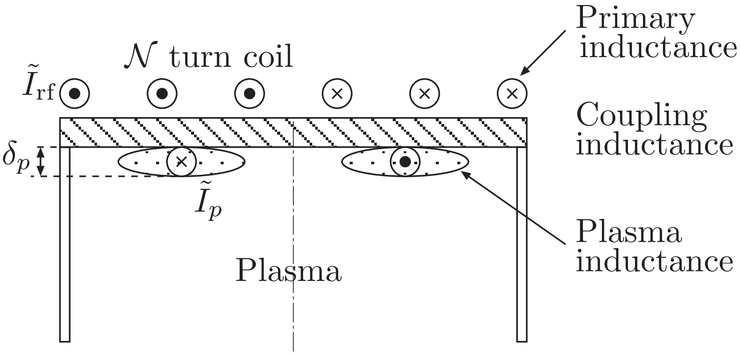
- For $P_\text{abs} = 600$ W, the 50 Ω source supplies $\tilde{I}_\text{rf} = 4.9$ A
- Voltage at source terminals (AA') $= I_\text{rf} R_T = 245$ V

PLANAR COIL DISCHARGE

- Magnetic field produced by planar coil



- RF power is deposited in ring-shaped plasma volume



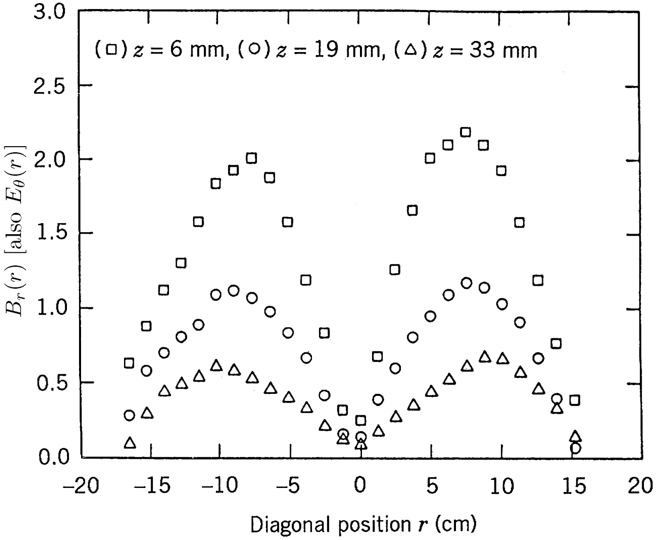
- As for a cylindrical discharge, there is a primary (L_{11}), coupling ($L_{12} = L_{21}$) and secondary ($L_p = L_{22}$) inductance

PLANAR COIL FIELDS

- A ring-shaped plasma forms because

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

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



INDUCTIVE DISCHARGES

POWER BALANCE

RESISTANCE AT HIGH AND LOW DENSITIES

- Plasma resistance seen by the coil [p. 50]

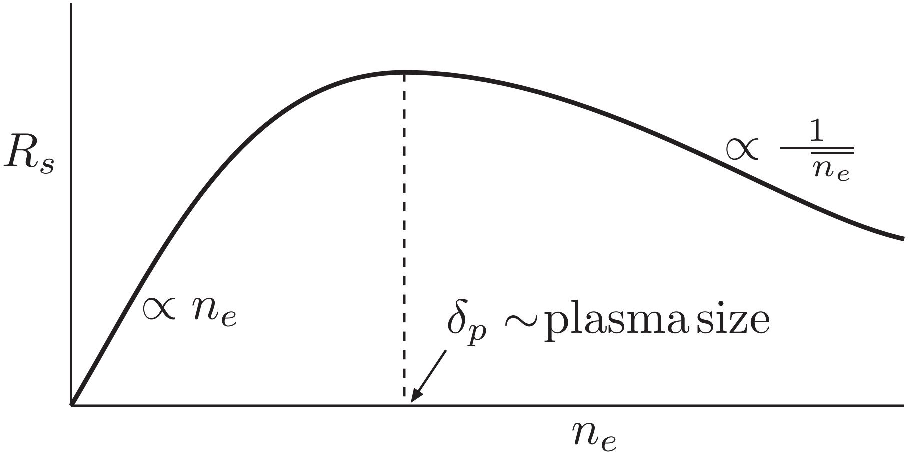
$$R_s = R_p \frac{\omega^2 L_{12}^2}{R_p^2 + \omega^2 L_p^2}$$

- High density (normal inductive operation)

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

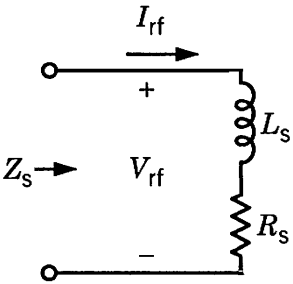
- Low density (skin depth > plasma size)

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

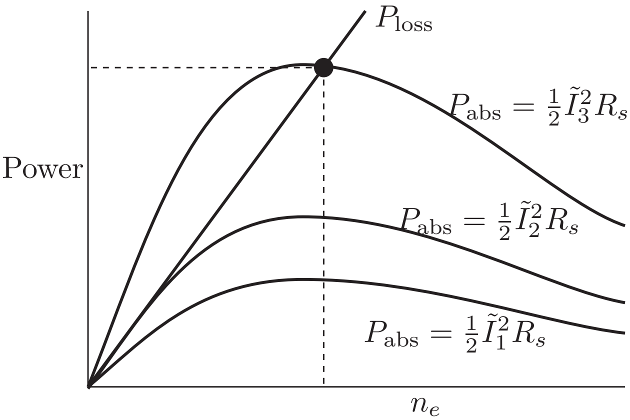


POWER BALANCE

- Drive discharge with rf current



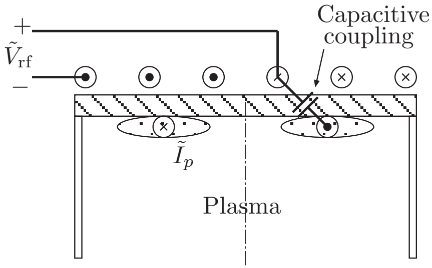
- Power absorbed by discharge is $P_{abs} = \frac{1}{2}|\tilde{I}_{rf}|^2 R_s(n_e)$
  Power lost by discharge $P_{loss} \propto n_e$ [p. 34]
- Intersection gives operating point; let $\tilde{I}_1 < \tilde{I}_2 < \tilde{I}_3$



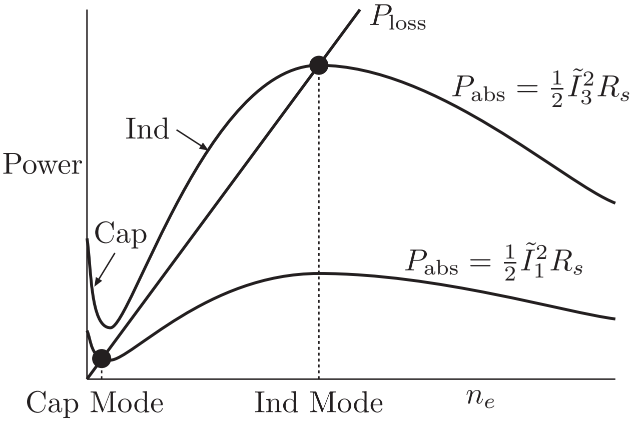
- Inductive operation impossible for $\tilde{I}_{rf} \leq \tilde{I}_2$, the critical current

CAPACITIVE COUPLING OF COIL TO PLASMA

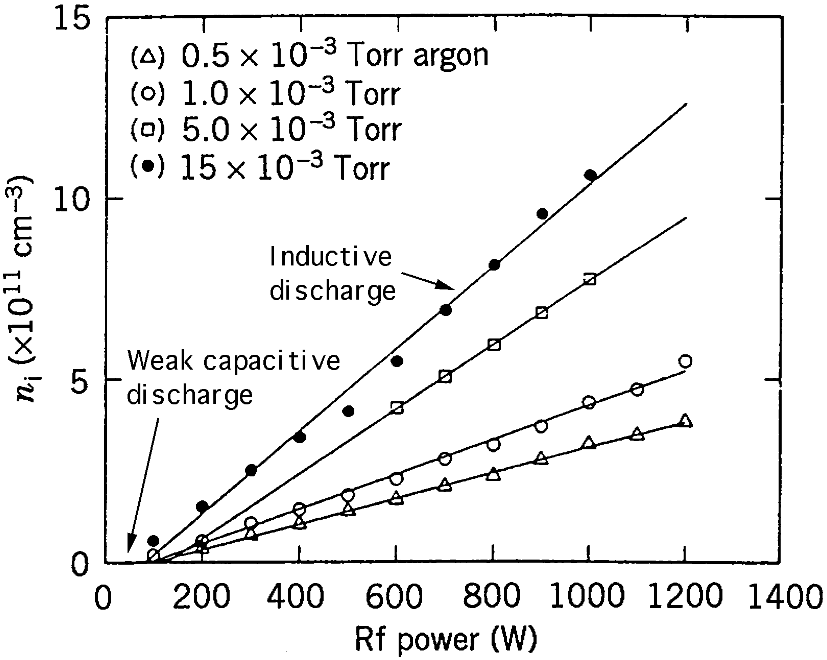
- For $\tilde{I}_{\text{rf}}$ below the critical current $\tilde{I}_2$, there is only a weak capacitive coupling of the coil to the plasma



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



MEASURMENTS OF ARGON ION DENSITY



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

FREE RADICAL BALANCE IN DISCHARGES

ONE-DIMENSIONAL SLAB MODEL

- N_2 discharge with low fractional ionization ($n_g \approx n_{N_2}$)
- Determine T_e:

  Assume $R \gg l =$ plate separation. Then ion particle balance is

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

  where $n_{is} = h_l n_i$. This yields [p. 30]

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

- Determine n_i and Γ_{is}:

  The overall discharge power balance is [p. 34]

  $$P_{abs} \approx 2Ae\mathcal{E}_T n_{is} u_B$$

  This yields

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

  and

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

- Determine ion bombarding energy [p. 32]

  $$\boxed{\mathcal{E}_i = 5.2\,T_e}$$

FREE RADICAL BALANCE

- For nitrogen:

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

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

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

- Solving for the free radical density at the surface

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

- The flux of N atoms is

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

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

- But how does $K_{\mathrm{diss}}(\mathrm{T}_e)$ depend on discharge pressure?

DISSOCIATION RATE COEFFICIENT

- Assume K_{diss} and K_{iz} have Arrhenius forms

$$K_{\text{diss}} = K_{\text{diss0}}\,\mathrm{e}^{-\mathcal{E}_{\text{diss}}/\mathrm{T}_e}$$
$$K_{\text{iz}} = K_{\text{iz0}}\,\mathrm{e}^{-\mathcal{E}_{\text{iz}}/\mathrm{T}_e}$$

- Eliminating T_e from these equations yields

$$K_{\text{diss}} = C_0 K_{\text{iz}}^{\mathcal{E}_{\text{diss}}/\mathcal{E}_{\text{iz}}}$$

  where $C_0 = K_{\text{diss0}}/K_{iz0}^{\mathcal{E}_{\text{diss}}/\mathcal{E}_{\text{iz}}}$

- Using ion particle balance [p. 62] to eliminate K_{iz} yields

$$\boxed{K_{\text{diss}} = C_0\left(\frac{2h_l u_B}{n_g l}\right)^{\mathcal{E}_{\text{diss}}/\mathcal{E}_{\text{iz}}}}$$

- In this form, K_{diss} depends only weakly on T_e, and the dependance of K_{diss} on $n_g l$ is made explicit
- Inserting n_i [p. 62] and K_{diss} [above] into $n_{\text{N}S}$ [p. 63] yields

$$\boxed{n_{\text{N}S} = 2C_0\frac{P_{\text{abs}}}{e\mathcal{E}_T S_p}\left(\frac{n_g l}{2h_l u_B}\right)^{1-\mathcal{E}_{\text{diss}}/\mathcal{E}_{\text{iz}}}}$$

  Typically, $\mathcal{E}_{\text{diss}}/\mathcal{E}_{\text{iz}} \approx 0.3$–$0.5$

RECOMBINATION, REACTION AND LOADING EFFECT

- Recall that [p. 64]:

$$\boxed{n_{\mathrm{N}S} = 2C_0 \frac{P_{\mathrm{abs}}}{e\mathcal{E}_T S_p} \left(\frac{n_g l}{2h_l u_B} \right)^{1-\mathcal{E}_{\mathrm{diss}}/\mathcal{E}_{\mathrm{iz}}}}$$

- Consider a recombination coefficient γ_{rec} for N atoms on the walls and a reaction coefficient γ_{reac} for N atoms on a substrate.
  The pumping speed S_p is replaced by:

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

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

- $n_{\mathrm{N}S}$ now depends on the substrate area A_{subs}, a *loading effect*

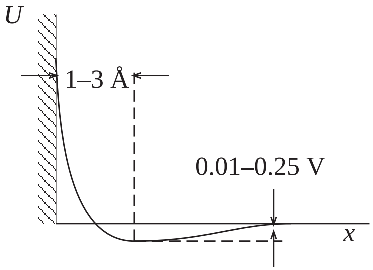
ADSORPTION AND DESORPTION KINETICS

ADSORPTION

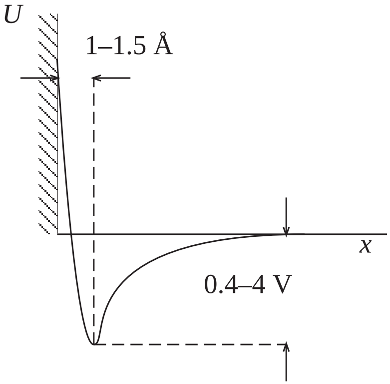
- Reaction of a molecule with the surface

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

- Physisorption (due to weak van der Waals forces)



- Chemisorption (due to formation of chemical bonds)



STICKING COEFFICIENT

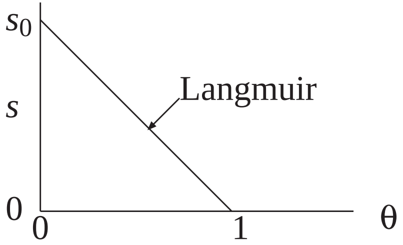
- Adsorbed flux

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

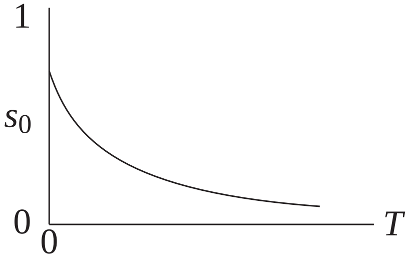
$s(\theta, T)$ = sticking coefficient
θ = fraction of surface sites covered with absorbate

- Langmuir kinetics

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



- Zero-coverage sticking coefficient $s_0 \sim 10^{-6}$–1



DESORPTION

- Rate constant

$$\mathrm{A\!:\!S} \longrightarrow \mathrm{A} + \mathrm{S}$$

$$\boxed{K_{\mathrm{desor}} = K_0\,\mathrm{e}^{-\mathcal{E}_{\mathrm{desor}}/\mathrm{T}} \qquad [\mathrm{s}^{-1}]}$$

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

$$K_0 \sim 10^{14}\text{–}10^{16}\ \mathrm{s}^{-1} \quad \text{physisorption}$$

$$\sim 10^{13}\text{–}10^{15}\ \mathrm{s}^{-1} \quad \text{chemisorption}$$

ADSORPTION-DESORPTION KINETICS

- Consider the reactions

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

- The adsorption flux is

$$\boxed{\Gamma_{\mathrm{ads}} = K_a n_{AS} n'_0 (1 - \theta)}$$

$n'_0 =$ area density (m^{-2}) of adsorption sites

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

$$K_a = s_0 \frac{1}{4} \bar{v}_A / n'_0 \qquad [\mathrm{m}^3/\mathrm{s}]$$

- The desorption flux is

$$\boxed{\Gamma_{\mathrm{desor}} = K_d n'_0 \theta}$$

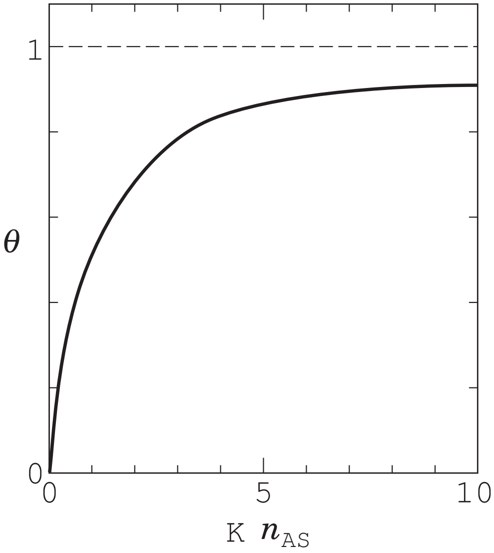
$$K_d = K_{d0}\, \mathrm{e}^{-\mathcal{E}_{\mathrm{desor}}/\mathrm{T}} \qquad [\mathrm{s}^{-1}]$$

LANGMUIR ISOTHERM

- Equate adsorption and desorption fluxes, $\Gamma_{\text{ads}} = \Gamma_{\text{desor}}$

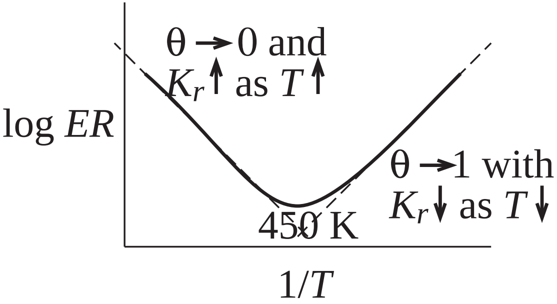
$$\boxed{\theta = \frac{\mathcal{K} n_{AS}}{1 + \mathcal{K} n_{AS}}}$$

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



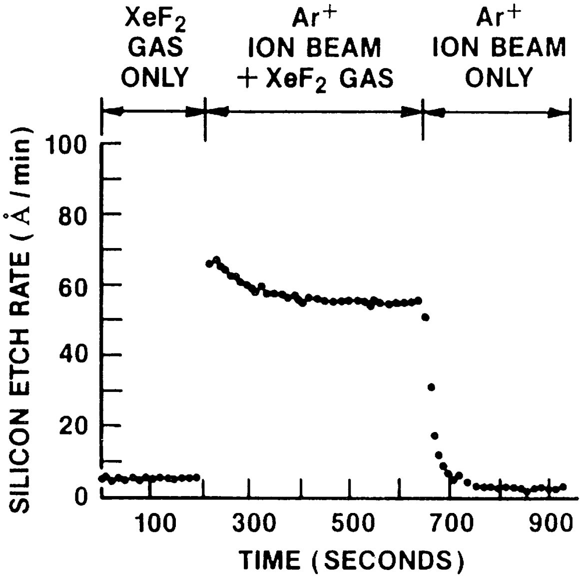
- Note that $T \uparrow \Rightarrow \mathcal{K} \downarrow \Rightarrow \theta \downarrow$

- Example: $2\text{XeF}_2(\text{g}) + \text{Si(s)} \rightarrow \text{SiF}_4(\text{g}) + 2\text{Xe}$



PLASMA-ASSISTED ETCH KINETICS

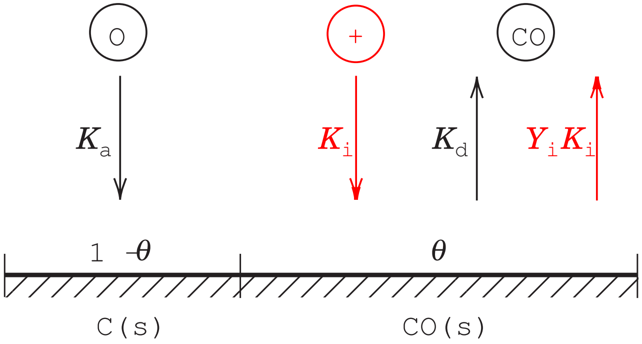
ION-ENHANCED PLASMA ETCHING



1. Low chemical etch rate of silicon in XeF_2 etchant gas
2. Tenfold increase in etch rate with the addition of argon ion bombardment of the substrate, simulating plasma-assisted etching
3. Very low "etch rate" due to the physical sputtering of silicon by the 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

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

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

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

SURFACE COVERAGE

- The steady-state surface coverage is found from

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

- n_{OS} is the neutral gas density near the surface

  n_{is} is the ion density at the plasma edge

- K_a is the rate coefficient for O-atom adsorption

  K_d is the rate coefficient for thermal desorption of CO

  K_i 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

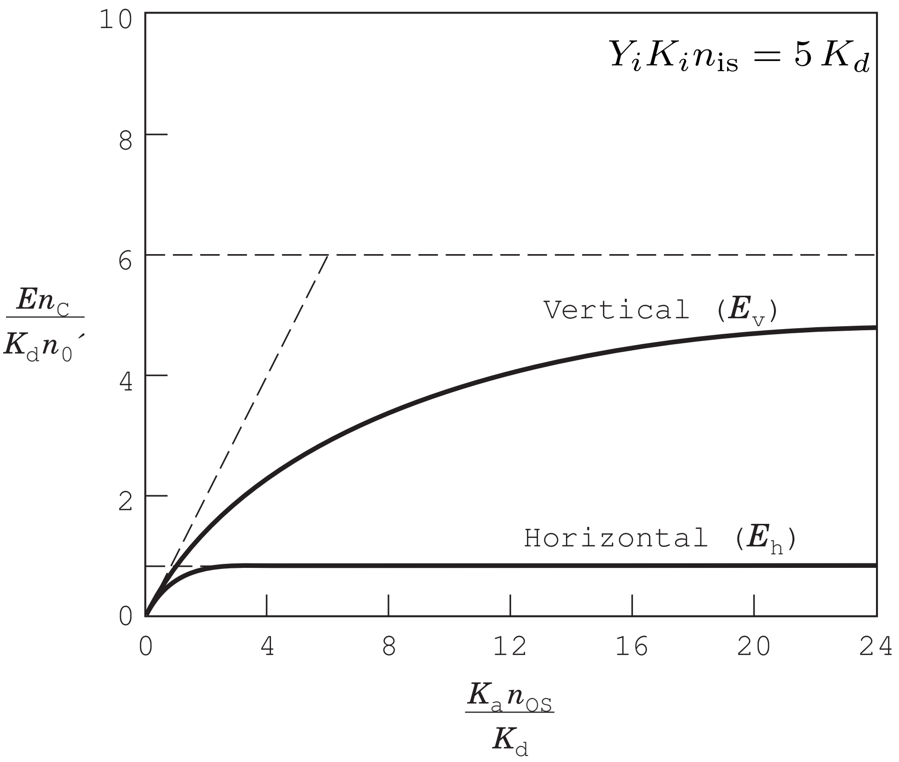
  Typically $Y_i \gg 1$ and $Y_i \propto \sqrt{\mathcal{E}_i - \mathcal{E}_{\mathrm{thr}}}$ (as for sputtering)

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

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 density ⇒ highest anisotropy $E_v/E_h = 1 + Y_i K_i n_{\text{is}}/K_d$
- Low O-atom density ⇒ low etch rates with $E_v/E_h \rightarrow 1$

SIMPLEST MODEL OF ION-ENHANCED ETCHING

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

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

- 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 neutral radical balance determines the flux of radicals 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