Tutorial on Using RF to Control DC Bias

Jim McVittie
<*mcvittie@stanford.edu*>
Stanford Nanofabication Facility
Stanford University

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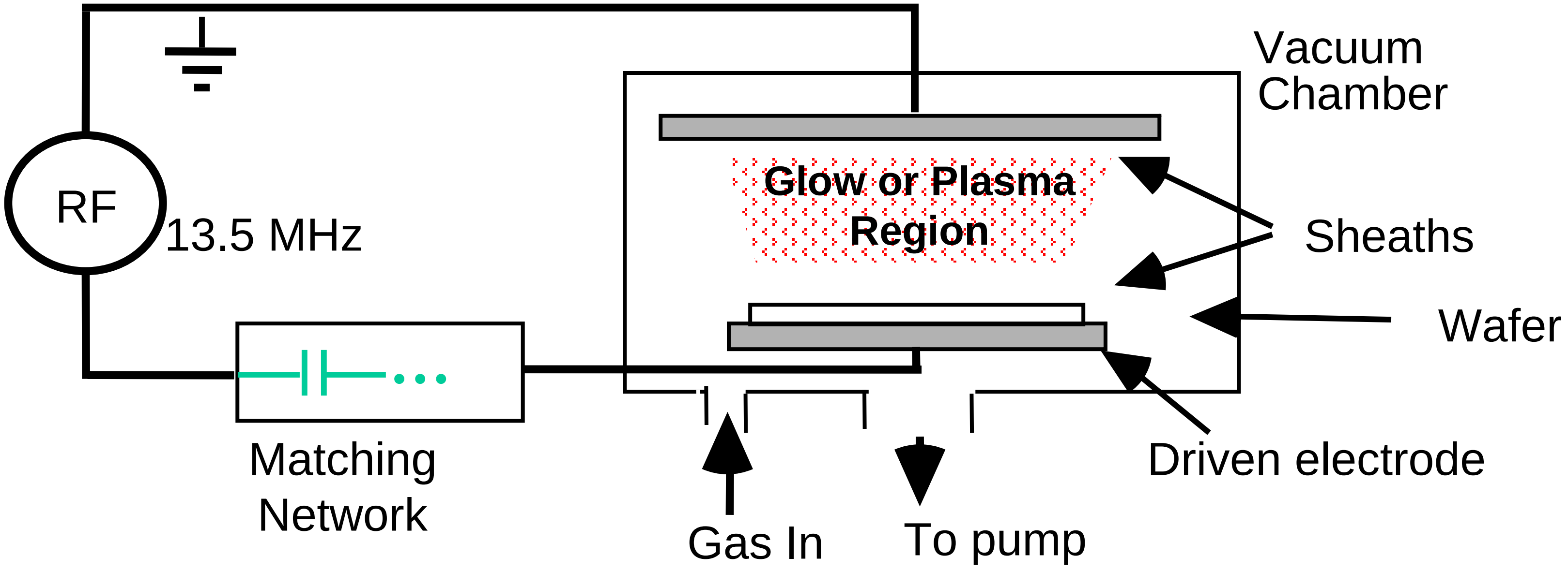
Outline

- Why we use RF excited plasmas
- The Capacitive Coupled Plasma (CCP)
- The current flow in a CCP
- How the rf current across sheath leads the DC bias
- Why controlling DC bias is important for etching
- Use of Inductive coupled plasmas (ICP) as low bias source
- Use of ICP with CCP to control DC bias (Ion Energy)
- Beyond simple DC biasing for ion energy control

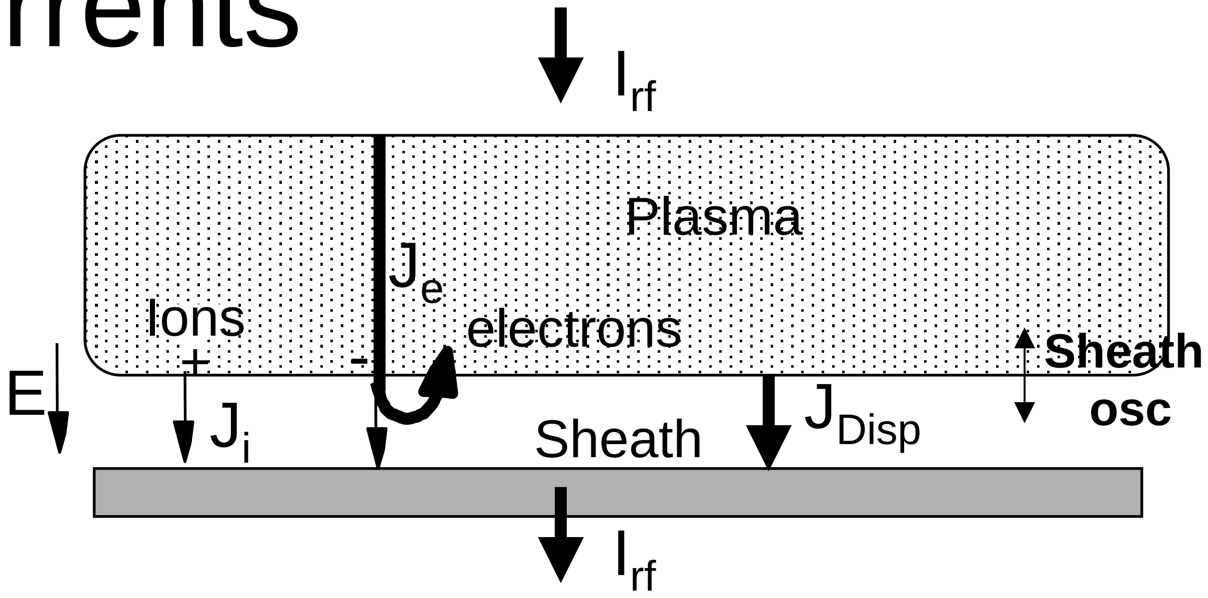
Why We Use RF

- DC plasmas ⇨ Wafer Damage
  - Leads to charging and DC currents through wafer
- Microwave Plasmas
  - No self (DC) bias (Needed for directional etching)
- RF plasmas
  - RF current through wafer causes no damage
  - No charging damage if plasma is uniform
    - Exception is electron shading caused charging in high aspect ratio structures
  - Easy to get induced self or DC bias

Capacitive Coupled Plasma (CCP)



CCP Currents



Plasma Region

- Small E field
- Quasi neutral

  $n_i^+ = n_e^-$
- e^- lighter & faster

  $v_e >> v_i$
- e^- carries current

  $J_{rf} = J_e >> J_i$

Sheath Regions

- Large E field – to keep mobile e^- in plasma region
- e_- depletion

  $n_i^+ >> n_e^-$
- e^- cannot carry current

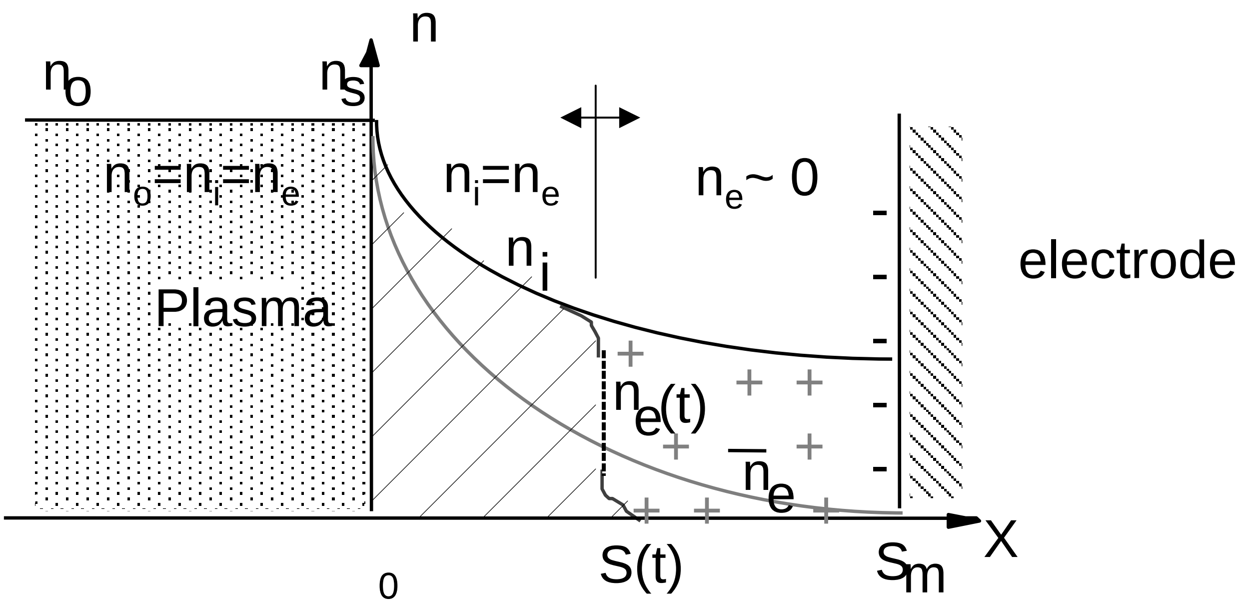
  $J_{rf} >> J_e$
- Conduction currents balanced over rf cycle

  $J_i = - J_e$
- J_{rf} carried by displacement (capacitor) current

  $J_{rf} = J_{disp}$
- Charge transfer by sheath width oscillation
- Sheath Charge ⇨ Dc bias

Oscillating RF Sheath

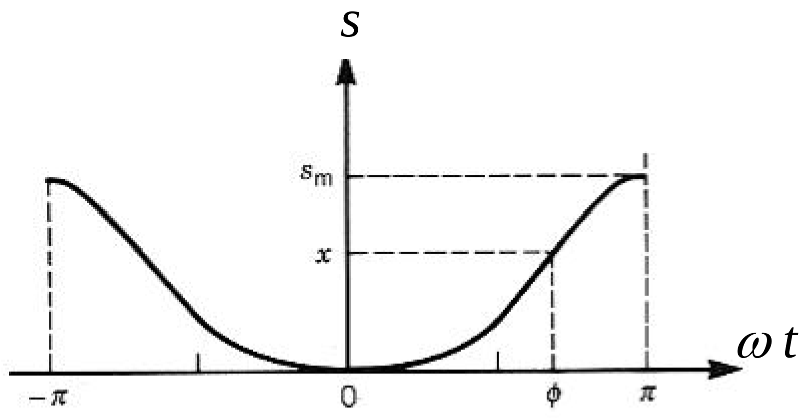
- RF current crosses sheath by displacement $i_{rf} = dq/dt$
- For $i_{rf} = i_o \sin \omega t$, a charge of $i_o/\omega \cos \omega t$ builds up on each of the sheath
- On plasma side of sheath there is no electrode, displacement develops by the sheath moving and generating a *dq/dt* by depleting and restoring the e's as the plasma edge oscillates in and out.



Have neglected pre-sheath region

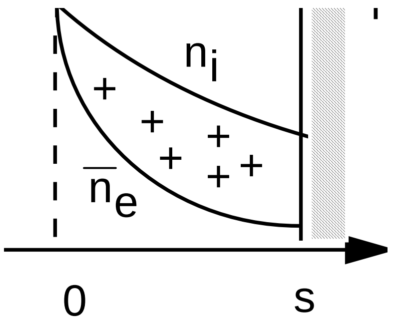
RF Sheath Analysis

After Lieberman



- Assume $J_{rf} = J_o \sin \omega t$
- Sheath oscillation is near sinusoidal

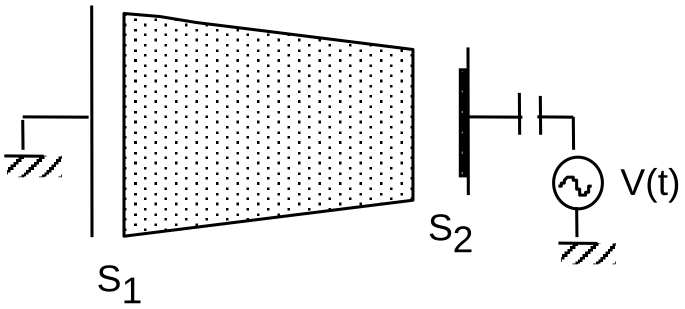
  $s \sim s_o \sin \omega t$ *Max Sheath width* $s_m \sim 2s_o$
- Analysis gives $s_o = J_o / \varepsilon \omega n_s$
  - Sheath width, s, increases with J_{rf}
  - s decreases with frequency and plasma density
- Charge stored in sheath $Q_{sh} = e\int_o^{s_m} (n_i - \bar{n}_e)dx$
- Poisson’s Eq $d^2V / dx^2 = e\big(n_i(x) - \bar{n}_e(x)\big) / \varepsilon_o$
- DC Sheath voltage $\bar{V}_s \approx 1.3 J_o / e\varepsilon_o\omega^2 n_s$
  - DC sheath voltage increases with RF current and decreases with RF frequency

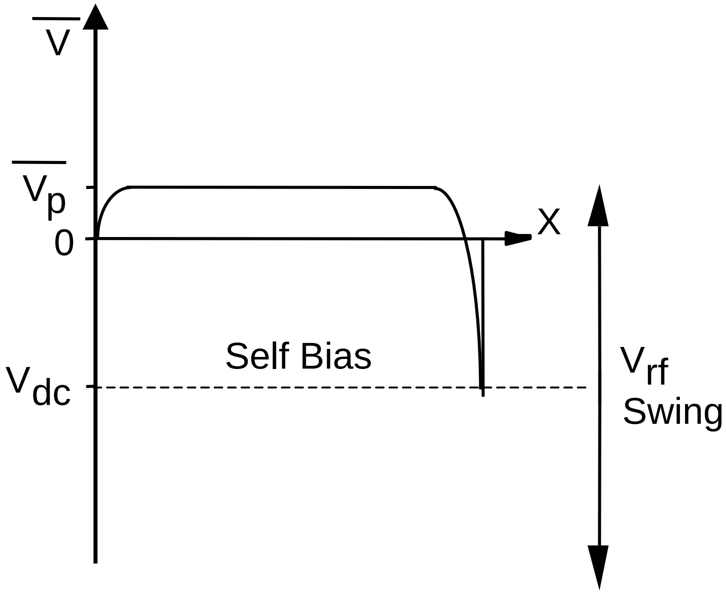


V_{dc} Depends on I_{rf} and Electrode Geometry

- Self bias voltage V_{dc} is the externally measured voltage
- V_{dc} is sum of two sheath sheath voltages

Asymmetric





$$J_{rf} = I_{rf} / A$$

$A_1 > A_2$ (Used to avoid sputtering gnd electode)

$$J_{rf1} < J_{rf2}$$

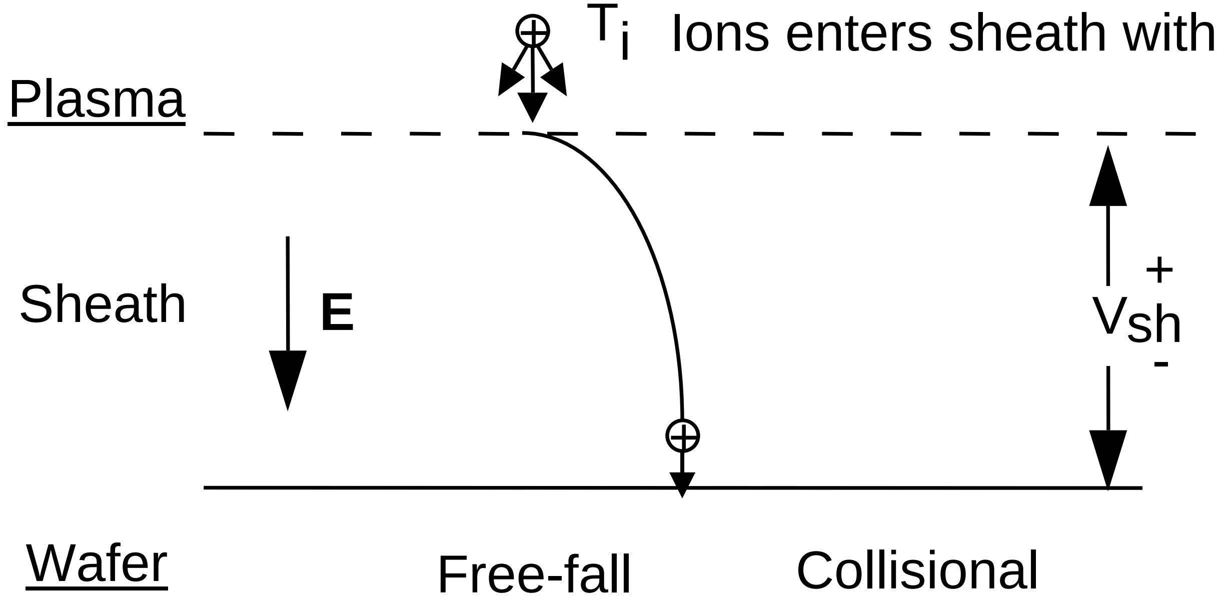
$$V_{s1} < V_{s2}$$

Typically $V_{s1} << V_{s2}$ and $V_{s1} \approx 10$ to 15V

$$V_{dc} = V_{s1} - V_{s2} \approx -V_{s2}$$

$$V_{dc} \approx 1.3 I_{rf} \Big/ e\varepsilon_o \omega^2 n_s A_2$$

Ion Directionality



T_i Ions enters sheath with transverse energy of T_i

Plasma

Sheath

E

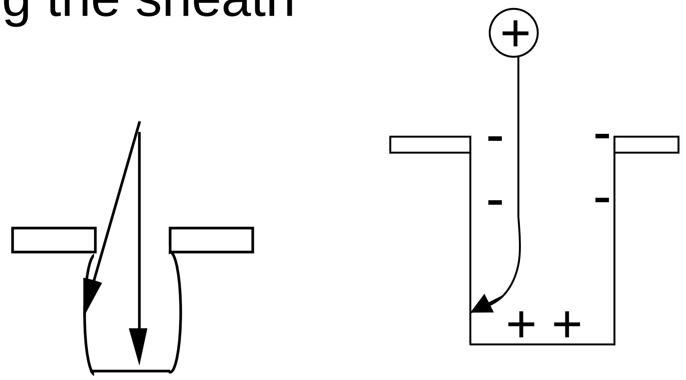
$+$ V_{sh} $-$

Wafer

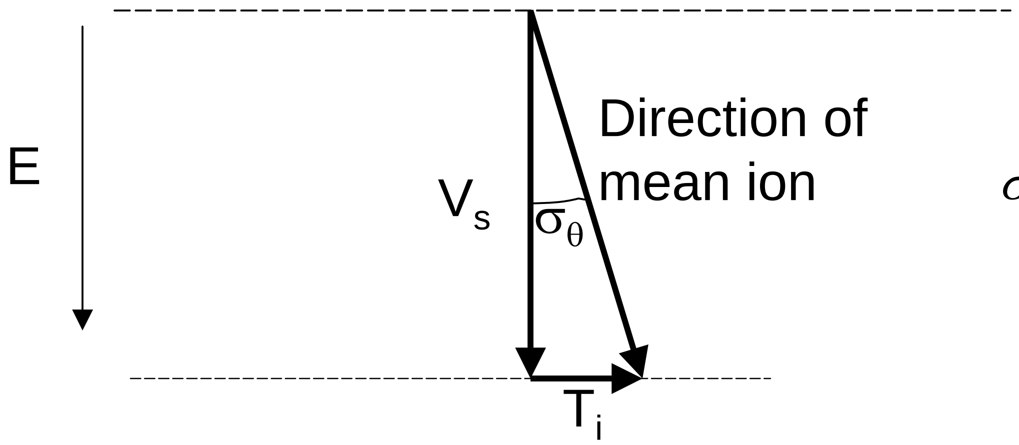
Free-fall

Collisional

- At 13.6 MHz most ions respond only to the average (DC) sheath field
- Ions gain directionality and energy crossing the sheath
- Ion directionality strongly affects
  - Etch bow (side wall etching)
  - Electron shading type charging



Collisionless Sheath Ion Directionality

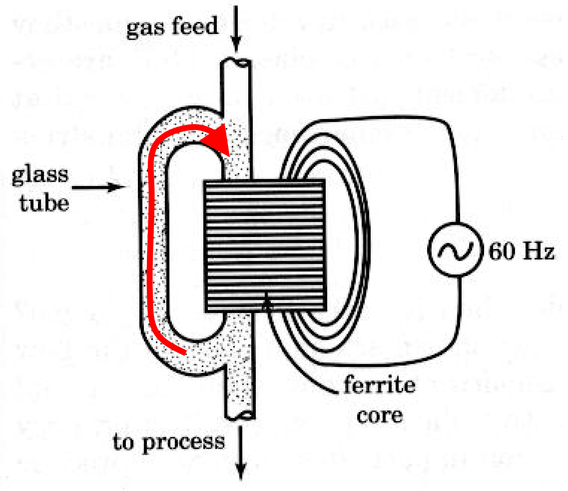


$$\sigma_\theta = \tan^{-1}\sqrt{\frac{T_i}{eV_s}}$$

- Ion directionality determined by $\overline{V_s}$ and T_i at sheath edge
- Mean ion arrives at wafer σ_θ degrees off the normal
- T_i is determined by collisions in pre-sheath and energy at ion creation. Typically, $T_i \approx 0.5$ eV
- Example: If $T_i = 0.5$ eV and $V_s = 100$V → $\sigma_\theta = 4.0°$
- For anisotropic etching, typically we need $\sigma_\theta \leq 4.0°$
- Sheath voltage control is essential for etch control

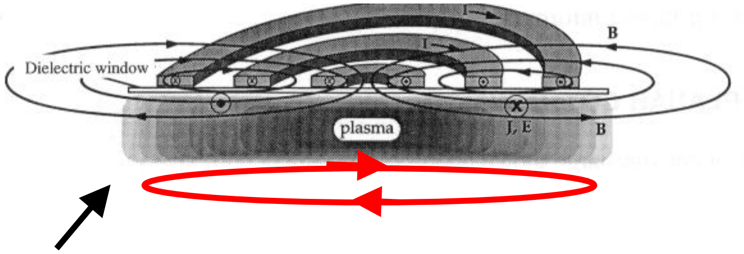
Use of Inductive Coupled Plasmas (ICP) as Low Bias Source

Simple ICP



Current in coil induces current loop in plasma in glass tube

Lam Style ICP

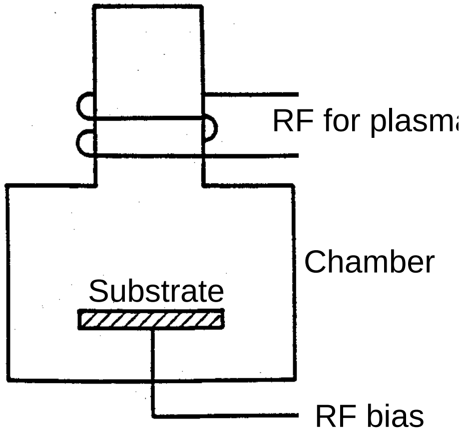


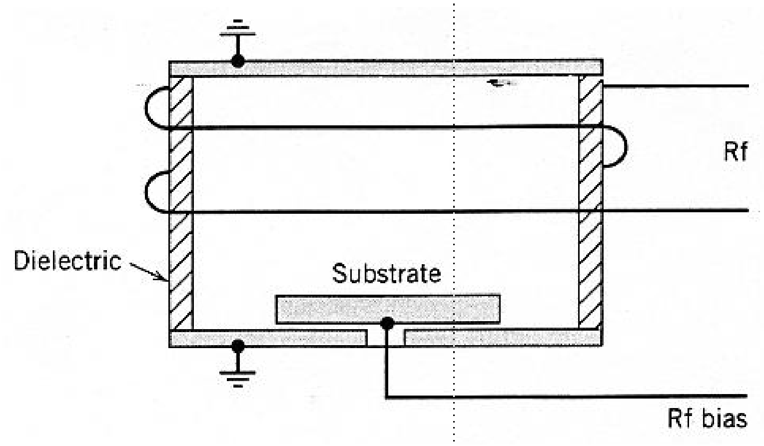
Toroid of high density plasma

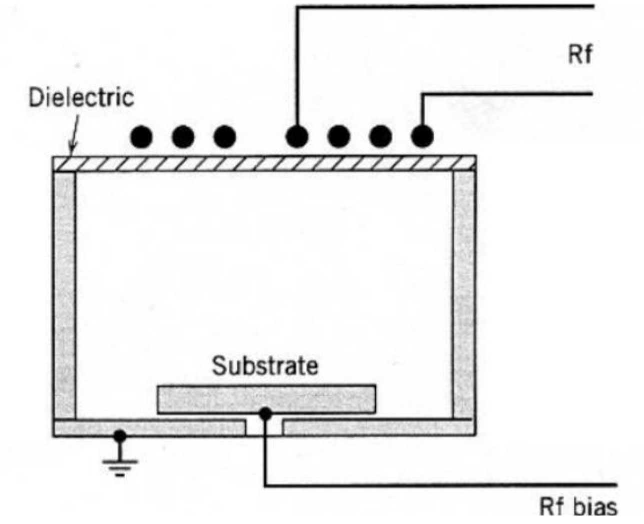
B field lines have been compressed because opposing B field from induced current loop in plasma toroid

- In ICP power is transferred to plasma by the oscillating B field.
- There is minimum rf current going across a sheath, so the sheath voltage is usually small
- For etch control, 2nd rf source is needed to increase ion energy and directionality at wafer

ICP Configurations







- Inductive coupling generates high density plasmas with low sheath voltages.
- ICP power controls plasma density, n_e .
- Capacitive coupling of rf current through wafer sheath used to control ion energy, E_i .

Beyond DC Biasing: RF Effects on Ions Crossing Sheath

- Sheath transit time effects -- Depending on their mass, the rf frequency, the sheath thickness and when in the rf cycle, they enter the sheath, ions are affected by the rf sheath fields.

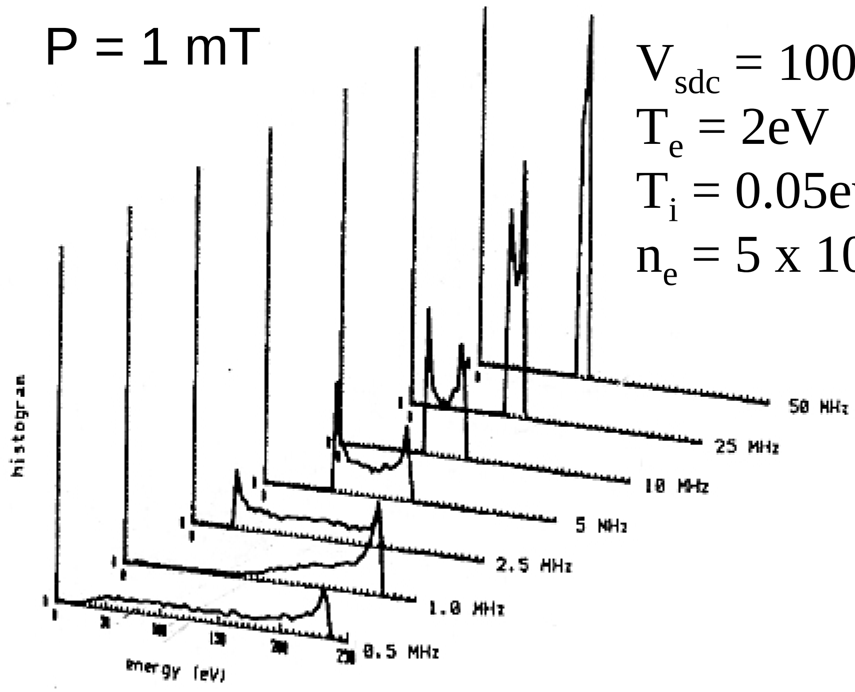
- The **ion energy distribution** IED can be shaped by changing, modulation or mixing the rf bias frequency and waveform.

- Changing the IED gives the etch engineer another for controlling profile shape.

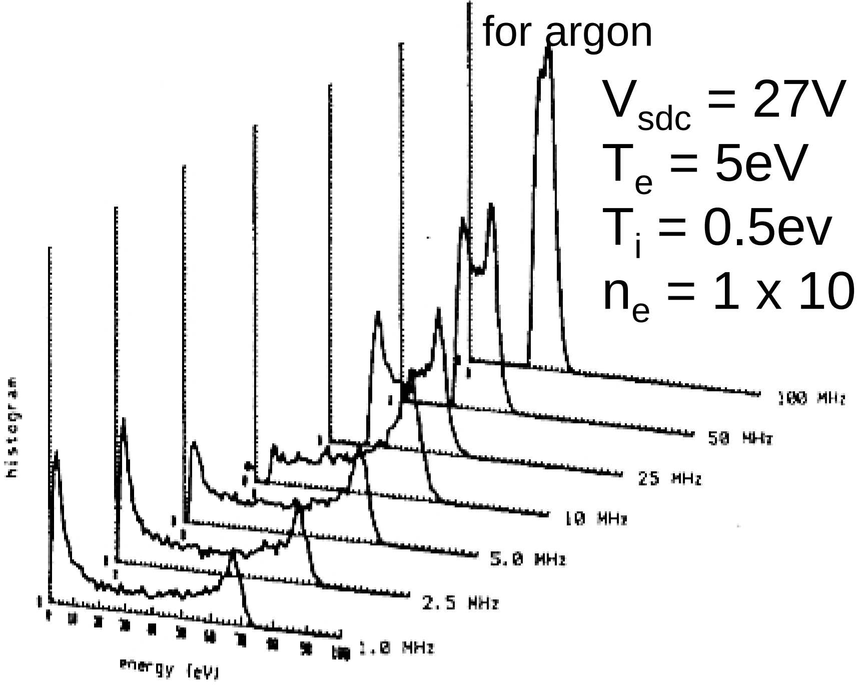
Effects of Frequency on IED

After Barnes et al, 1991
for argon

P = 1 mT



$V_{sdc} = 100V$
$T_e = 2eV$
$T_i = 0.05ev$
$n_e = 5 \times 10^9$

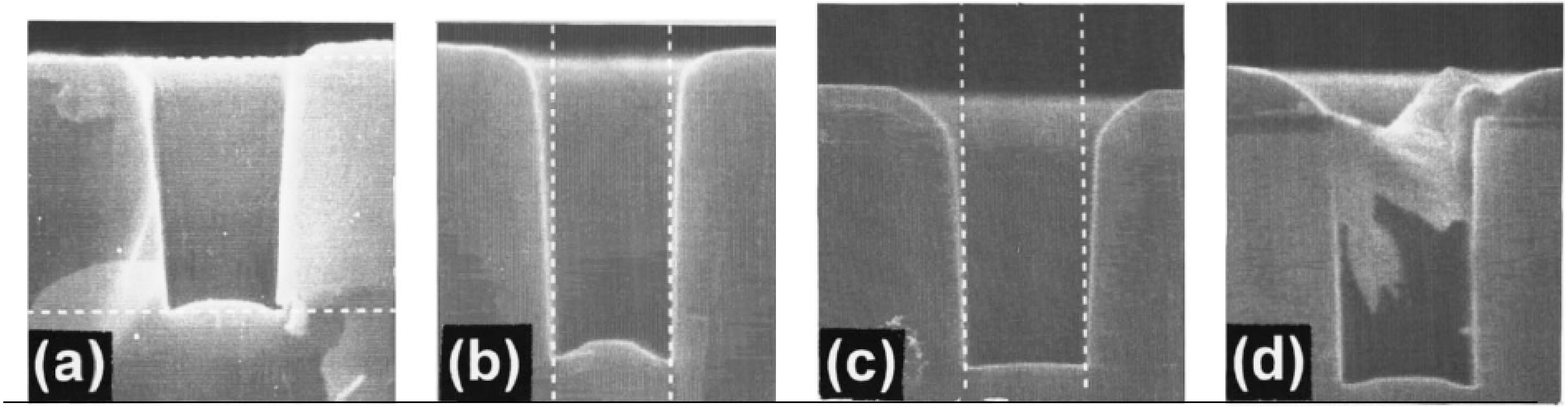


$V_{sdc} = 27V$
$T_e = 5eV$
$T_i = 0.5ev$
$n_e = 1 \times 10^{11}$

- For oscillating rf sheath **ion energy distribution (IED)** at wafer surface depends strongly on sheath transit effect
- IED tends to be bimodal with $\Delta\varepsilon_{ion}$ decreasing with increasing RF frequency
- IED strongly affects electron shading type charging. Less charging with more low energy ions.
- IED also affects etch profile.

Using Bias Frequency to Control Etch Profile

After Schaepkens 1999



-85V, 1.3 MHz -120V, 1.3 MHz -85V, 10.5 MHz -120V, 10.5 MHz

FIG. 1. SEM micrographs of 1 μm trenches etched for 300 s at 6 mTorr, 40 sccm CHF_3, and 1400 W at self-bias voltage and rf bias frequency of: (a) −85 V and 1.3 MHz, (b) −120 V and 1.3 MHz, (c) −85 V and 10.5 MHz, and (d) −120 V and 10.5 MHz.

Summary

- DC self bias is a result of rf current flowing across a plasma sheath
  - Increases with rf current and decreases with rf frequency
- RF biasing applied to wafer to control E_i in high density plasma systems
- Biasing is needed for controlled anisotropic etching
- Recent etch equipment designs go beyond simple DC biasing to shape energy distribution of ions bombarding wafer surface to better control etch characteristics