Chapter 7
Plasma Basic

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Objectives

- List at least three IC processes using plasma
- Name three important collisions in plasma
- Describe mean free path
- Explain how plasma enhance etch and CVD processes
- Name two high density plasma sources

Topics of Discussion

- What is plasma?
- Why use plasma?
- Ion bombardment
- Application of plasma process

Applications of Plasma

- CVD
- Etch
- PVD
- Ion Implantation
- Photoresist strip
- Process chamber dry clean

What Is Plasma

- A plasma is a ionized gas with equal numbers of positive and negative charges.

- A more precise definition: *a plasma is a quasi-neutral gas of charged and neutral particles which exhibits collective behavior*.

- Examples: Sun, flame, neon light, etc.

Components of Plasma

- A plasma consists of neutral atoms or molecules, negative charges (electrons) and positive charges (ions)
- Quasi-neutral: n_i » n_e
- Ionization rate: h » $n_e/(n_e + n_n)$

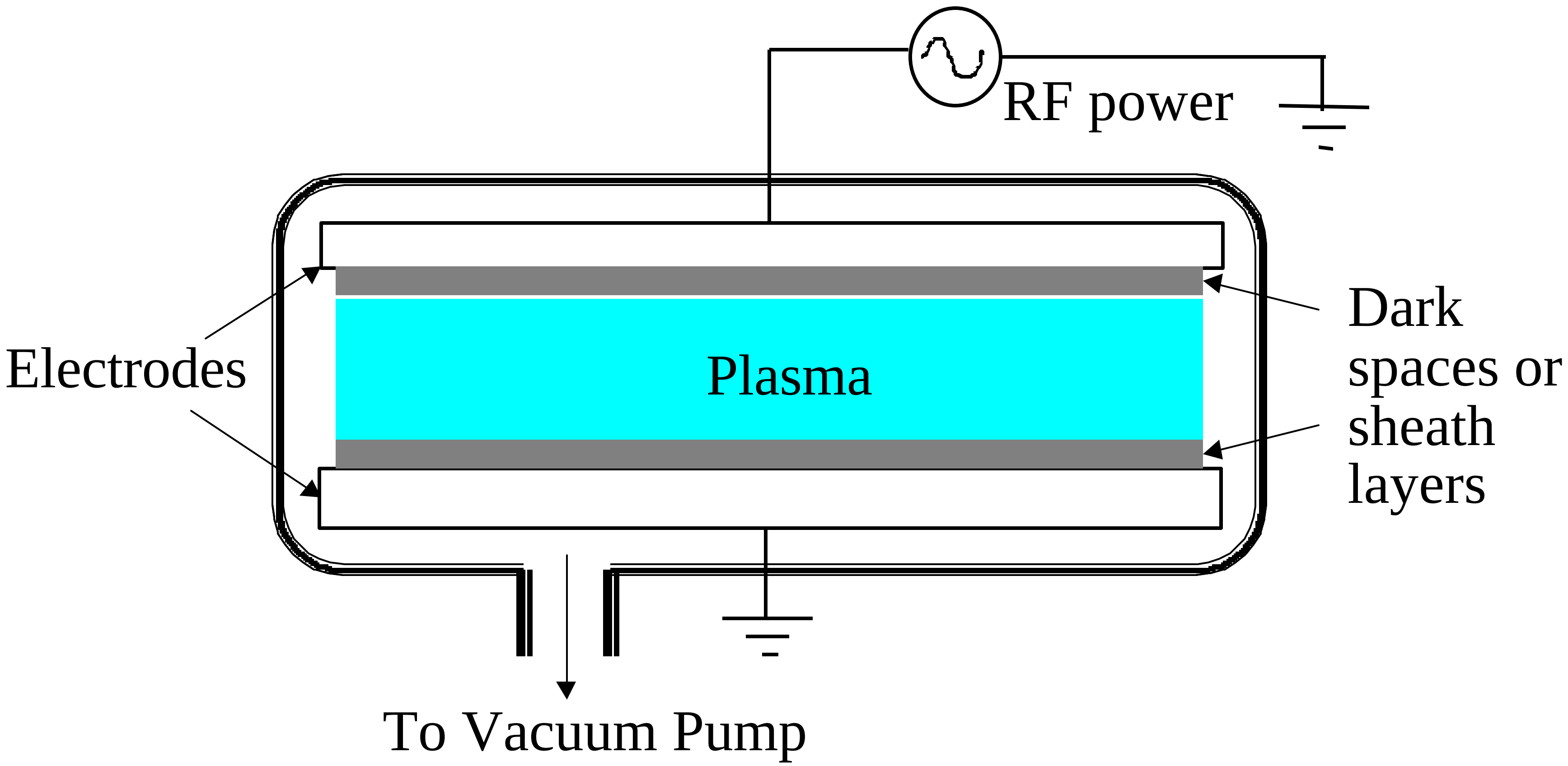
Ionization Rate

- Ionization rate is mainly determined by electron energy in plasma
- In most plasma processing chambers, the ionization rate is less than 0.001%.
- The ionization rate of high density plasma (HDP) source is much higher, about 1%.
- Ionization rate in the core of sun is ~100%.

Neutral Gas Density

- Idea gas
  - 1 mole = 22.4 Litter = 2.24×10^{4} cm^{3}
  - 1 mole = 6.62×10^{23} molecules
- At 1 atm, gas density is 2.96×10^{19} cm^{-3}
- At 1 Torr, gas density is 3.89×10^{16} cm^{-3}
- At 1 mTorr, gas density is 3.89×10^{13} cm^{-3}
- RF plasma has very low ionization rate

Parallel Plate Plasma System



Generation of a Plasma

- External power is needed
- Radio frequency (RF) power is the most commonly used power source
- Vacuum system is required to generate a stable RF plasma

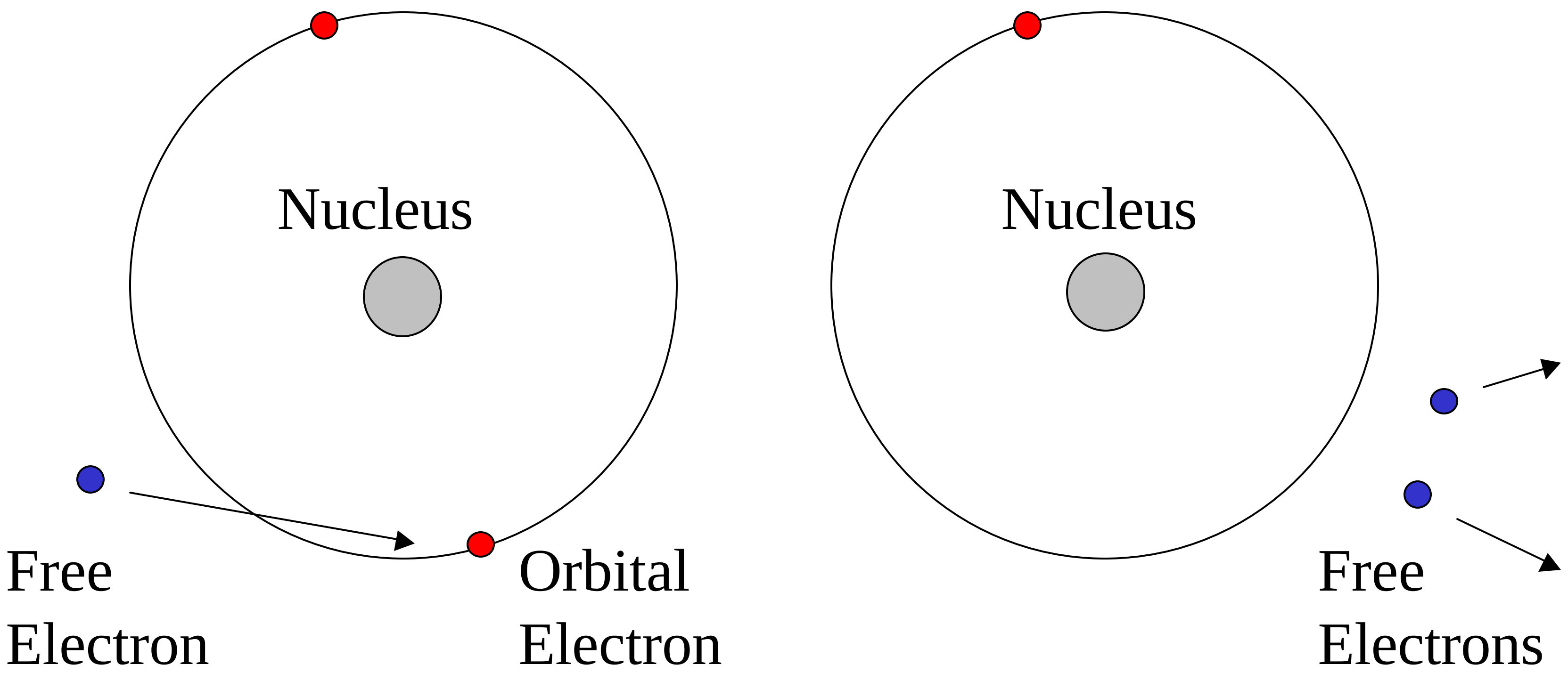
Ionization

- Electron collides with neutral atom or molecule
- Knock out one of orbital electron

$$e + A \longrightarrow A^{+} + 2\,e$$

- Ionization collisions generate electrons and ions
- It sustains the stable plasma

Illustration of Ionization



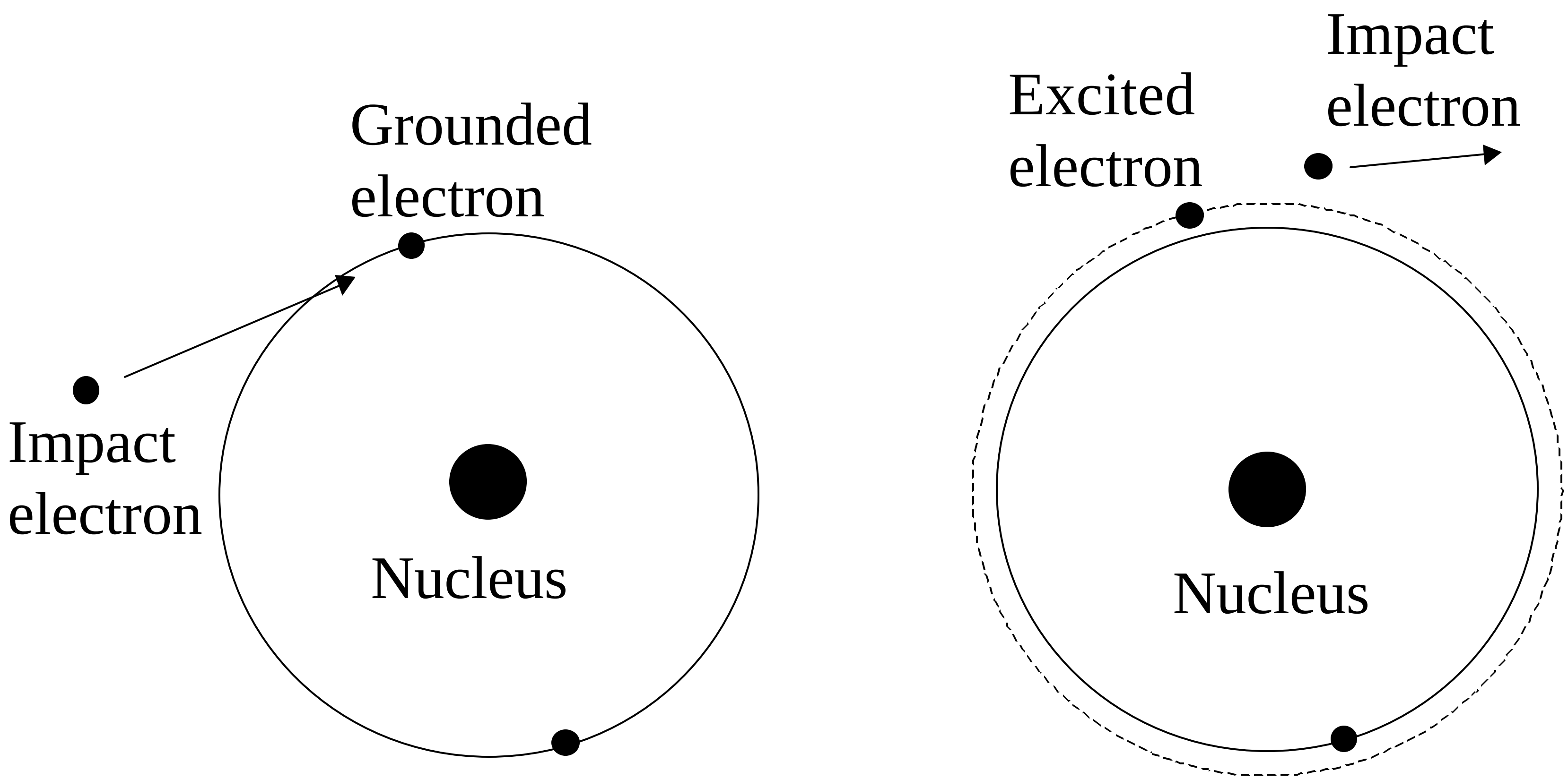
Excitation-Relaxation

$$e + A \longrightarrow A^* + e$$

$$A^* \longrightarrow A + h\nu \text{ (Photos)}$$

- Different atoms or molecules have difference frequencies, that is why different gases have different glow colors.
- The change of the glow colors is used for etch and chamber clean process **endpoint**.

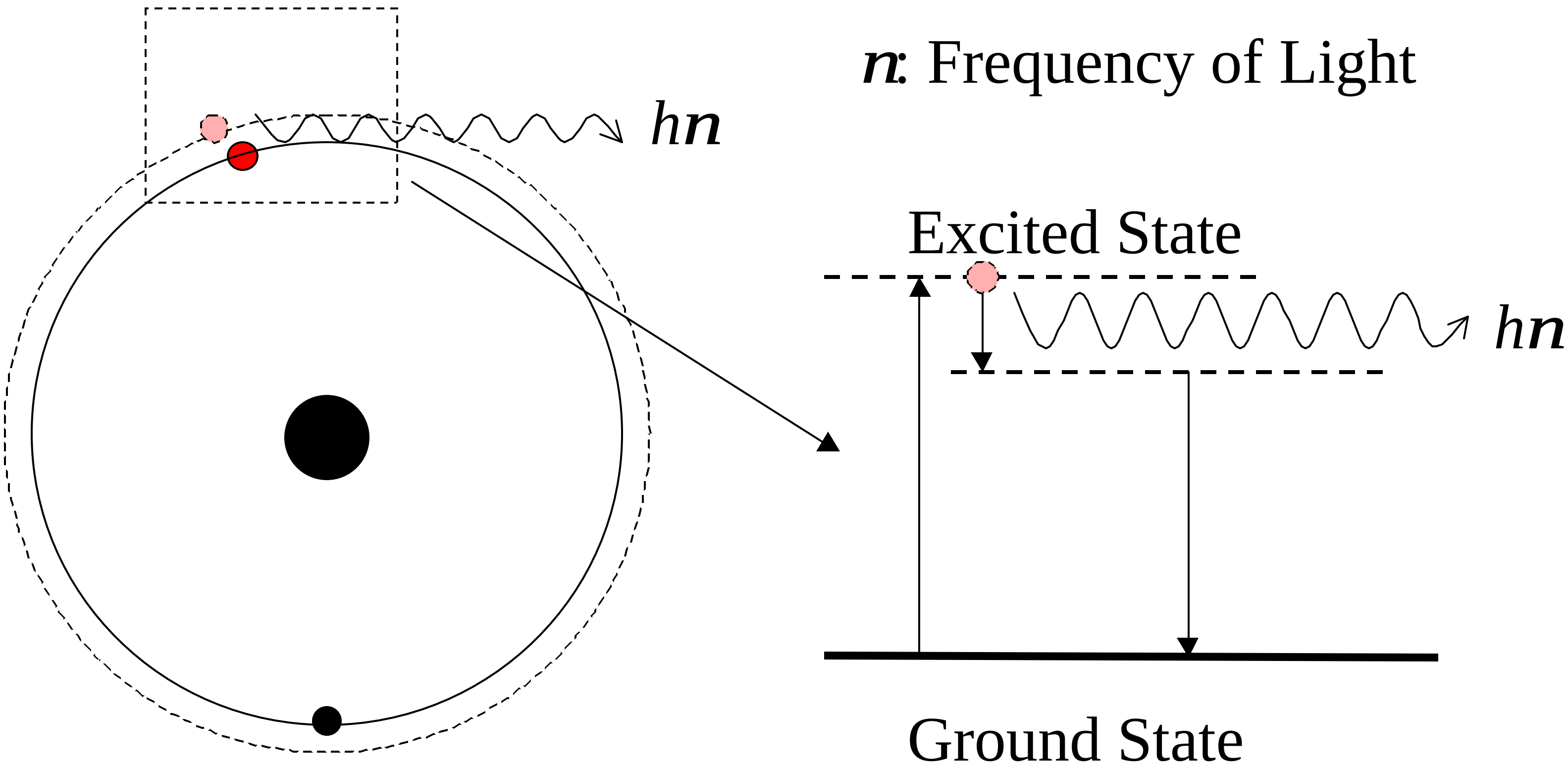
Excitation Collision



Relaxation

h: Planck Constant

ν: Frequency of Light



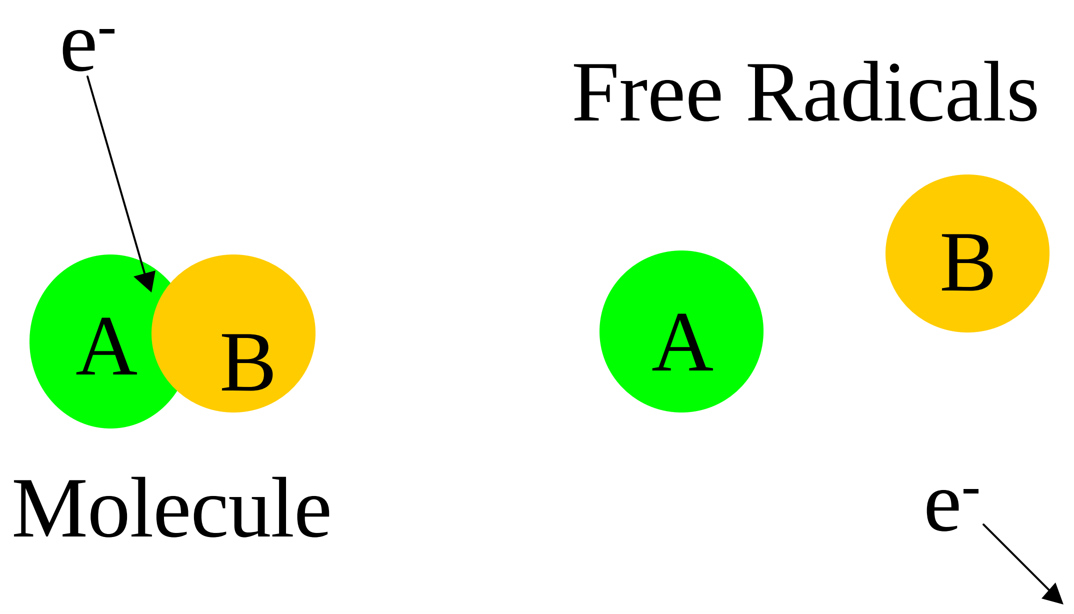
Dissociation

- Electron collides with a molecule, it can break the chemical bond and generate free radicals:

$$e + AB \longrightarrow A + B + e$$

- Free radicals have at least one unpaired electron and are chemically very reactive.
- Increasing chemical reaction rate
- Very important for both etch and CVD.

Dissociation



Plasma Etch

- CF_4 is used in plasma to generate fluorine free radical (F) for oxide etch

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

$$4F + SiO_2 \rightarrow SiF_4 + 2O$$

- Enhanced etch chemistry

Plasma **Enhanced** CVD

- PECVD with SiH_4 and NO_2 (laughing gas)

$$e^- + SiH_4 \rightarrow SiH_2 + 2H + e^-$$

$$e^- + N_2O \rightarrow N_2 + O + e^-$$

$$SiH_2 + 3O \rightarrow SiO_2 + H_2O$$

- Plasma enhanced chemical reaction
- PECVD can achieve high deposition rate at relatively lower temperature

Q & A

- Why are dissociation not important in the aluminum and copper PVD processes?

- Aluminum and copper sputtering processes only use argon. Argon is a noble gas, which exist in the form of atoms instead of molecules. Thus there is no dissociation process in argon plasma

Q & A

- Is there any dissociation collision in PVD processes?

- Yes. In TiN deposition process, both Ar and N_2 are used. In plasma, N_2 is dissociated to generate free radical N, which reacts with Ti target to from TiN on the surface. Ar^+ ions sputter TiN molecules from the surface and deposit them on wafer surface.

Table 7.1 Silane Dissociation

Collisions	Byproducts	Energy of Formation
$e^- + SiH_4$	$SiH_2 + H_2 + e^-$	2.2 eV
	$SiH_3 + H + e^-$	4.0 eV
	$Si + 2\ H_2 + e^-$	4.2 eV
	$SiH + H_2 + H + e^-$	5.7 eV
	$SiH_2^* + 2H + e^-$	8.9 eV
	$Si^* + 2H_2 + e^-$	9.5 eV
	$SiH_2^+ + H_2 + 2\ e^-$	11.9 eV
	$SiH_3^+ + H + 2\ e^-$	12.32 eV
	$Si^+ + 2H_2 + 2\ e^-$	13.6 eV
	$SiH^+ + H_2 + H + 2\ e^-$	15.3 eV

Q & A

- Which one of collisions in Table 7.1 is most likely to happen? Why?

- The one that requires the least energy is the one most likely to happen.

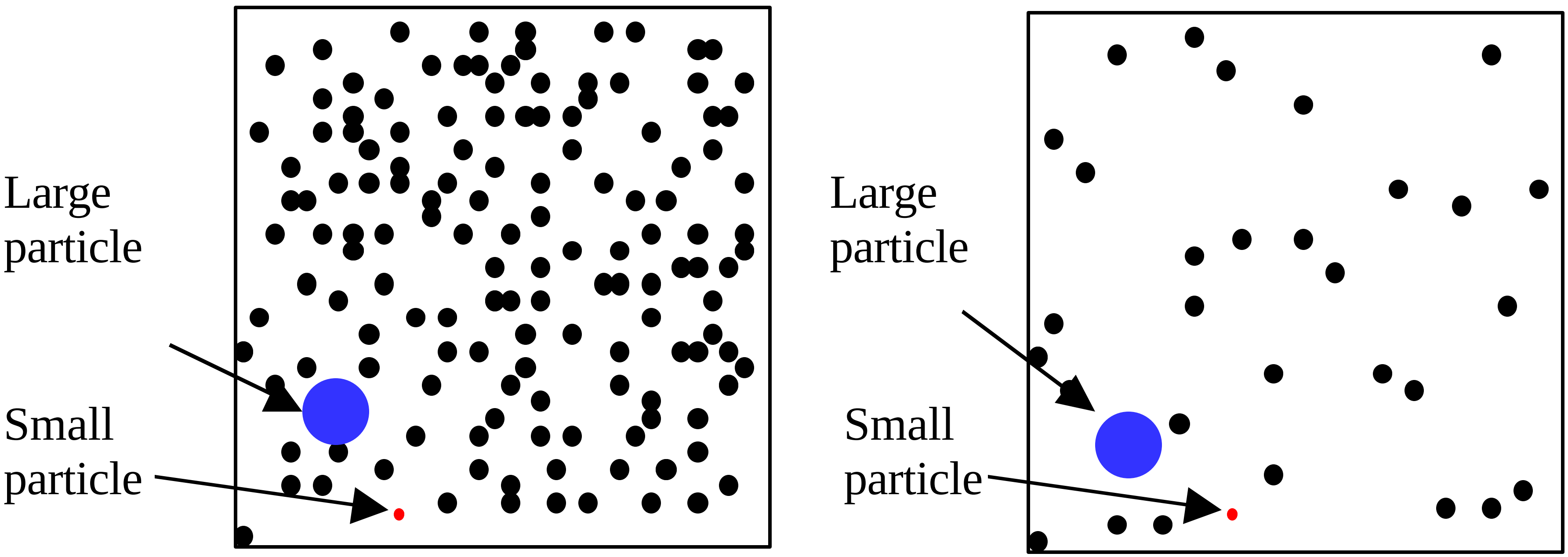
Mean Free Path (MFP)

- The average distance a particle can travel before colliding with another particle.

$$l = \frac{1}{n s}$$

- n is the density of the particle
- s is the collision cross-section of the particle

MFP Illustration



(a) (b)

Mean Free Path (MFP)

- Effect of pressure:

$$l \propto \frac{1}{p}$$

- Higher pressure, shorter MFP

- Lower pressure, longer MFP

Q & A

- Why does one need a vacuum chamber to generate a stable plasma?
- At atmospheric pressure (760 Torr), MFP of an electron is very short. Electrons are hard to get enough energy to ionize gases molecules.
- Extremely strong electric field can create plasma in the form of arcing (lightening) instead of steady state glow discharge.

Movement of Charged Particle

- Electron is much lighter than ion

$$m_e << m_i$$

$$m_e : m_{Hydrogen} = 1:1836$$

- Electric forces on electrons and ions are the same

$$F = qE$$

- Electron has much higher acceleration

$$a = F/m$$

Movement of Charged Particle

- RF electric field varies quickly, electrons are accelerated very quickly while ions react slowly
- Ions have more collisions due to their larger cross-section that further slowing them down
- Electrons move much faster than ions in plasma

Thermal Velocity

- Electron thermal velocity

$$v = (kT_e/m_e)^{1/2}$$

- RF plasma, T_e is about 2 eV

$$v_e \approx 5.93\times10^7 \text{ cm/sec} = 1.33\times10^7 \text{ mph}$$

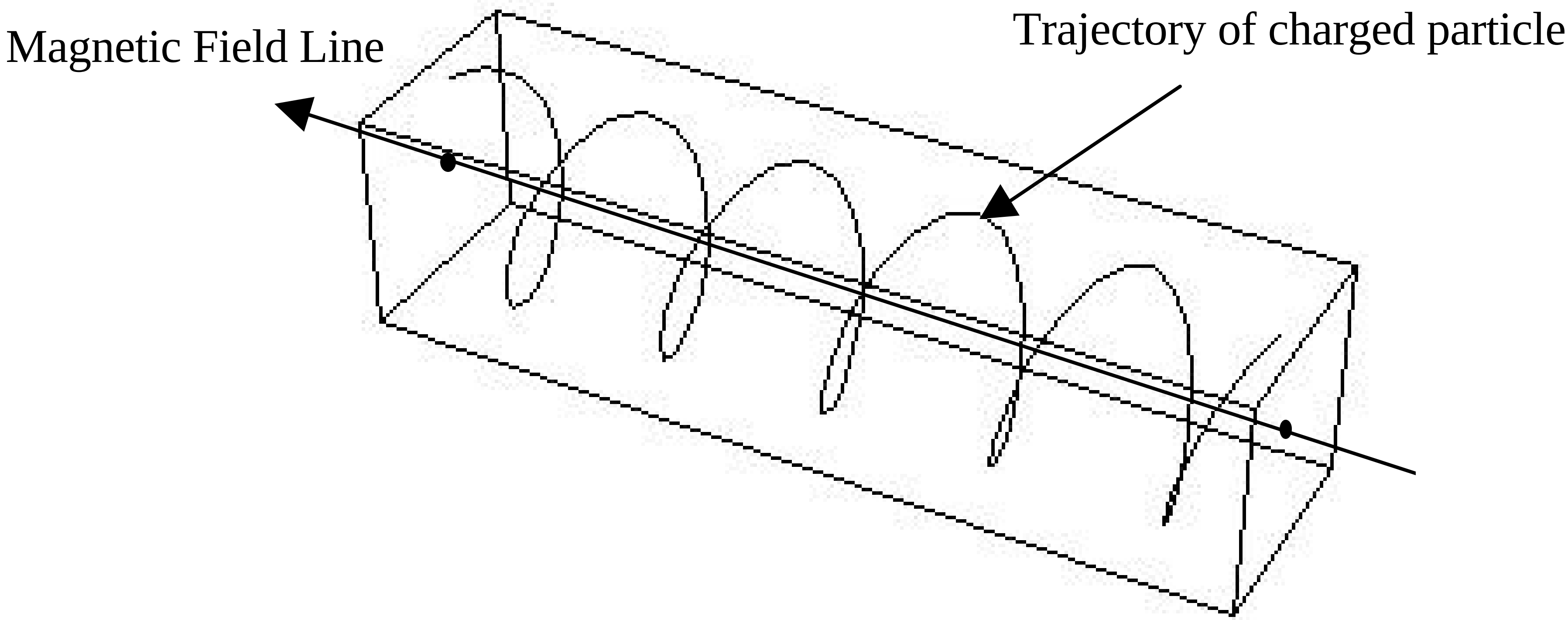
Magnetic Force and Gyro-motion

- Magnetic force on a charged particle:

$$\mathbf{F} = q\mathbf{v}\times\mathbf{B}$$

- Magnetic force is always perpendicular to the particle velocity
- Charged particle will spiral around the magnetic field line.
- Gyro-motion.

Gyro-motion



Gyrofrequency

- Charged particle in gyro motion in magnetic field

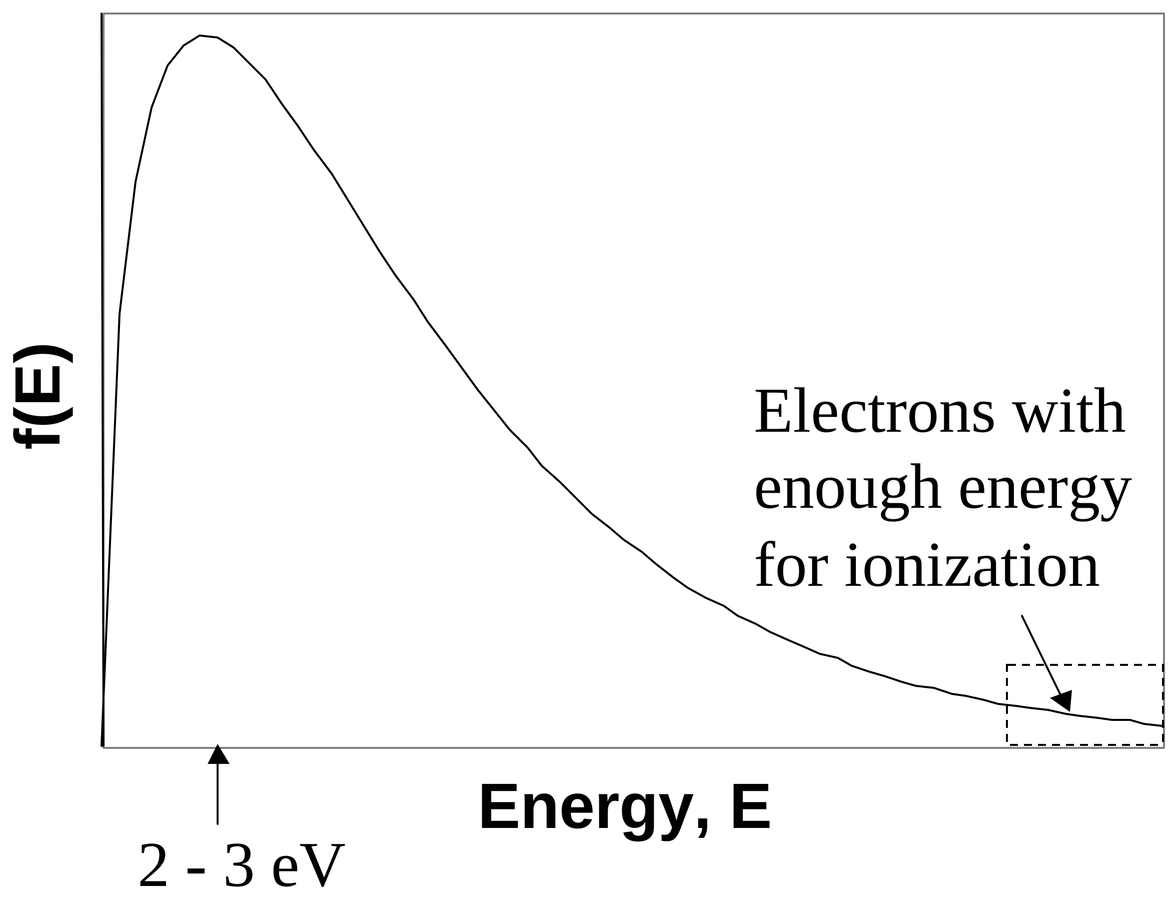
$$\Omega = \frac{qB}{m}$$

Gyro radius

- Gyroradius of charged particle in a magnetic field, r, can be expressed as:

$$r = v_{\perp}/\Omega$$

Boltzmann Distribution



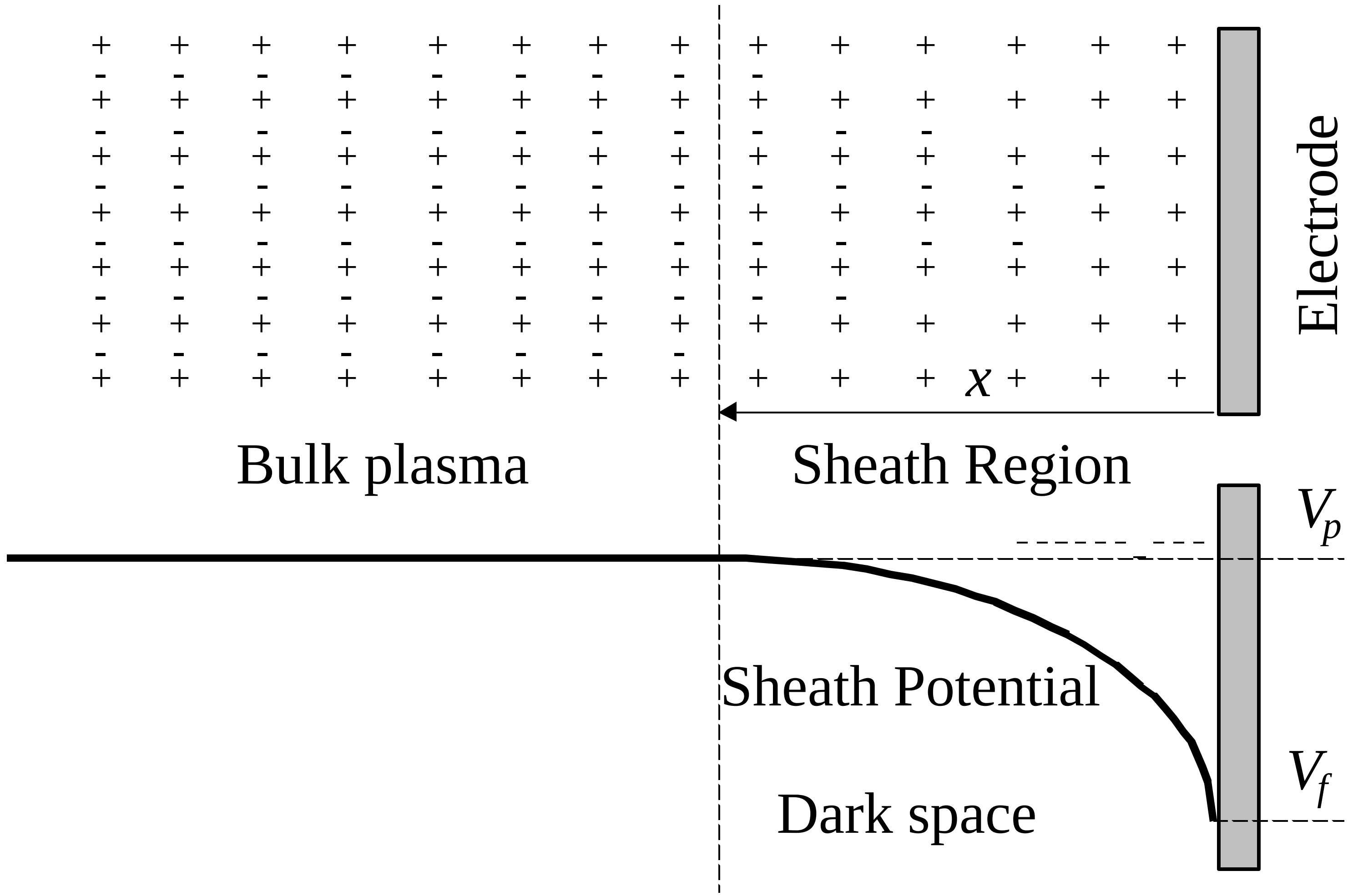
Ion Bombardment

- Anything close to plasma gets ion bombardment
- Very important for sputtering, etch and PECVD
- Mainly determined by RF power
- Pressure also can affect bombardment

Ion Bombardment

- Electrons reach electrodes and chamber wall first
- Electrodes charged negatively, repel electrons and attract ions.
- The sheath potential accelerates ions towards the electrode and causes ion bombardment.
- Ion bombardment is very important for etch, sputtering and PECVD processes.

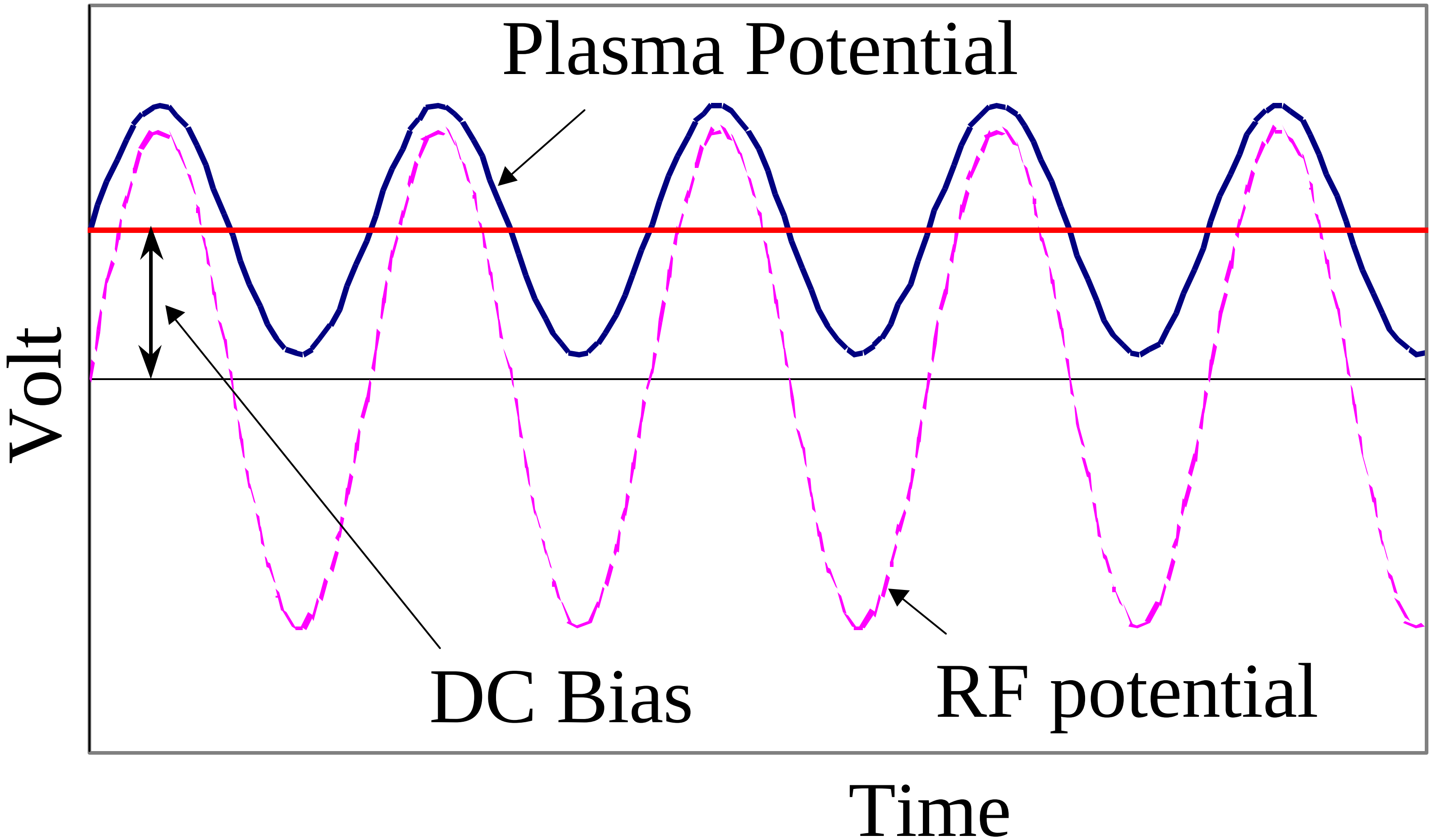
Sheath Potential



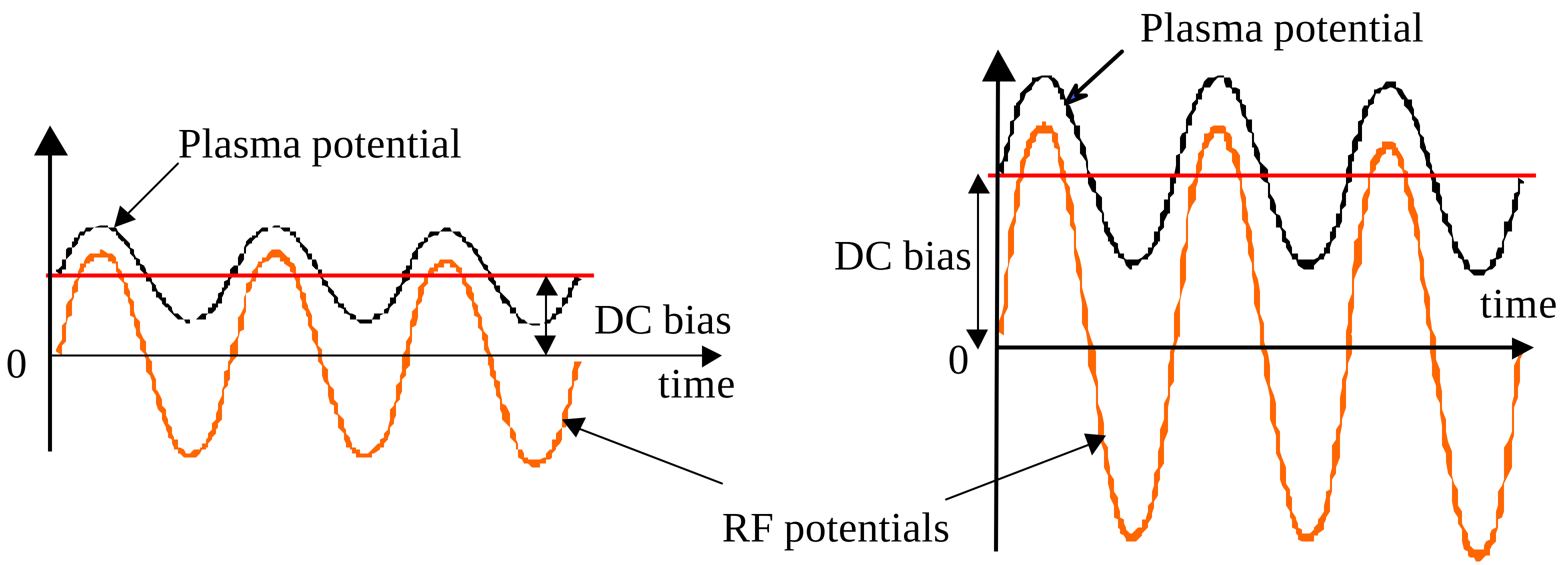
Applications of Ion bombardment

- Help to achieve anisotropic etch profile
  - Damaging mechanism
  - Blocking mechanism
- Argon sputtering
  - Dielectric etch for gap fill
  - Metal deposition
- Help control film stress in PECVD processes
  - Heavier bombardment, more compressive film

Plasma Potential & DC Bias



DC biases and RF powers



- Lower RF power
- Smaller DC bias

- Higher RF power
- Larger DC bias

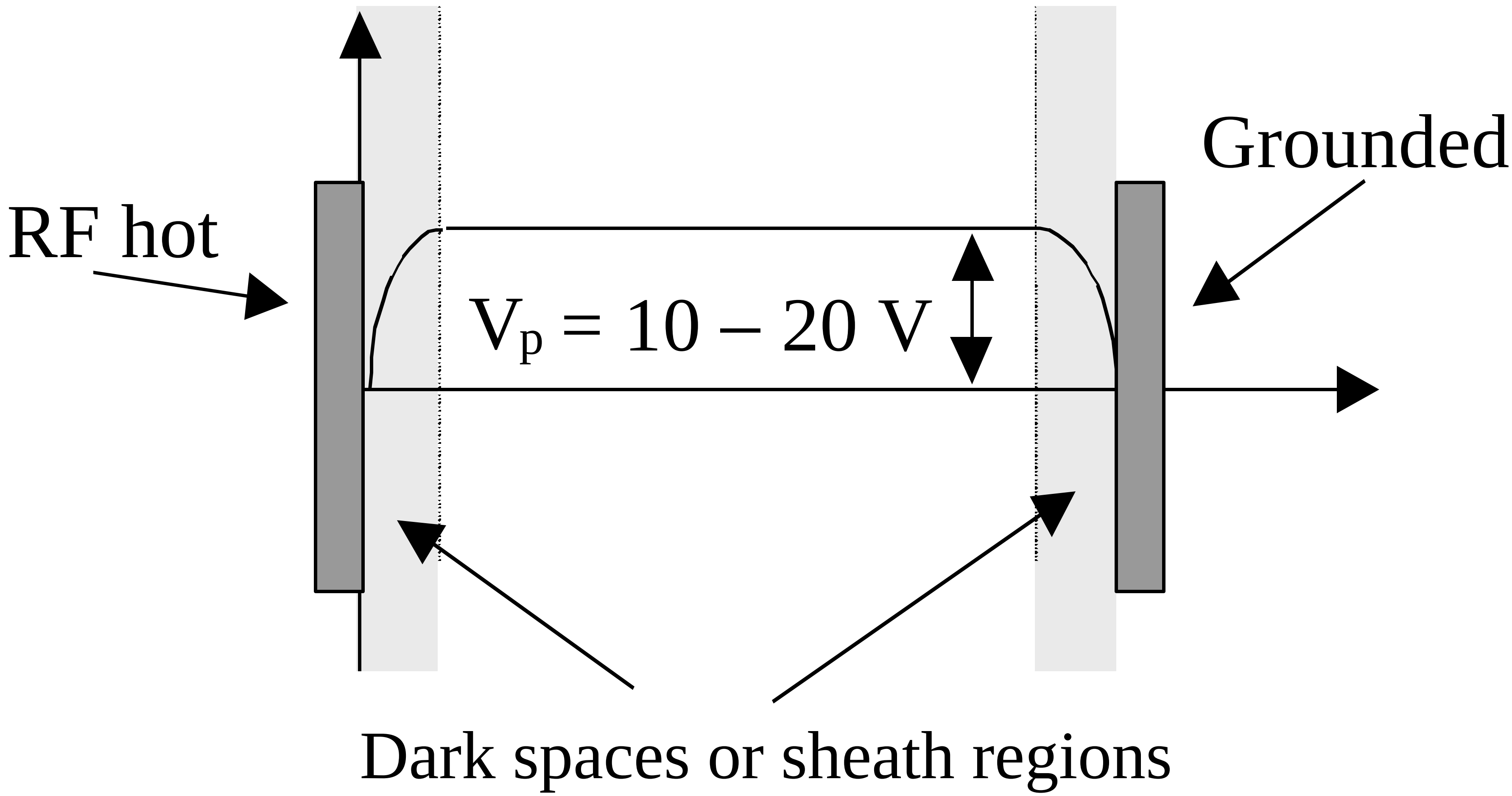
Ion Bombardment

- Ion energy
- Ion density
- Both controlled by RF power

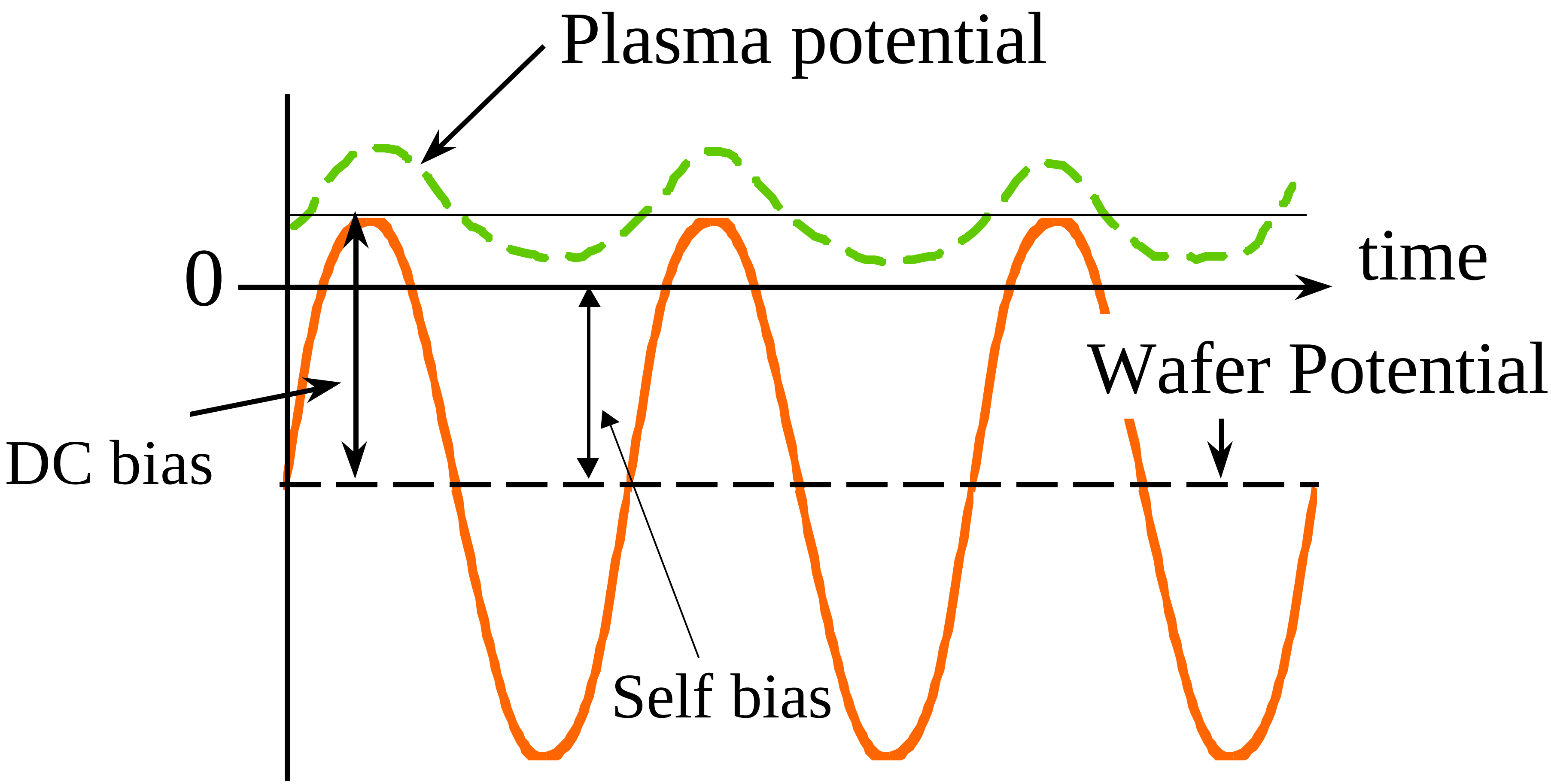
Ion Bombardment Control

- Increasing RF power, DC bias increases, ion density also increases.
- Both ion density and ion bombardment energy are controlled by RF power.
- RF power is the most important knob controlling ion bombardment
- RF power also used to control film stress for PECVD processes

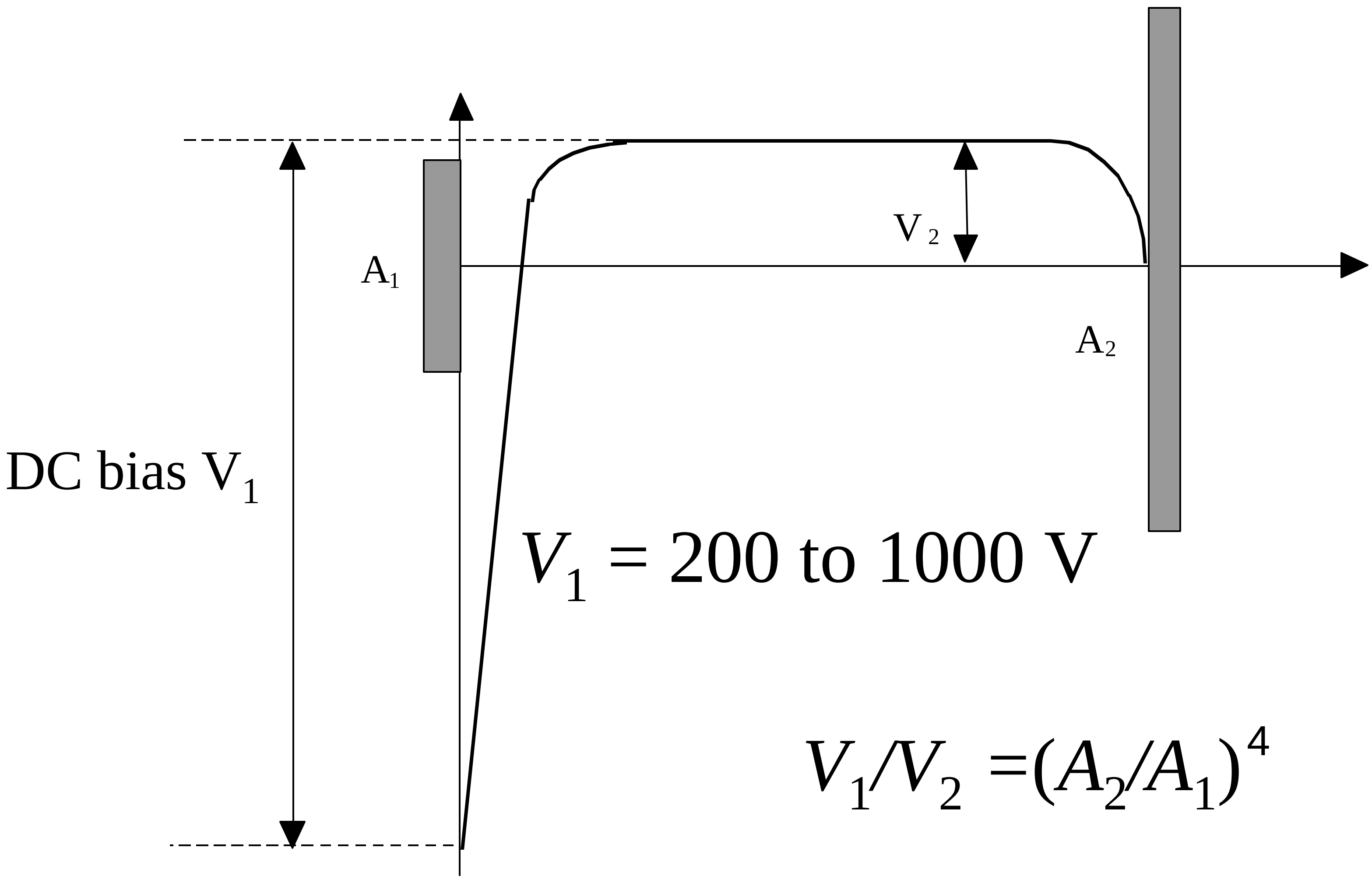
DC Bias of CVD Chamber Plasma



DC Bias of Etch Chamber Plasma



DC Bias of Etch Chamber Plasma



$$V_1 = 200 \text{ to } 1000 \text{ V}$$

$$V_1/V_2 = (A_2/A_1)^4$$

Question and Answer

- If the electrode area ratio is 1:3, what is the difference between the DC bias and the self-bias compare with the DC bias?

- The DC bias is V_1, the self-bias is $V_1 - V_2$, therefore, the difference is

$$[V_1 - (V_1 - V_2)]/V_1 = V_2/V_1 = (A_1/A_2)^4 = (1/3)^4 = 1/81 = 1.23\%$$

Question and Answer

- Can we insert a fine metal probe into the plasma to measure the plasma potential V_2?
- Yes, we can. However, it is not very accurate because of sheath potential near probe surface
- Measurement results are determined by the theoretical models of the sheath potential, which have not been fully developed, yet.

Ion Bombardment and Electrode Size

- Smaller electrode has more energetic ion bombardment due to self-bias
- Etch chambers usually place wafer on smaller electrode

Advantages of Using Plasma

- Plasma processes in IC fabrication:
  - PECVD
    - CVD chamber dry clean
  - Plasma Etch
  - PVD
  - Ion implantation

Benefits of Using Plasma For CVD Process

- High deposition rate at relatively lower temperature.
- Independent film stress control
- Chamber dry clean

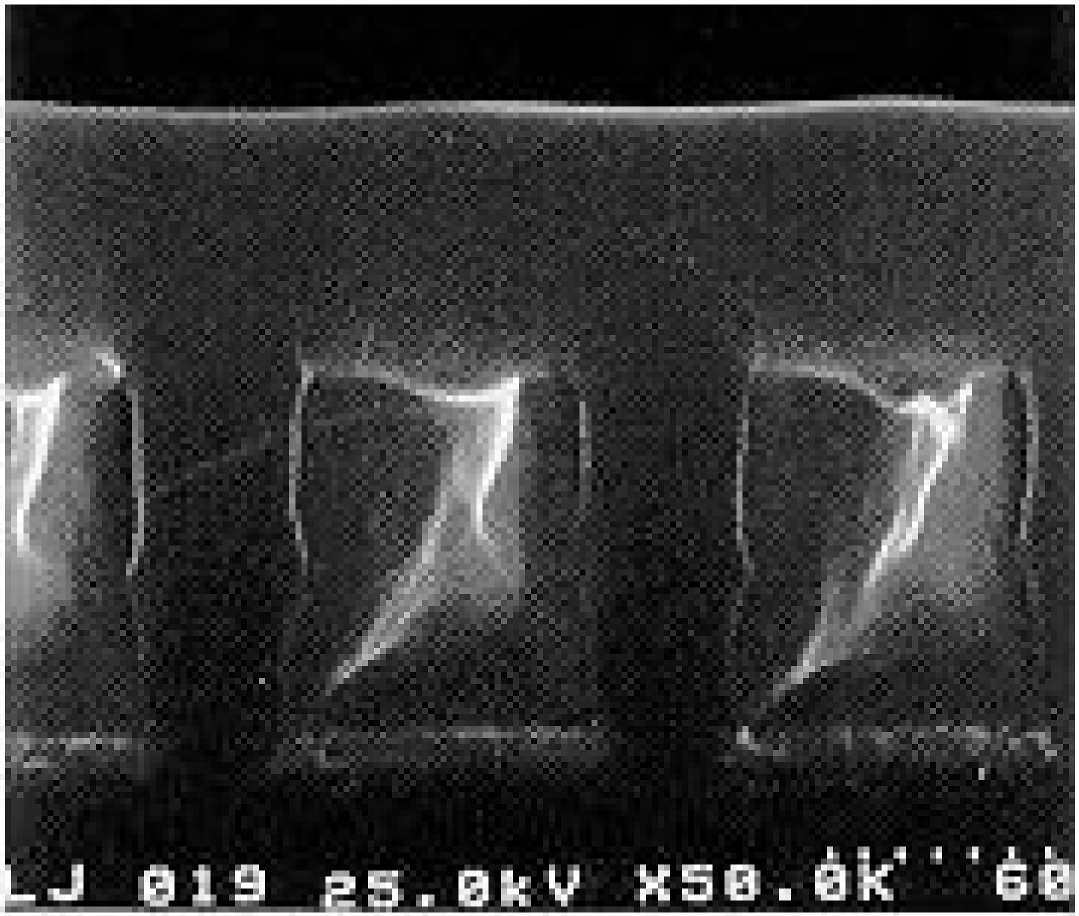
Comparison of PECVD and LPCVD

Processes	**LPCVD (150 mm)**	**PECVD (150 mm)**
Chemical reaction	$SiH_4 + O_2 \rightarrow SiO_2 + \ldots$	$SiH_4 + N_2O \rightarrow SiO_2 + \ldots$
Process parameters	p =3 Torr, T=400 °C	p=3 Torr, T=400 °C and **RF=180 W**
Deposition rate	**100 to 200 Å/min**	**^{3} 8000 Å/min**
Process systems	Batch system	Single-wafer system
Wafer to wafer uniformity	Difficult to control	Easier to control

Gap Fill by HDP-CVD

- Simultaneously deposition and sputtering
- Tapering the gap opening
- Fill gap between metal lines bottom up

HDP CVD Void-free Gap Fill



0.25 μm, A/R 4:1

Benefits of Using Plasma For Etch Process

- High etch rate
- Anisotropic etch profile
- Optical endpoint
- Less chemical usage and disposal

Benefits of Using Plasma For PVD Process

- Argon sputtering
- Higher film quality
  - Less impurity and higher conductivity
- Better uniformity
- Better process control
- Higher process integration capability.
- Easier to deposit metal alloy films

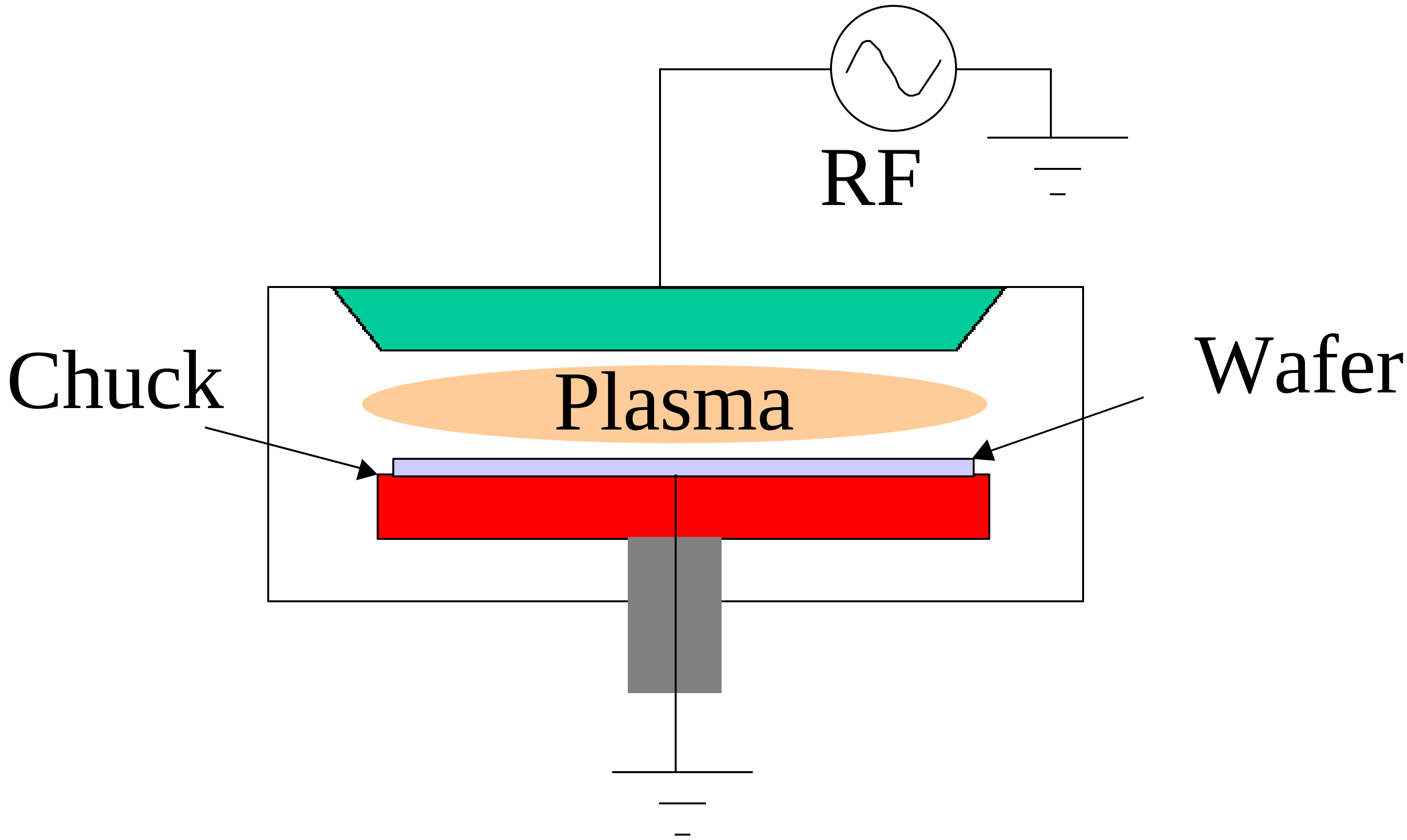
PECVD and Plasma Etch Chambers

- CVD: Adding materials on wafer surface
  - Free radicals
  - Some bombardment for stress control
- Etch: Removing materials from wafer surface
  - Free radicals
  - Heavy bombardment
  - Prefer low pressure, better directionality of ions

PECVD Chambers

- Ion bombardment control film stress
- Wafer is placed grounded electrode
- Both RF hot and grounded electrodes have about the same area
- It has very little self-bias
- The ion bombardment energy is about 10 to 20 eV, mainly determined by the RF power

Schematic of a PECVD Chamber



Plasma Etch Chambers

- Ion bombardment
  - Physically dislodge
  - break chemical bonds
- Wafer on smaller electrode
- Self-bias
- Ion bombardment energy
  - on wafer (RF hot electrode): 200 to 1000 eV
  - on lid (ground electrode): 10 to 20 eV.

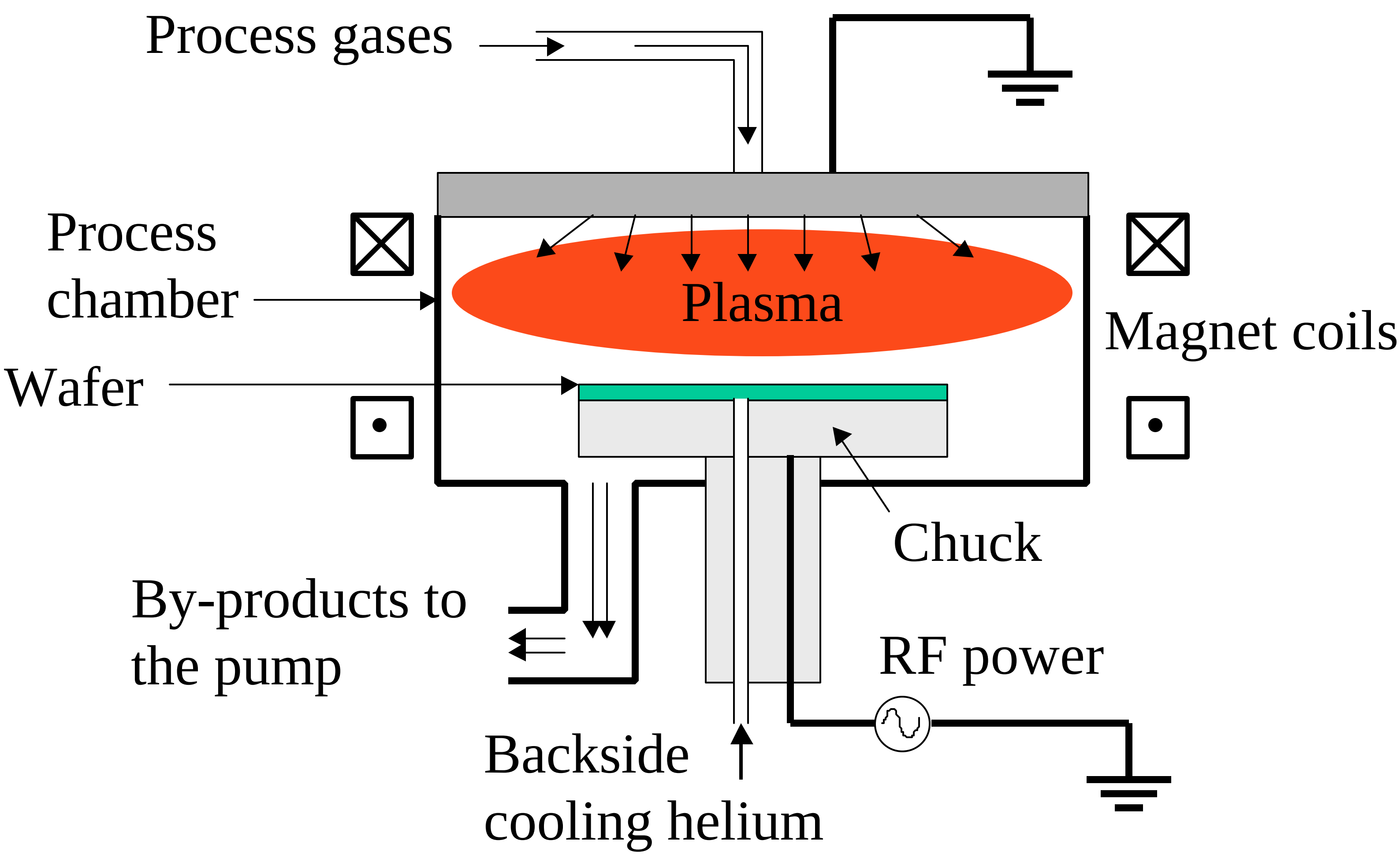
Plasma Etch Chambers

- Heat generation by heavy ion bombardment
- Need control temperature to protect masking PR
- Water-cool wafer chuck (pedestal, cathode)
- Lower pressure not good to transfer heat from wafer to chuck
- Helium backside cooling required
- Clamp ring or electrostatic chuck (E-chuck) to hold wafer

Plasma Etch Chambers

- Etch prefer lower pressure
  - longer MFP, more ion energy and less scattering
- Low pressure, long MFP, less ionization collision
  - hard to generate and sustain plasma
- Magnets are used to force electron spin and travel longer distance to increase collisions

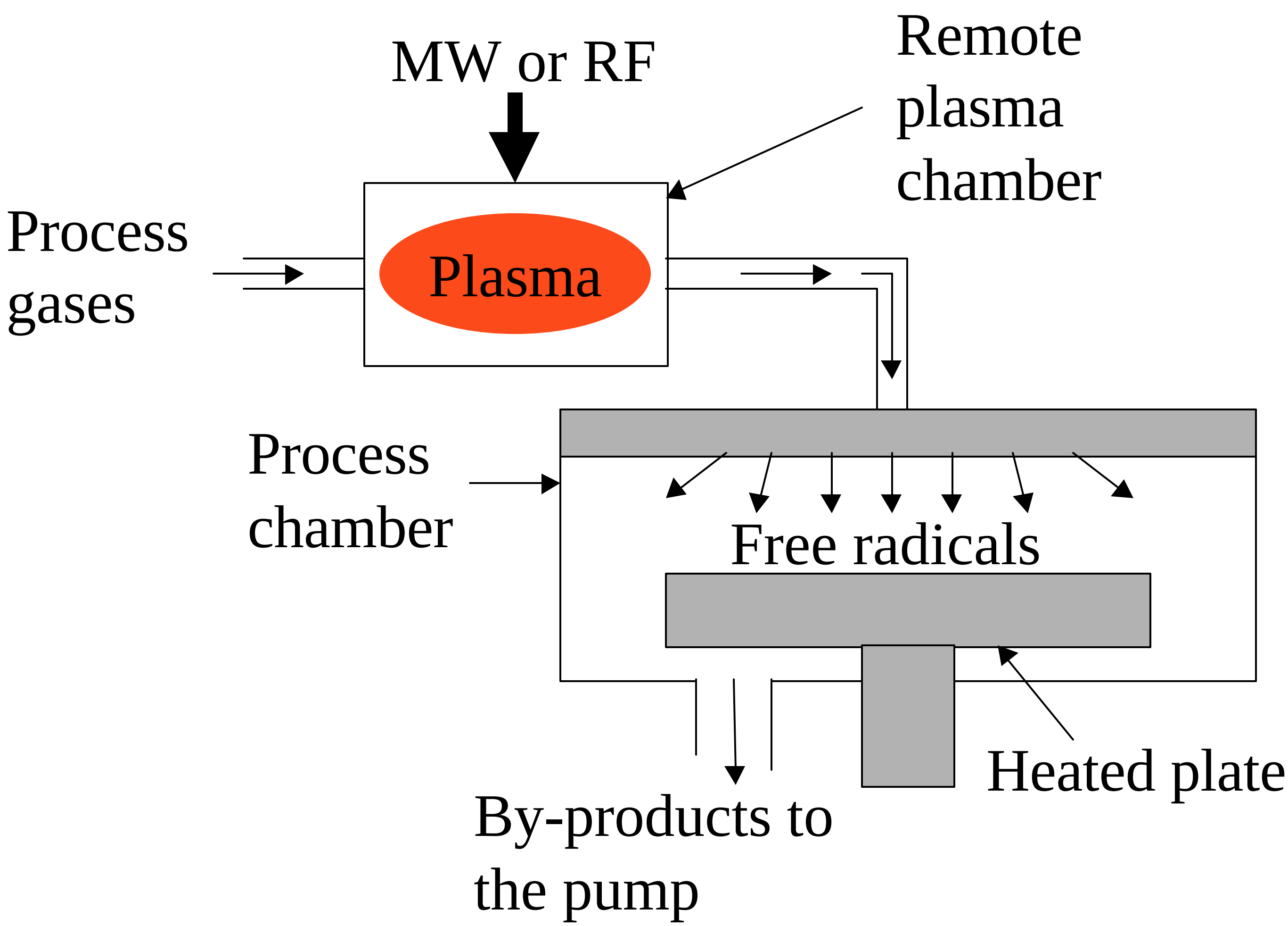
Schematic of an Etch Chamber



Remote Plasma Processes

- Need free radicals
  - Enhance chemical reactions
- Don't want ion bombardment
  - Avoid plasma-induced damage
- Remote plasma systems

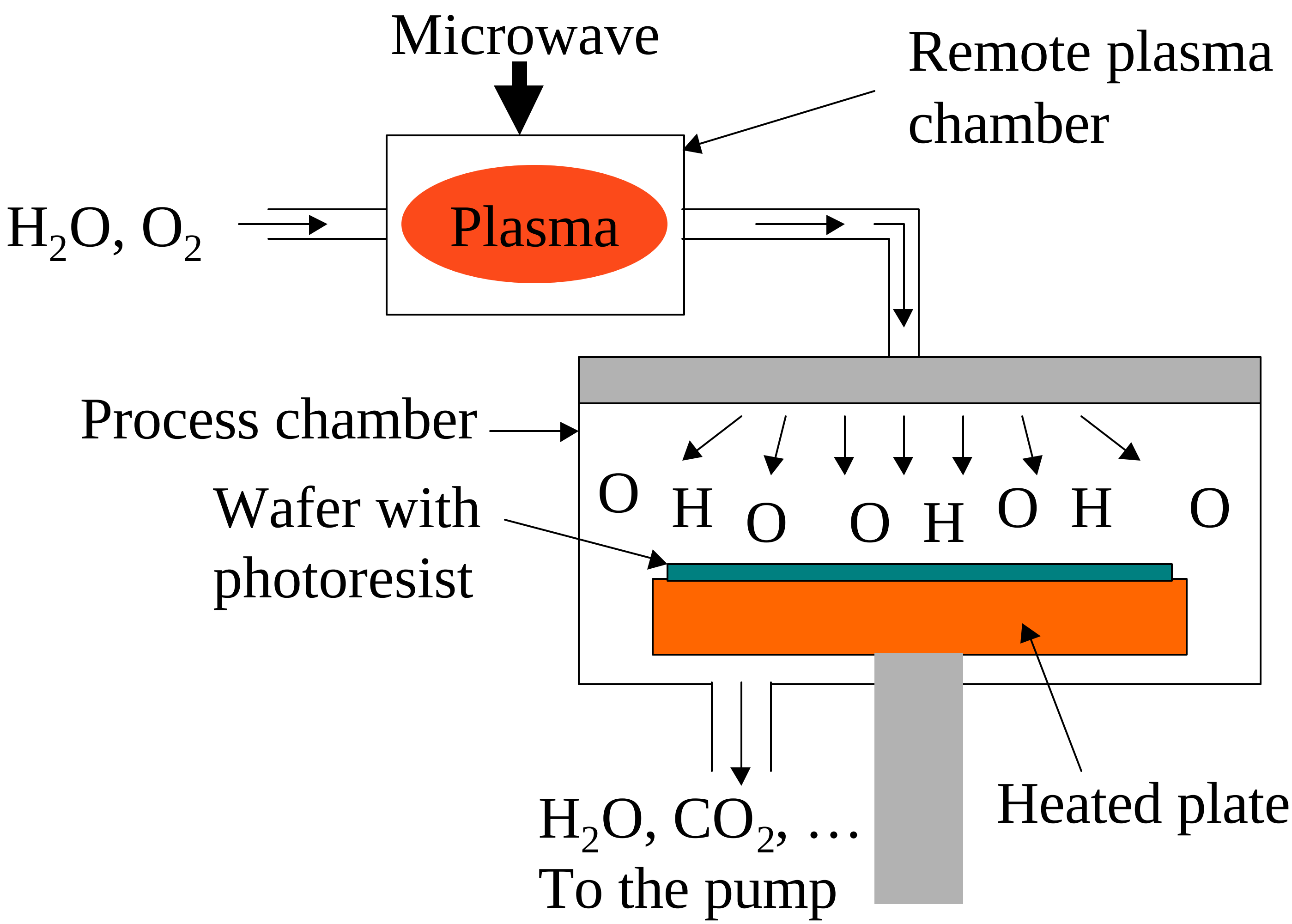
Remote Plasma System



Photoresist Strip

- Remove photoresist right after etch
- O_2 and H_2O chemistry
- Can be integrated with etch system
- In-situ etch and PR strip
- Improve both throughput and yield

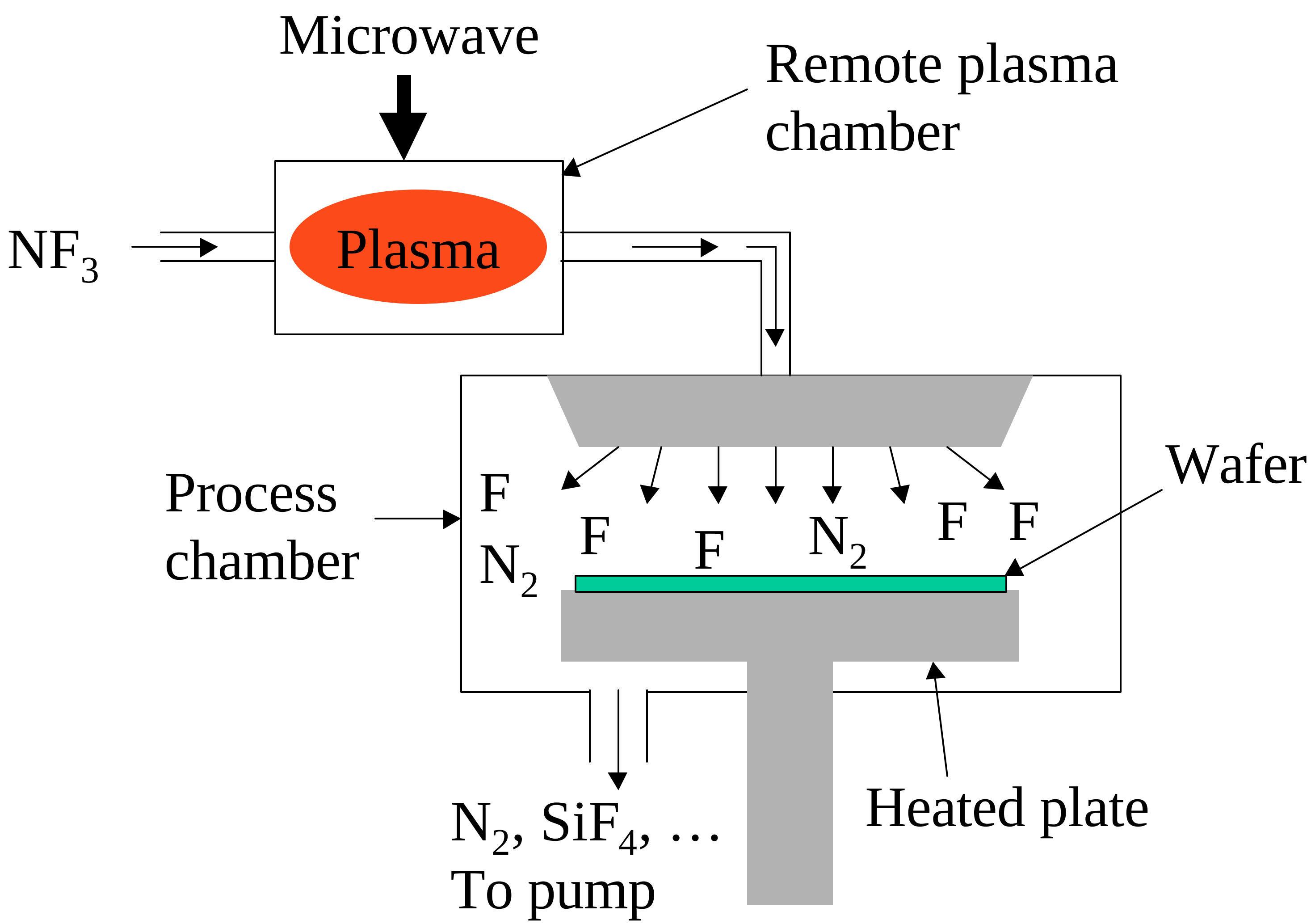
Photoresist Strip Process



Remote Plasma Etch

- Applications: isotropic etch processes:
  - LOCOS or STI nitride strip
  - wineglass contact hole etch
- Can be integrated with plasma etch system
  - improve throughput
- Part of efforts to replace wet process

Remote Plasma Etch System



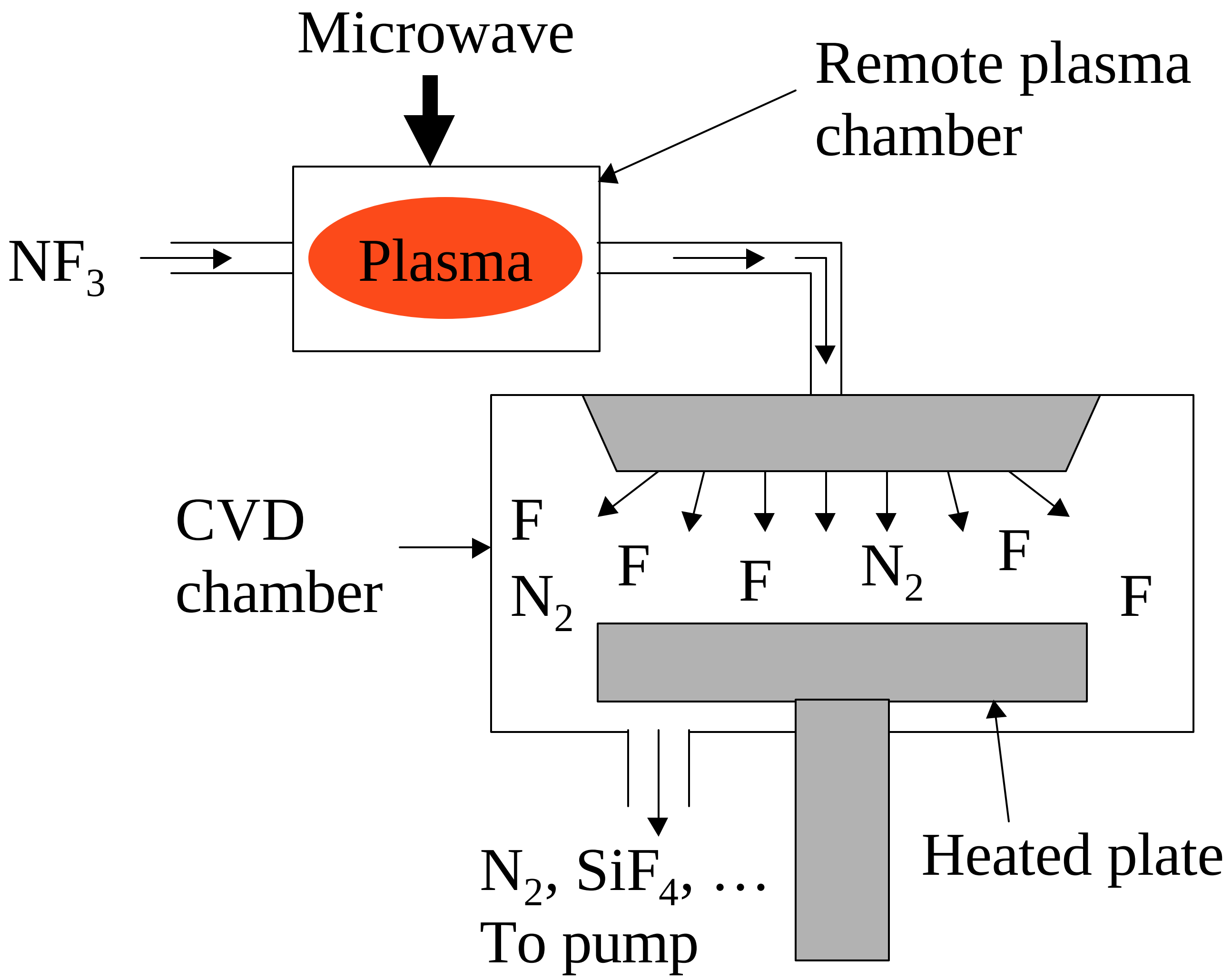
Remote Plasma Clean

- Deposition not only on wafer surface
- CVD chamber need clean routinely
  - Prevent particle contamination due to film crack
- Plasma clean with fluorocarbon gases is commonly used
  - Ion bombardment affects parts lifetime
  - Low dissociation rate of fluorocarbon
  - Environmental concern of fluorocarbon releases

Remote Plasma Clean

- Microwave high-density plasma
- The free radicals flow into CVD chamber
- React and remove deposited film
- Clean the chamber while
  - gentle process, prolonged part lifetime
  - high dissociation, little fluorocarbon releases

Remote Plasma Clean System



Remote Plasma CVD (RPCVD)

- Epitaxial Si-Ge for high-speed BiCMOS
- Still in R&D
- Gate dielectric: SiO_2, SiON, and Si_3N_4
- High-κ dielectrics: HfO_2, TiO_2, and Ta_2O_5
- PMD barrier nitride
  - LPCVD: budget limitations
  - PECVD: plasma induced damage

High-density Plasma

- High-density at low pressure are desired
- Lower pressure longer MFP, less ion scattering, enhances etch profile control.
- Higher density, more ions and free radicals
  - Enhance chemical reaction
  - Increase ion bombardment
- For CVD processes, HDP in-situ, simultaneous dep/etch/dep enhance gap fill

Limitation of Parallel Plate Plasma Source

- Capacitively coupled plasma source
- Can not generate high-density plasma
- Hard to generate plasma even with magnets at low pressure, about a few mTorr.
  - electron MFP too long, no enough ionization collisions.

Limitation of Parallel Plate Plasma Source

- Cannot independently control ion flux and ion energy
- Both are directly related to RF power
- Better process control requires a plasma source that capable to independently control both of them

ICP and ECR

- Most commonly used in IC industry
- Inductively coupled plasma, ICP
  - also called transformer coupled plasma, or TCP
- Electron cyclotron resonance, ECR,
- Low press at few mTorr
- Independently control ion flux and ion energy

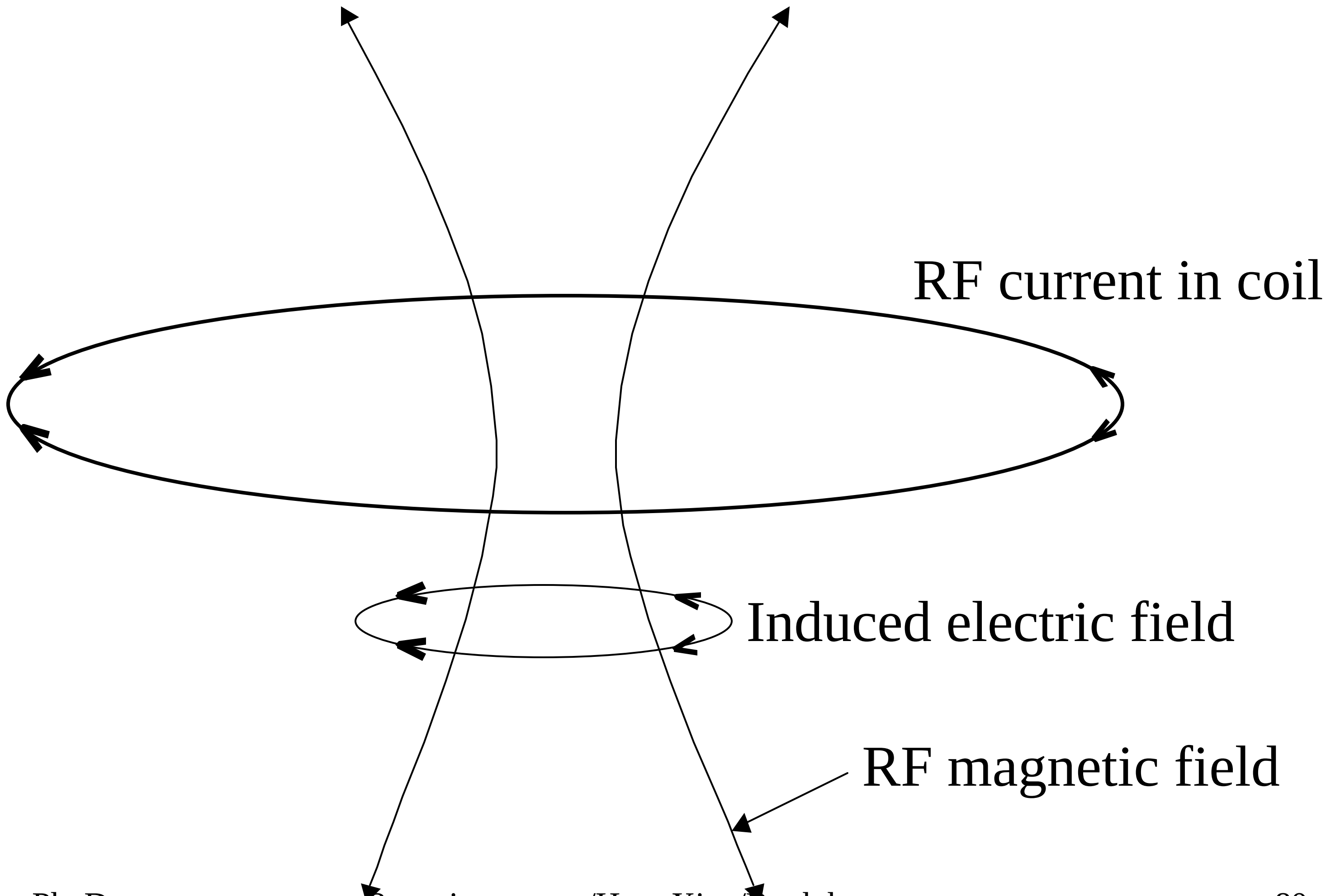
Inductively Coupled Plasma (ICP)

- RF current flows in the coils generates a changing electric field via inductive coupling
- The angular electric field accelerates electrons in angular direction.
- Electrons to travel a long distance without collision with the chamber wall or electrode.
- Ionization collisions generate high-density plasma at low pressure

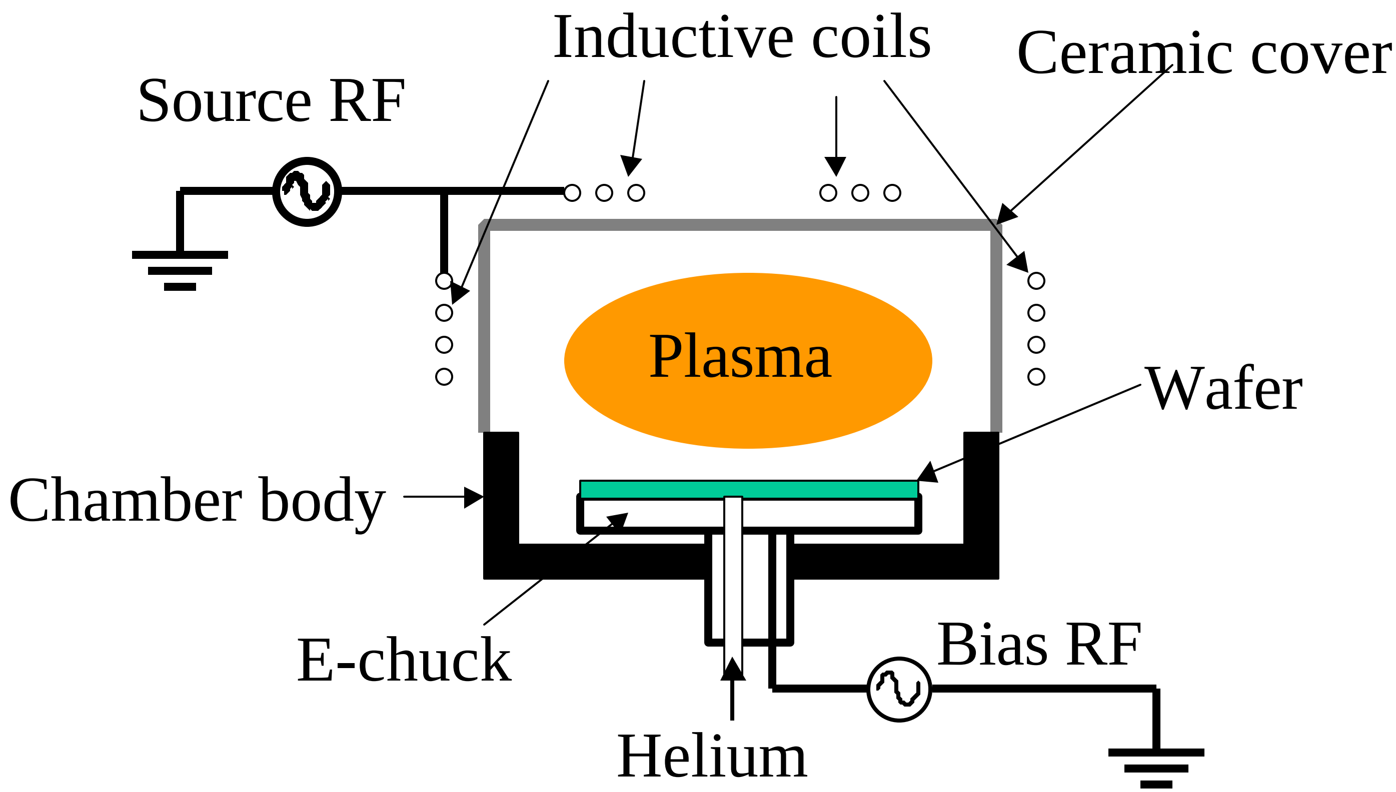
Inductively Coupled Plasma (ICP)

- Bias RF power controls the ion energy
- Source RF power controls the ion flux
- Helium backside cooling system with E-chuck controls wafer temperature

Illustration of Inductive Coupling



Schematic of ICP Chamber



Application of ICP

- Dielectric CVD
- All patterned etch processes
- Sputtering clean prior to metal deposition
- Metal plasma PVD
- Plasma immersion ion implantation

ECR

- Gyro-frequency or cyclotron frequency:

$$\Omega = \frac{qB}{m}$$

- Determined by magnetic field

ECR

- Electron cyclotron resonance when $w_{MW} = W_e$
- Electrons get energy from MW
- Energetic electrons collide with other atoms or molecules
- Ionization collisions generate more electrons
- Electrons are spiraling around the field line
- Many collisions even at very low pressure

Illustration of ECR

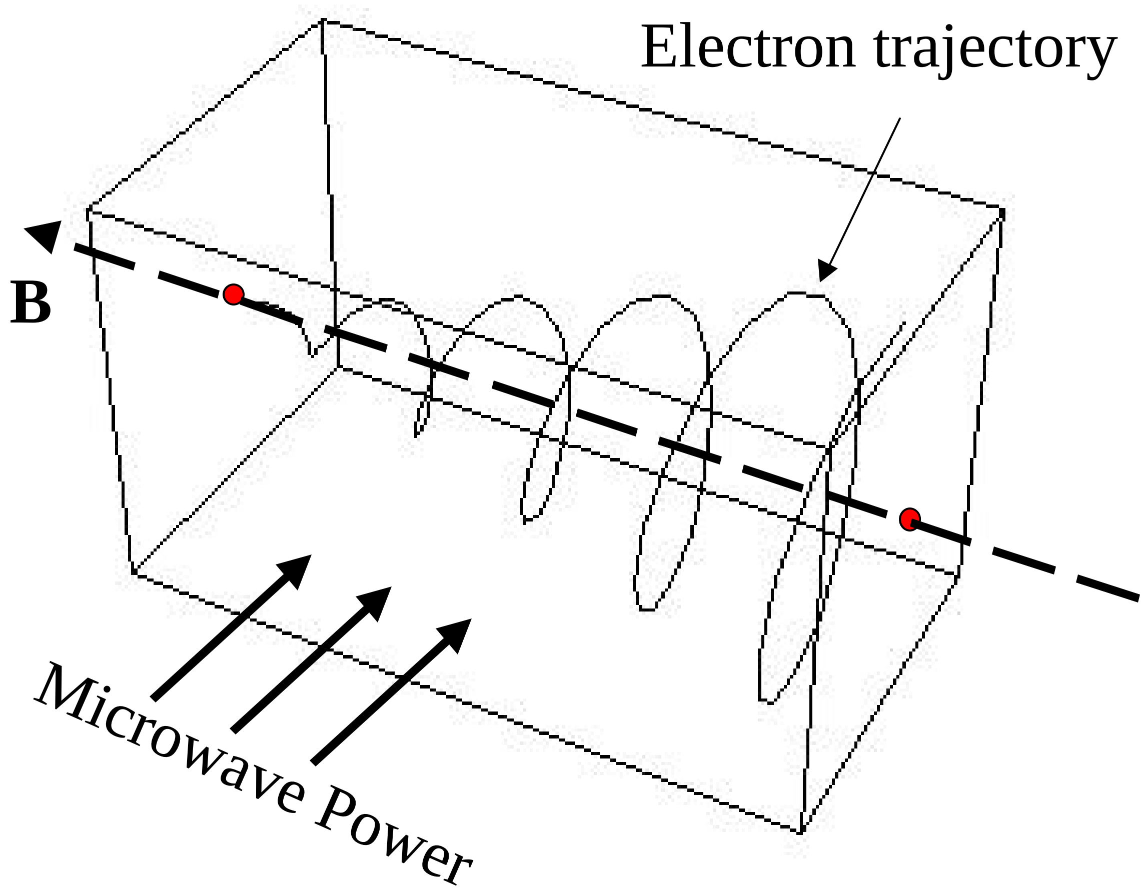
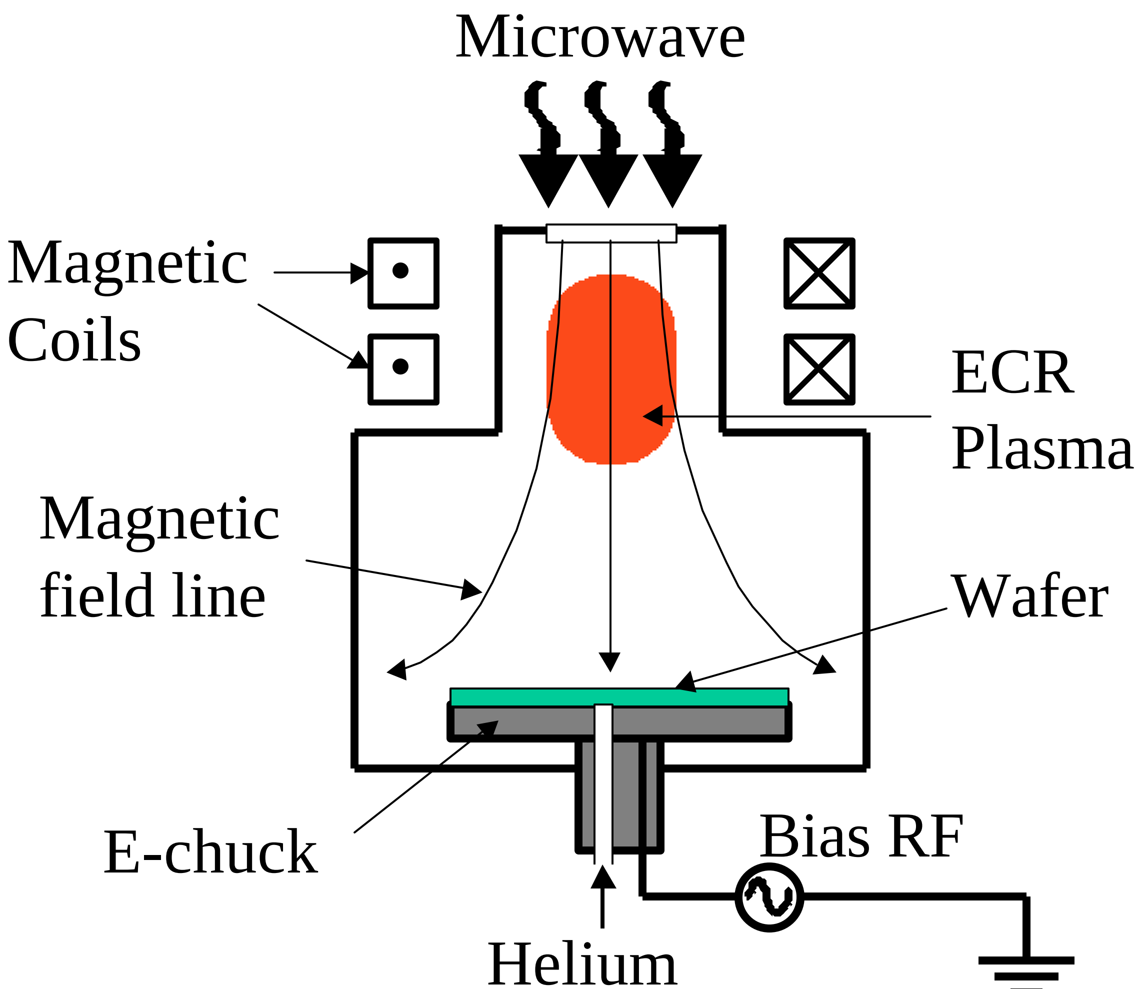


Illustration of ECR



ECR

- Bias RF power controls the ion energy
- Microwave power controls the ion flux
- Magnet coil current controls plasma position and process uniformity
- Helium backside cooling system with E-chuck controls wafer temperature

Application of ECR

- Dielectric CVD
- All patterned etch processes
- Plasma immersion ion implantation

Summary

- Plasma is ionized gas with $n_{-} = n_{+}$
- Plasma consist of *n*, *e*, and *i*
- Ionization, excitation-relaxation, dissociation
- Ion bombardment help increase etch rate and achieve anisotropic etch
- Light emission can be used for etch end point
- MFP and its relationship with pressure
- Ions from plasma always bombard electrodes

Summary

- Increasing RF power increases both ion flux and ion energy in capacitive coupled plasmas
- Low frequency RF power gives ions more energy, causes heavier ion bombardment
- The etch processes need much more ion bombardment than the PECVD
- Low pressure, high density plasma are desired
- ICP and ECR are two HDP systems used in IC fabrication