Chapter 7

Plasma Basics

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: $n_i \approx n_e$
- Ionization rate: $\eta \approx n_e/(n_e + n_n)$

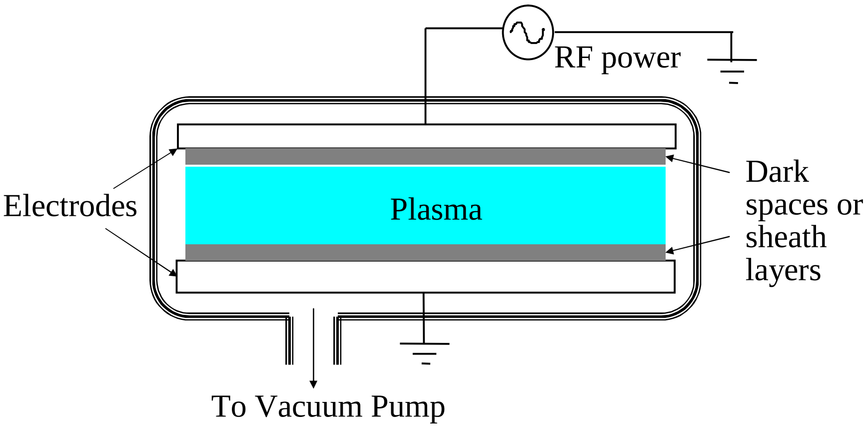
Neutral Gas Density

- 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

Ionization Rate

- Ionization rate is mainly determined by electron energy in plasma, which is in turn controlled by the applied power. Also related to pressure, electrode spacing, gas species and chamber design.
- In most plasma processing chambers, the ionization rate is less than 0.01%.
- The ionization rate of high density plasma (HDP) source such as inductively coupled plasma (ICP) or electron cyclotron resonance (ECR), is much higher, which is about 1~ 5%.
- Ionization rate in the core of sun is ~100%.

Parallel Plate Plasma System



Generation of a Plasma

- External power is needed
- Radio frequency (RF) power is the most commonly used power source with which a varying electric field is established
- Electrons and ions are continually generated and lost by collisions and recombination
- A plasma is stabilized when generation rate of electrons is equal to loss rate of electrons
- Vacuum system is required to generate a stable RF plasma

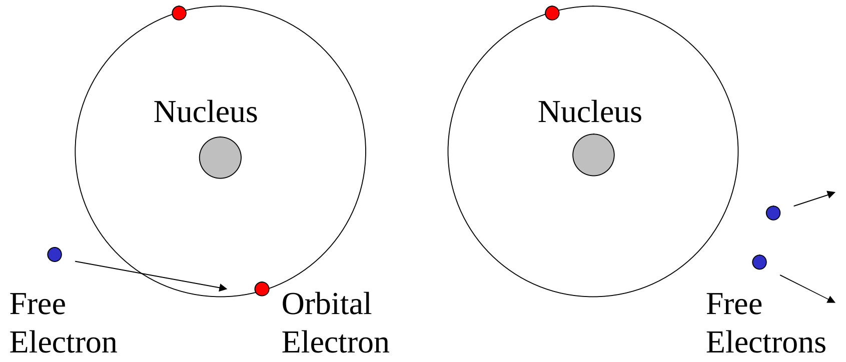
Ionization Process

- 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 a stable plasma

Illustration of Ionization



Excitation and Relaxation

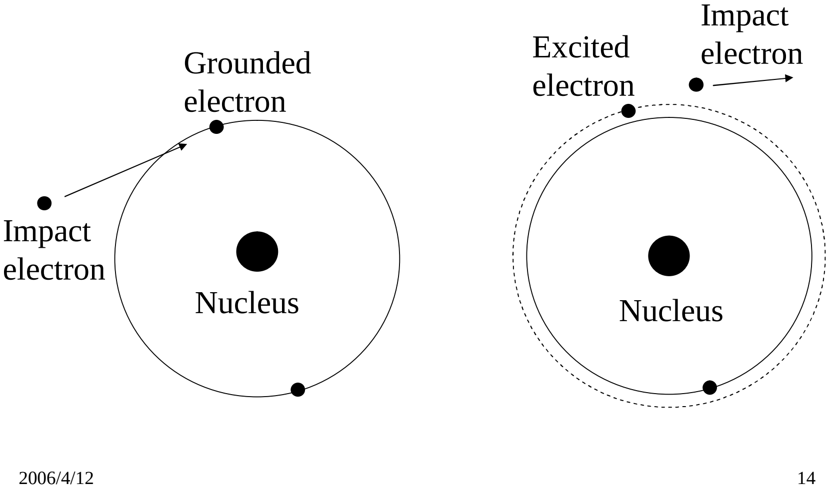
$$e + A \longrightarrow A^* + e$$ where A^* is excited state

$$A^* \longrightarrow A + h\nu$$ (Photons) *light emission*

- 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**.

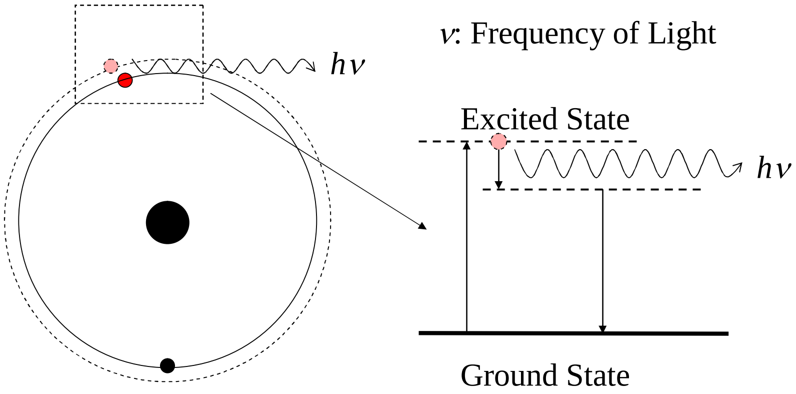
Excitation Collision



Relaxation

h: Planck Constant

ν: Frequency of Light



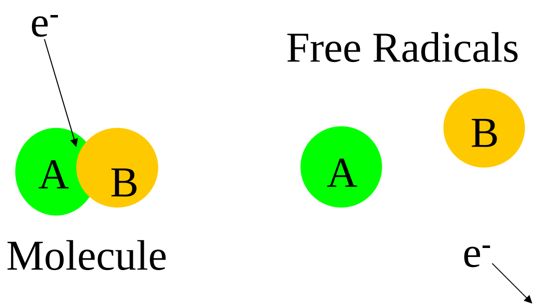
Dissociation

- 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 very chemically reactive.
- Increasing chemical reaction rate
- Very important for both etch and CVD.

Dissociation



e^-

Free Radicals

A B

Molecule

A

B

e^-

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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

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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**
$e^- + SiH_4 \rightarrow$	$SiH_2 + H_2 + e^-$	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.

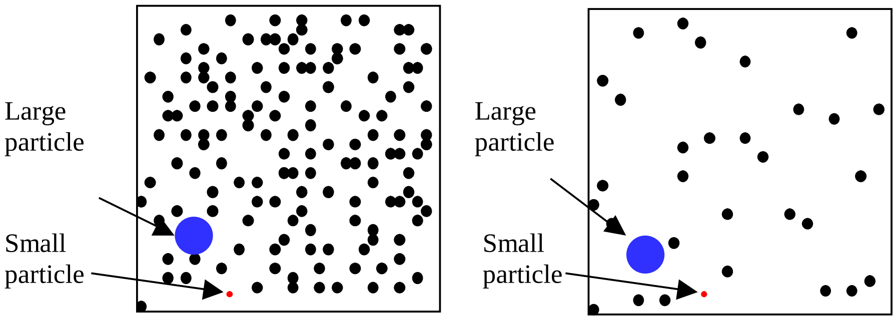
Mean Free Path (MFP)

- The average distance a particle can travel before colliding with another particle.
- Larger molecules have shorter MFP because it is proportional to molecule size and cross-section

$$\lambda = \frac{1}{\sqrt{2}n\sigma}$$

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

MFP Illustration



(a) (b)

Mean Free Path (MFP)

- Effect of pressure:

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

- Higher pressure, shorter 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, 1eV = 11594 K

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

- RF plasma, T_e is about 2 eV

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

(equivalent to airplane's speed)

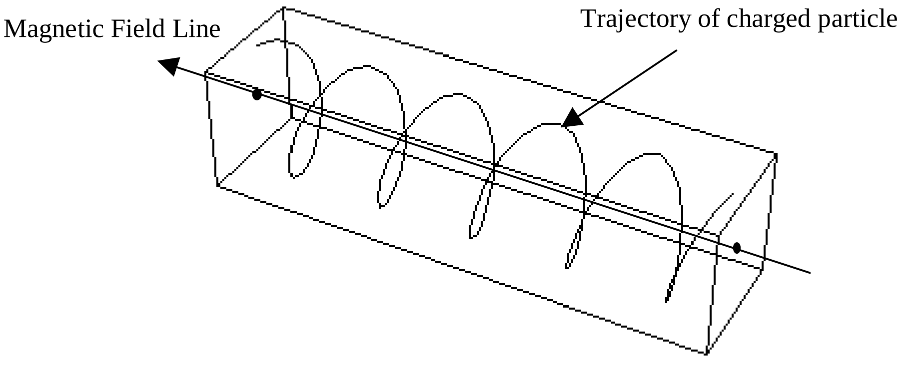
Magnetic Force and Gyro-motion

- 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

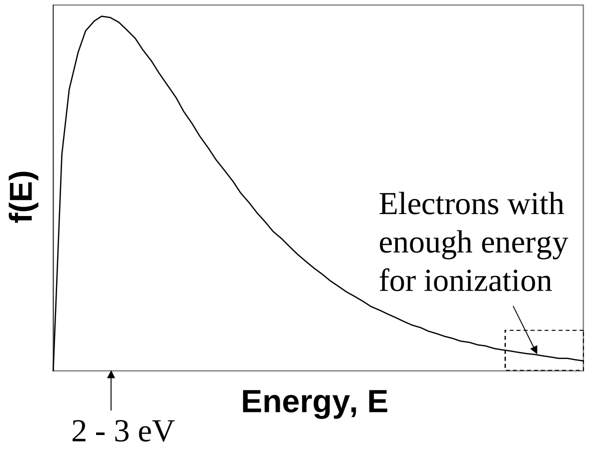
$$\Omega = \frac{qB}{m}$$

Gyro radius

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

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

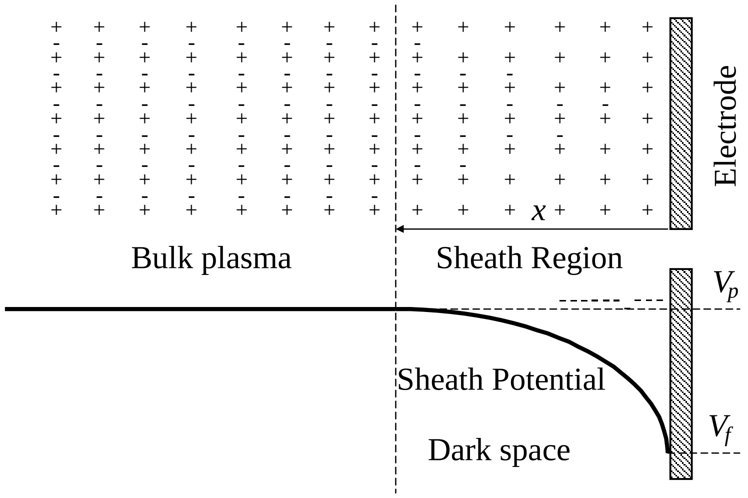
Boltzmann Distribution



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



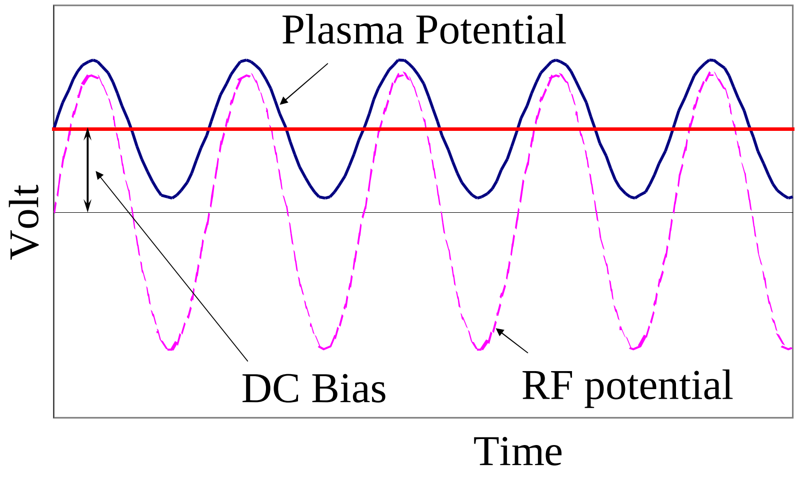
Ion Bombardment

- Anything close to plasma gets ion bombardment
- Mainly determined by RF power
- Pressure also can affect bombardment

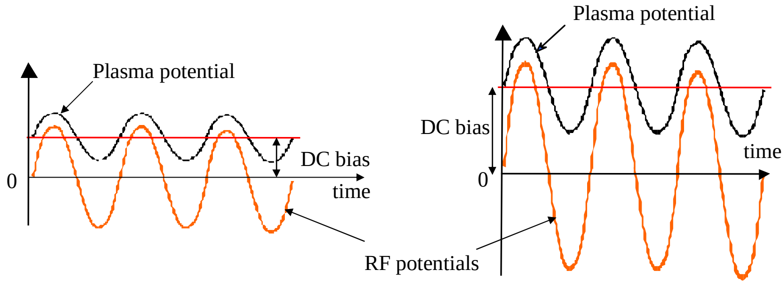
Applications of Ion bombardment

- 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

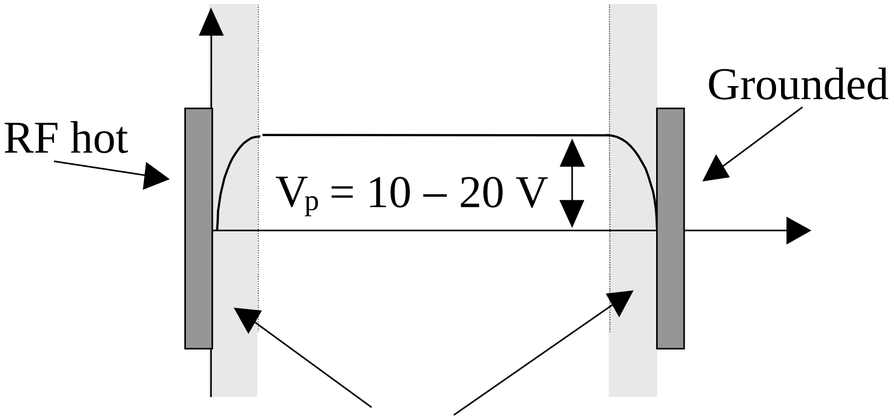
Ion Bombardment

- Ion energy
- Ion flux (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



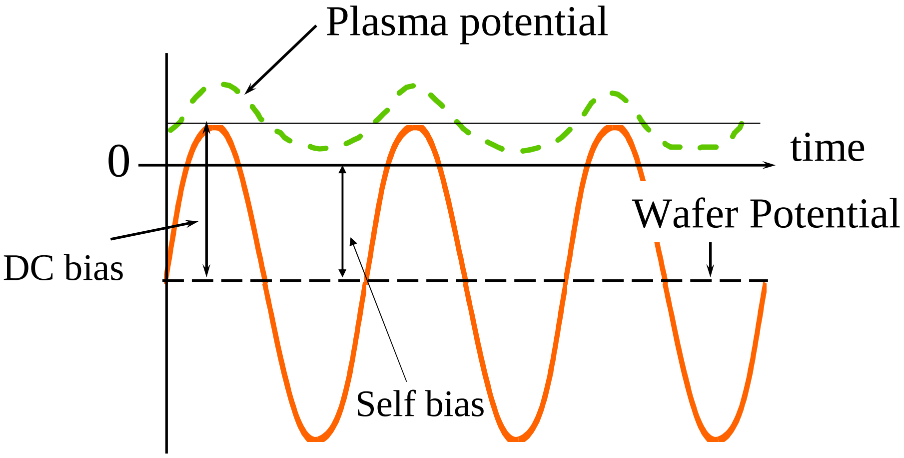
RF hot

Grounded

V_p = 10 – 20 V

Dark spaces or sheath regions

DC Bias of Etch Chamber Plasma



Plasma potential

0

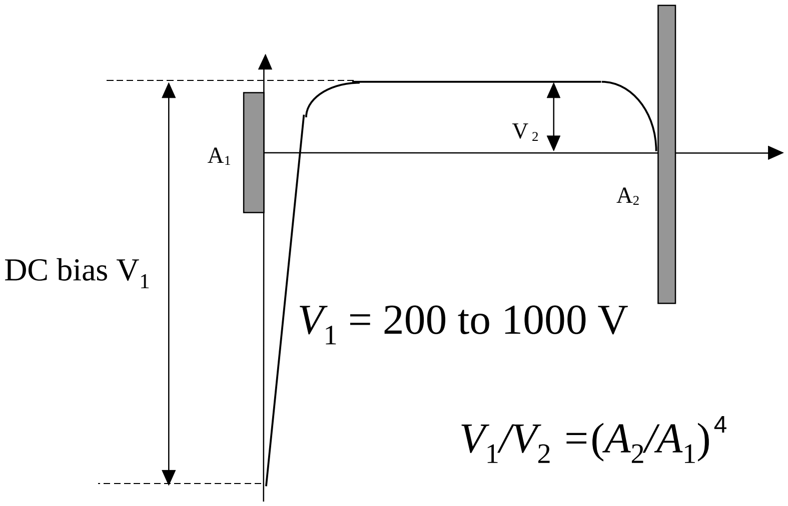
time

Wafer Potential

DC bias

Self bias

DC Bias of Etch Chamber Plasma



V_1 = 200 to 1000 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

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

Q and A

- 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 in CVD Process

- High deposition rate at relatively lower temperature.

- Independent film stress control

- Chamber dry clean

- Gap fill capability

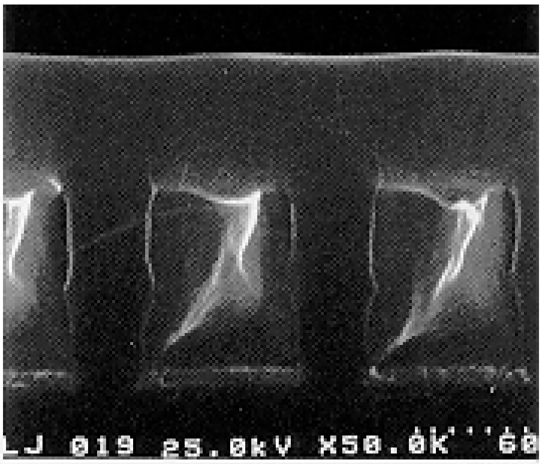
Comparison of PECVD and LPCVD

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**	**≥ 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

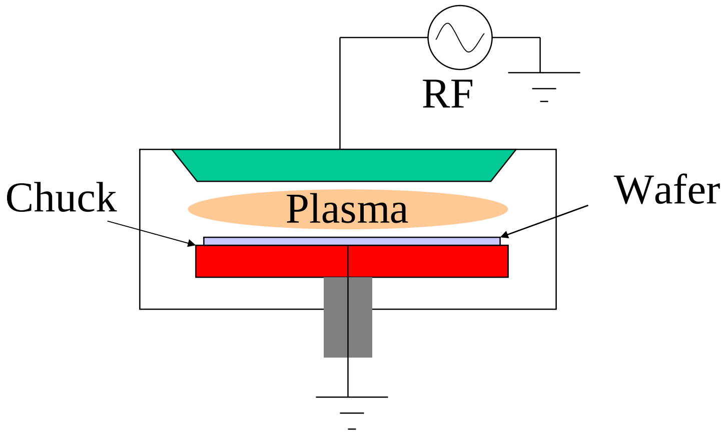
PECVD and Plasma Etch Chambers

- 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.

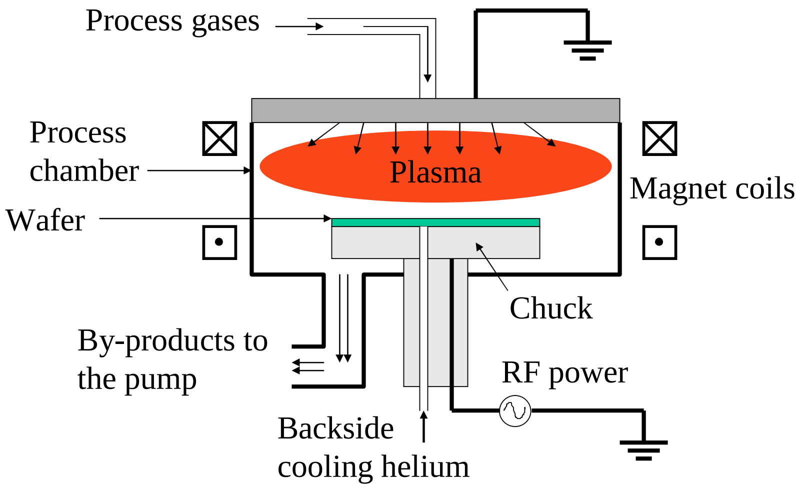
Plasma Etch Chambers

- 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



Process gases

Process chamber

Wafer

Plasma

Magnet coils

Chuck

By-products to the pump

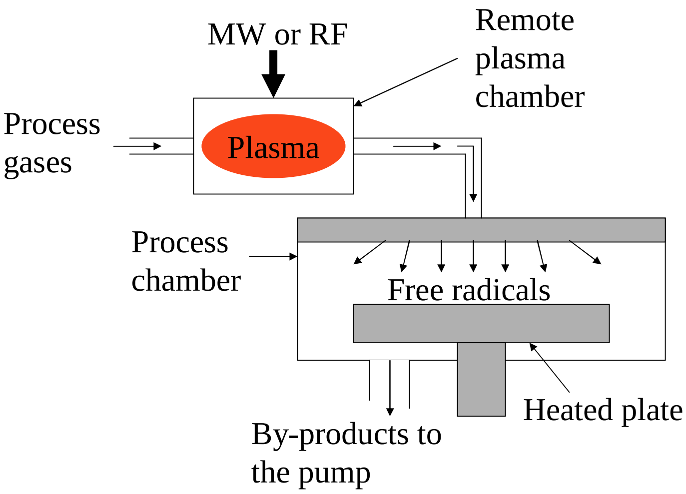
RF power

Backside cooling helium

Remote Plasma Processes

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

Remote Plasma System



MW or RF

Remote
plasma
chamber

Process
gases

Plasma

Process
chamber

Free radicals

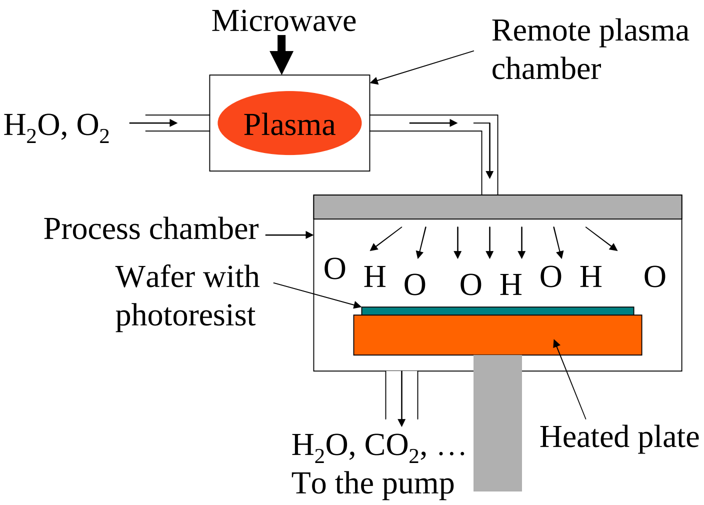
Heated plate

By-products to
the pump

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

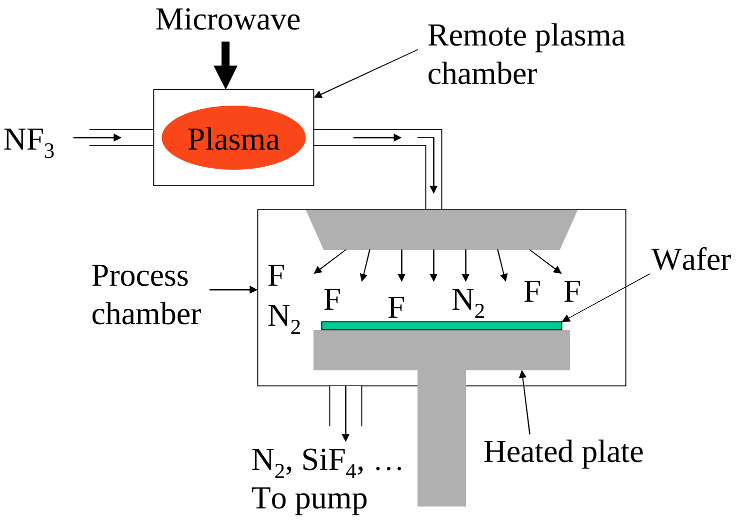
Photoresist Strip Process



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



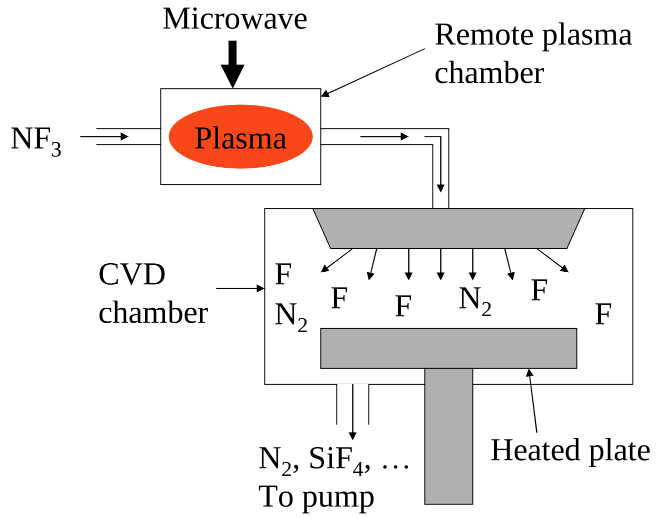
Remote Plasma Clean

- Deposition occurs 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, which enhance 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

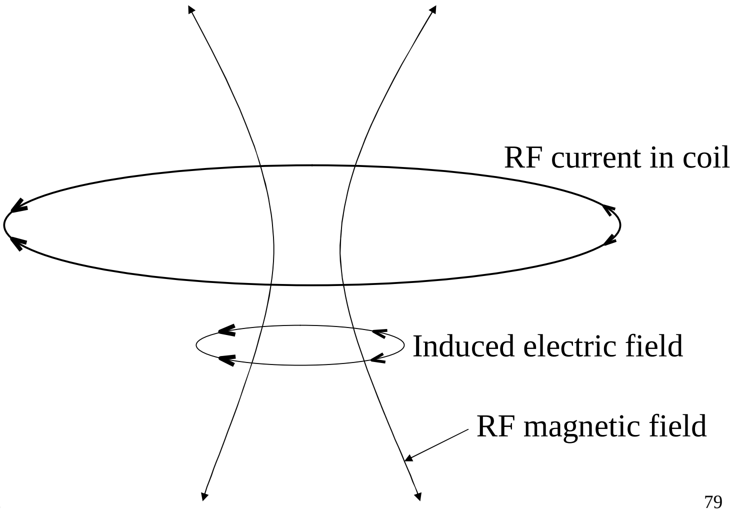
Inductively Coupled Plasma (ICP)

- 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

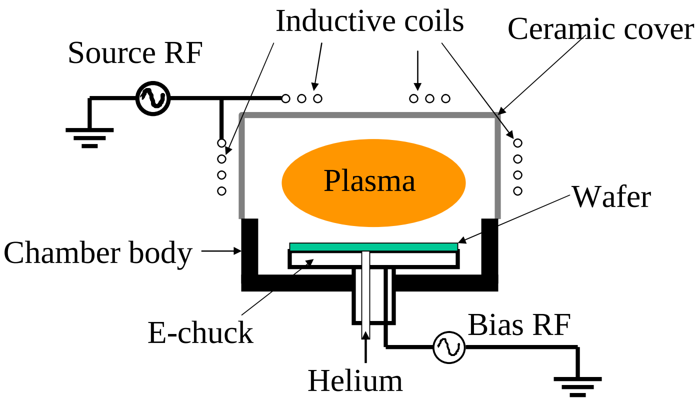


RF current in coil

Induced electric field

RF magnetic field

Schematic of ICP Chamber



Source RF

Inductive coils

Ceramic cover

Plasma

Wafer

Chamber body

E-chuck

Bias RF

Helium

Application of ICP

- Dielectric CVD
- All patterned etch processes, particularly for high aspect-ration structure
- 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 $\omega_{MW} = \Omega_e$
- 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

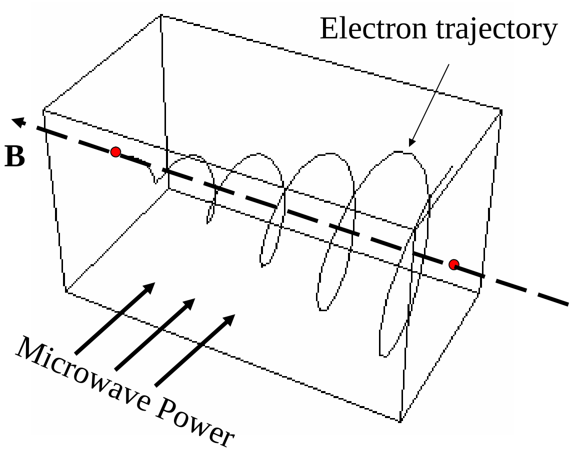
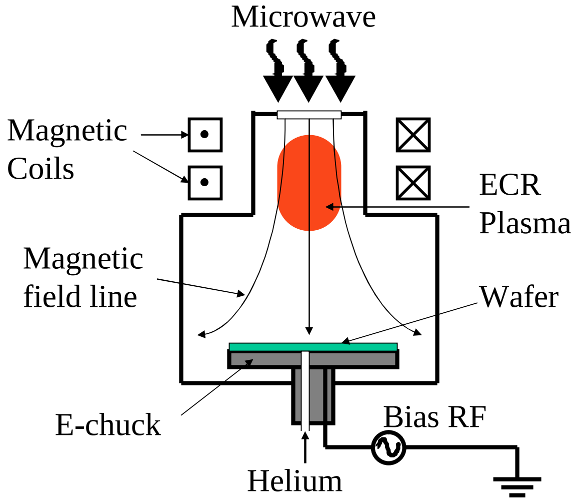


Illustration of ECR



Microwave

Magnetic Coils

ECR Plasma

Magnetic field line

Wafer

E-chuck

Bias RF

Helium

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