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Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Etching – Dry Etching

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Etching Techniques – What is Dry Etching?

Etching can be done either in **“wet”** or **“dry”** method:

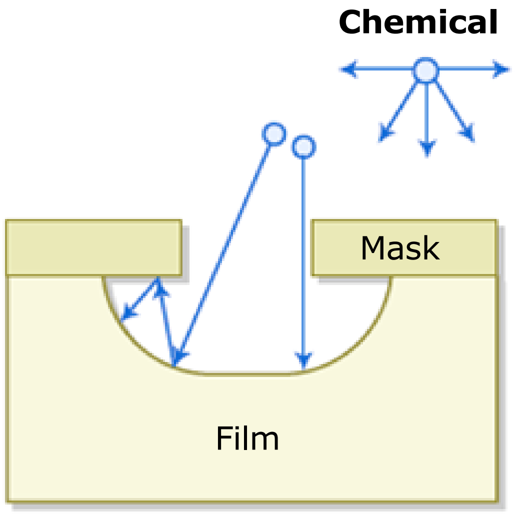
Wet etching

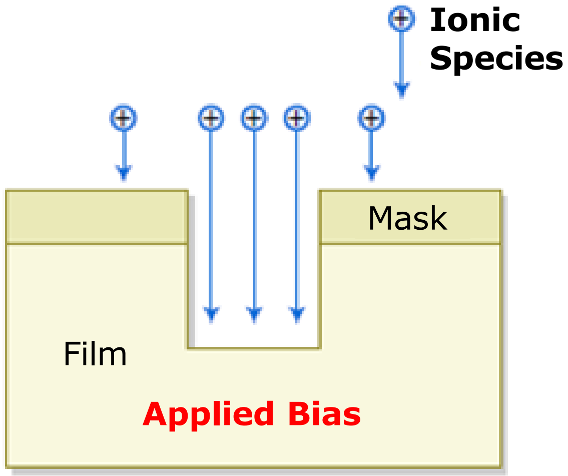
- Wet etching is a process whereby materials are removed by liquid etchants.
- Wet etching is fast, cheap and simple, but harder to control. Hence, it is not popular in nanofabrication.

Dry etching

- Dry etch uses gas phase etchants in plasma.
- In comparison, dry etching is slower, requires sophisticated equipment, but easier to control.
- It works for many dielectric materials and some metals (Al, Ti, Cr, Ta, W, etc.).
- Since the gas phase etchants in plasma are used in dry etching, dry etching is sometimes called plasma etching.

Anisotropy in Dry Etching





- Since ionic species are present in the plasma driven by an applied bias, it can result in directional etching.
- Therefore, anisotropic profile can be achieved by dry etching technique.

Why Dry Etching?

General Etch Requirement:

- Achieve desirable profile (slope or vertical)
- Minimal undercut
- Uniformity and reproducibility

Can be achieved by dry etching.

Dry Etching – Lesson Overview

Dry etching:

- Plasma generation and processes
- Plasma interaction with the substrate
  1. Physical interaction (sputter etching)
  2. Physical + chemical interaction (reactive ion etching)
- Factors controlling the plasma etch rate
- Plasma damage and general issues in etching

Plasma Generation and Processes

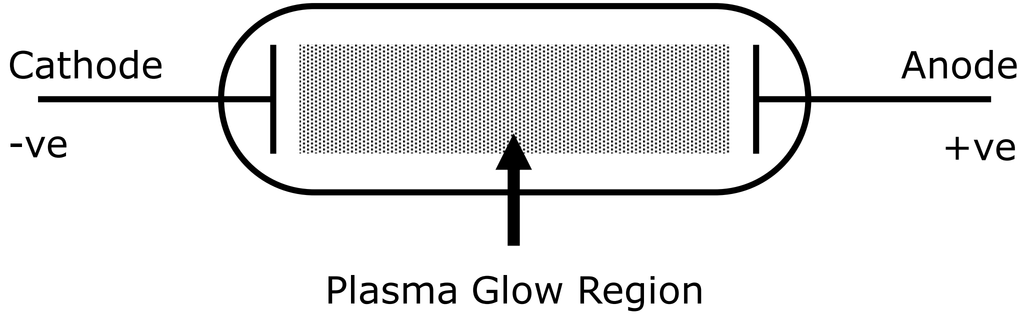
Dry Etching (Plasma)

What is a Plasma?

- An ionised gas with about equal amounts of positive ions and negatively charged particles
- Usually electrons, positive ions, and a small amount of negative ions
- It has a neutral charge in macroscopic sense

Plasma Generation

- A neutral gas is placed within a tube with a DC potential applied across two electrodes.
- The released electrons accelerate toward the positive electrode or anode, and along the way undergo a series of elastic and inelastic collisions, and the plasma is therefore formed.
- Kinetic energy is conserved in elastic collisions. An electron has a smaller mass than an atom, the energy transfer is negligible and the electron will simply change direction.
- All other types of electron collision are inelastic and will result in ionised species or excited neutral species in the plasma.



Plasma Processes: Ionisation and Recombination

Ionisation

- Electron impact ionisation (**inelastic collisions**)
- The primary electron **removes an electron** from the atom, **producing** a positive **ion** and two electrons
- Example:

$$\boxed{e^{-} + M \rightarrow M^{+} + 2e^{-}}$$

Where M is the gas molecule

Recombination

- Inverse process of ionisation
- An **electron coalesces with a positive ion** to form a neutral atom
- Example:

$$\boxed{e^{-} + M^{+} \rightarrow M}$$

Where M is the gas molecule

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Excitation

- **Energy provided** to atoms **enables the electron to jump** to a **higher energy level** within the atom with a corresponding quantum absorption of energy, but insufficient to ionise the atom
- It can result from both electron impact excitation or photo excitation
- Example:

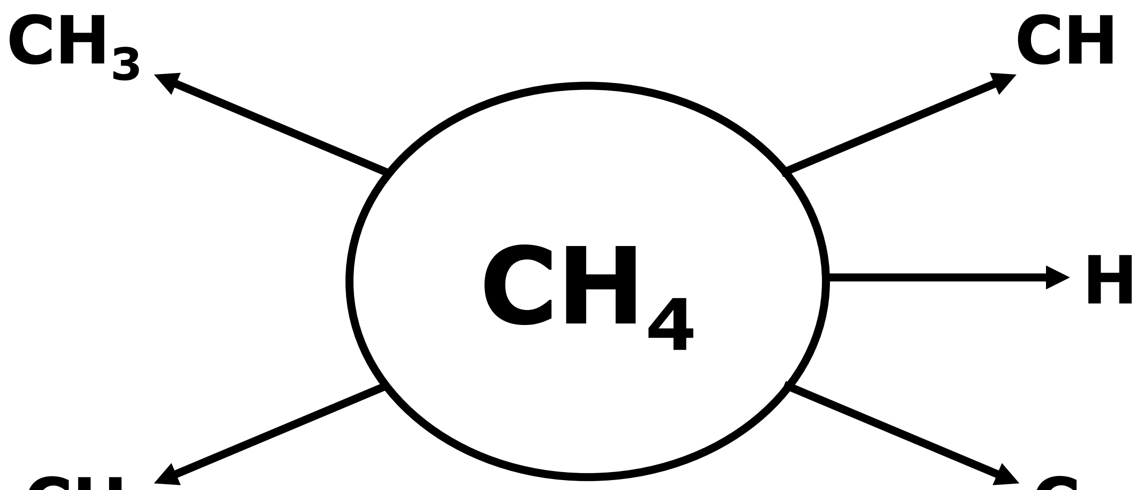
$$\boxed{e^- + M \rightarrow M^* + e^-}$$

Relaxation

- Inverse process of excitation
- The **excited states are rather unstable** and the electron configuration soon **returns to the ground state** in one or several transitions, with lifetimes varying from nanoseconds to seconds
- Each transition is accompanied by the **emission of a photon** of various specific energy $h\upsilon$

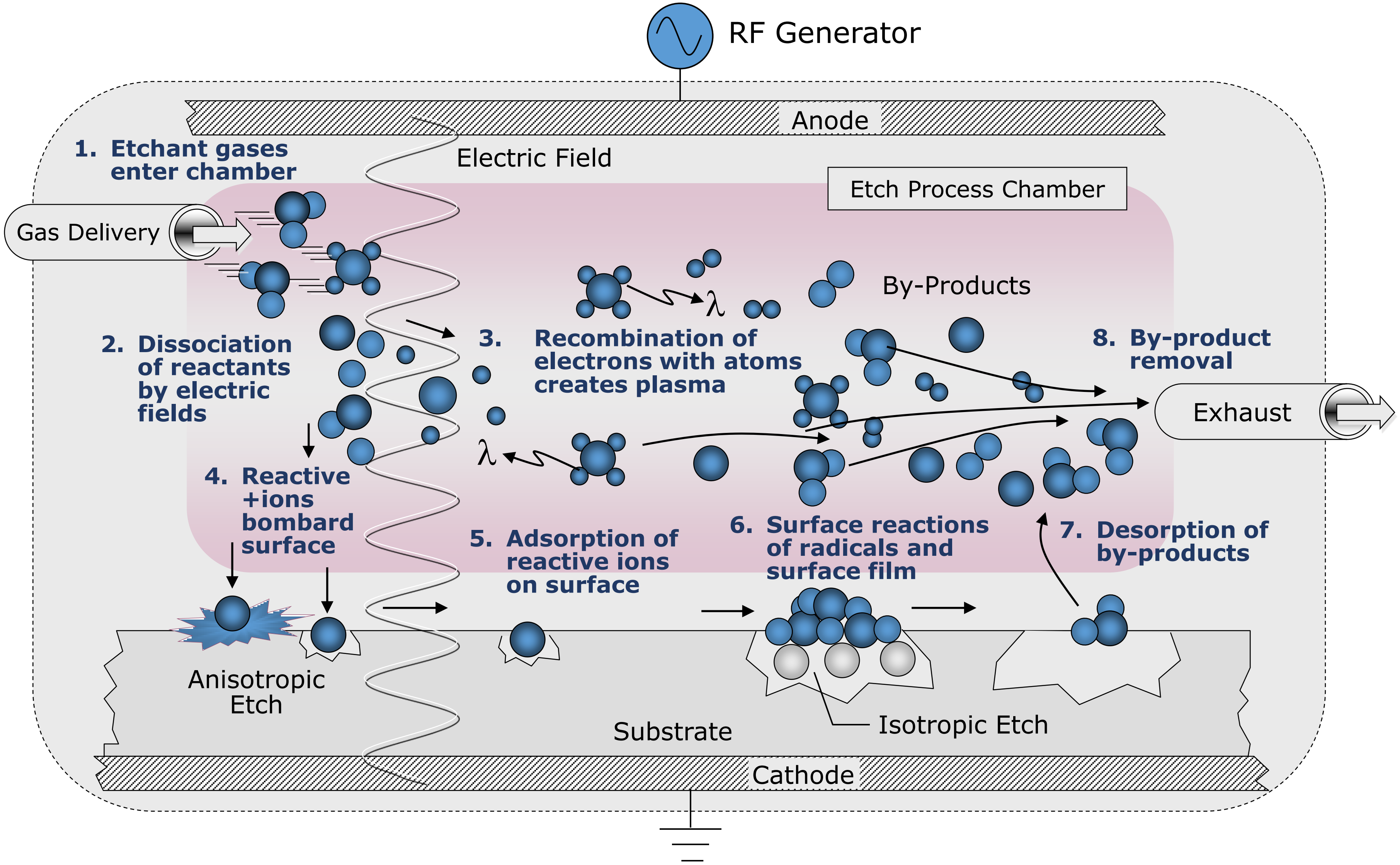
Plasma Processes: Dissociation of Gas Molecules

- As the energy of plasma electrons is much higher than the chemical bond energy, molecules in a plasma are essentially randomised, breaking down into all conceivable fragments.
- For example, a plasma of methane (CH_4) can be expected to include the fragments of CH_3, CH_2, CH, H, and C.

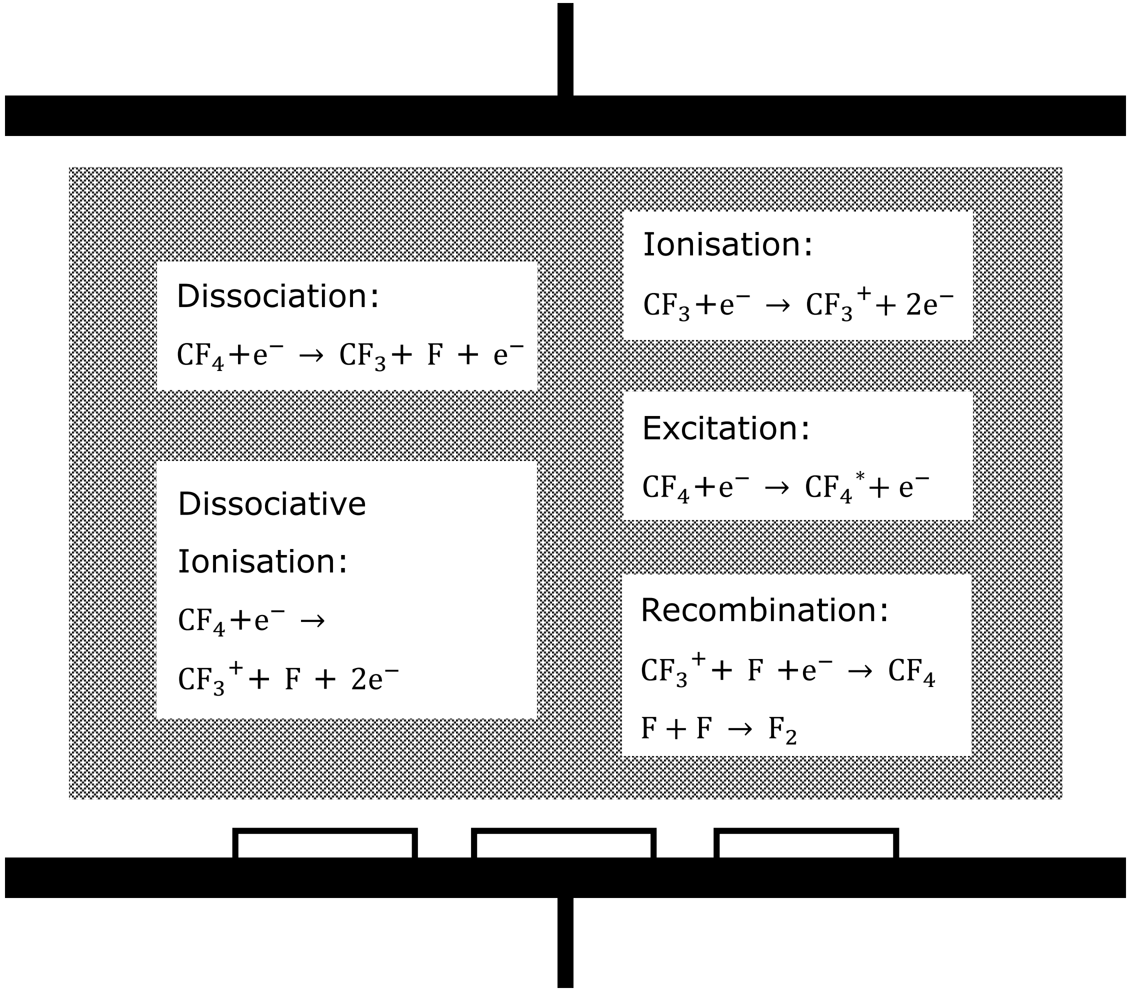


Possible Fragments

Plasma Processes



Etching Gas: CF_4



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Plasma Interaction with the Substrate

Plasma Interaction with the Substrate (Outline)

Plasma interaction with the substrate:

- **Physical interaction (sputter etching)**
- Physical + chemical interaction (reactive ion etching)

Interaction of Plasma with the Surface

Types of plasma interactions:

- **Physical** — Surface bombarded with energetic ions. The ions' loss of kinetic energy on the surface dominates the interaction. E.g.: Argon (inert gas) plasma etching
- **Physical & Chemical** — In addition to physical etching, chemical erosion by the bombarding ions contribute to etching process. E.g.: CF_4 (reactive gas) plasma etching

Physical Interaction with the Surface – Argon Plasma

Argon gas is usually used for physical plasma etching:

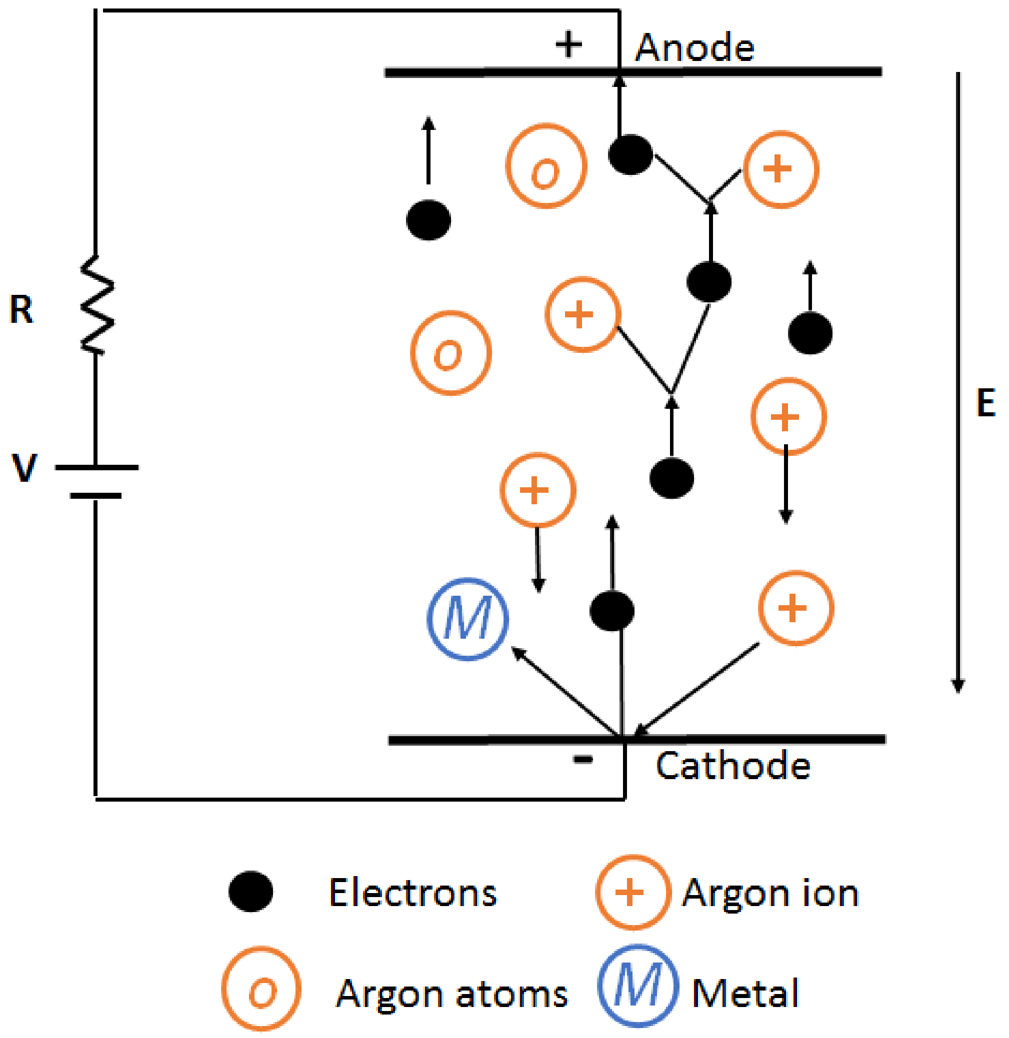
- Argon is an inert gas
- Relatively heavy gas for momentum transfer
- High energy bombardment to sputter away the surface

Such physical plasma etching can also be called sputter etching.

Sputtering Etching (Physical)

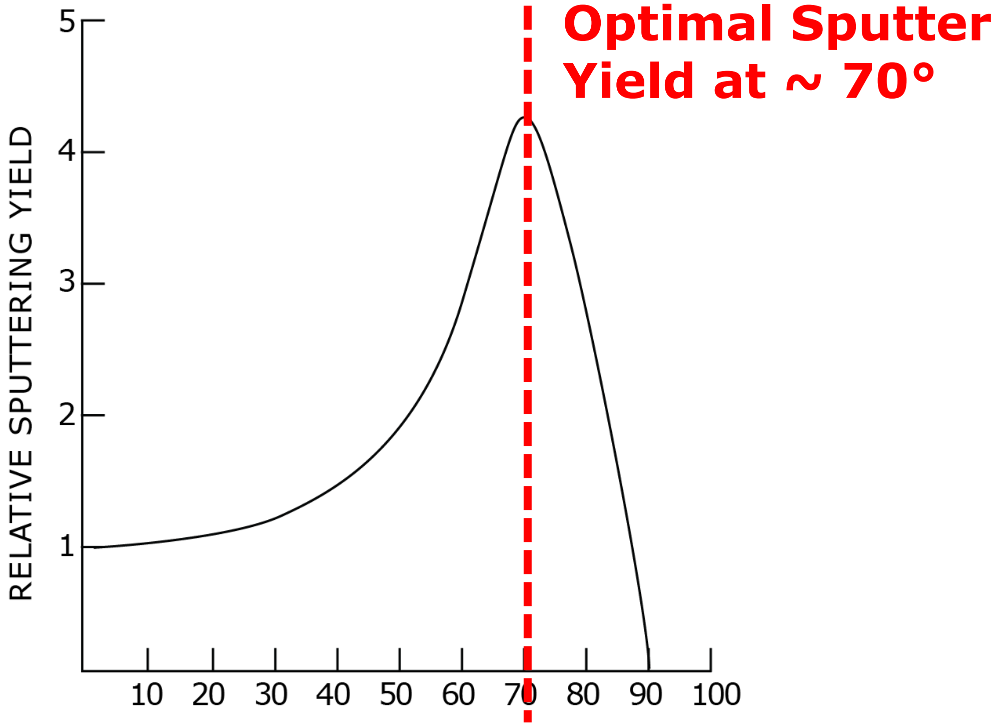
Sputter etching:

- **High particle energy** (>500eV) **noble gas ions** (Ar+) created by DC/RF power to remove the target surface
- Operating pressure: 0.01 to 0.1 torr
- Interaction is **purely physical**, with **no chemical reaction** between the gas ion and the target
- Due to the vertical bombardment of ions onto the target surface, **good anisotropy** can be achieved
- **Poor selectivity** (no differentiation between different target elements)

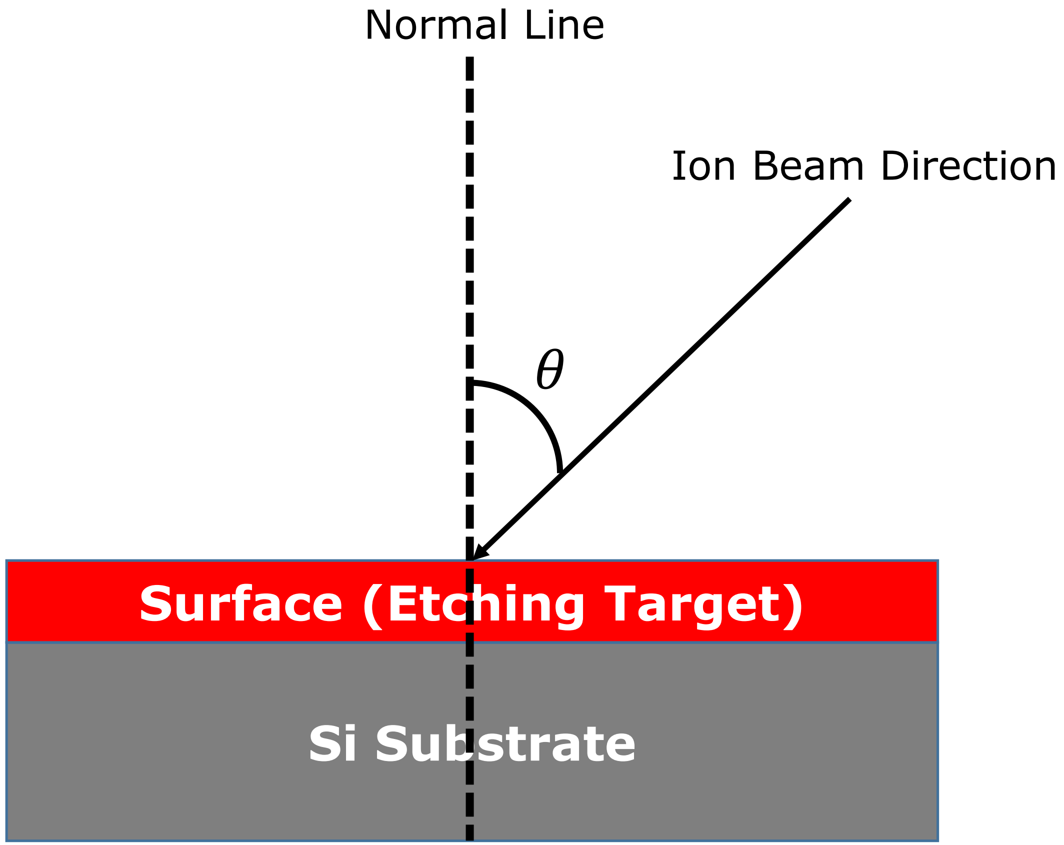


Sputter yield:

- Ratio of the **number of ejected target atoms per bombarding ion** at a given energy
- Yield depends on the angle of ion flux



A typical curve of relative sputtering yield versus incident angle, θ, of the ion flux.



Plasma Interaction with the Substrate (Outline)

Plasma interaction with the substrate:

- Physical interaction (sputter etching)
- **Physical + chemical interaction (reactive ion etching)**

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Physical + Chemical Interaction: Reactive Ion Etching

How do we achieve a combination of physical and chemical interaction between the surface and ions in a plasma etching system?

- Reactive ions (CF_4) is used to replace argon ions as the etchant

- Two etching mechanisms involved: physical and chemical mechanisms

Physical etching mechanism: Ion bombardment induced momentum transfer.

Chemical etching mechanism: Formation of volatile etch products between reactive etchants and target surface.

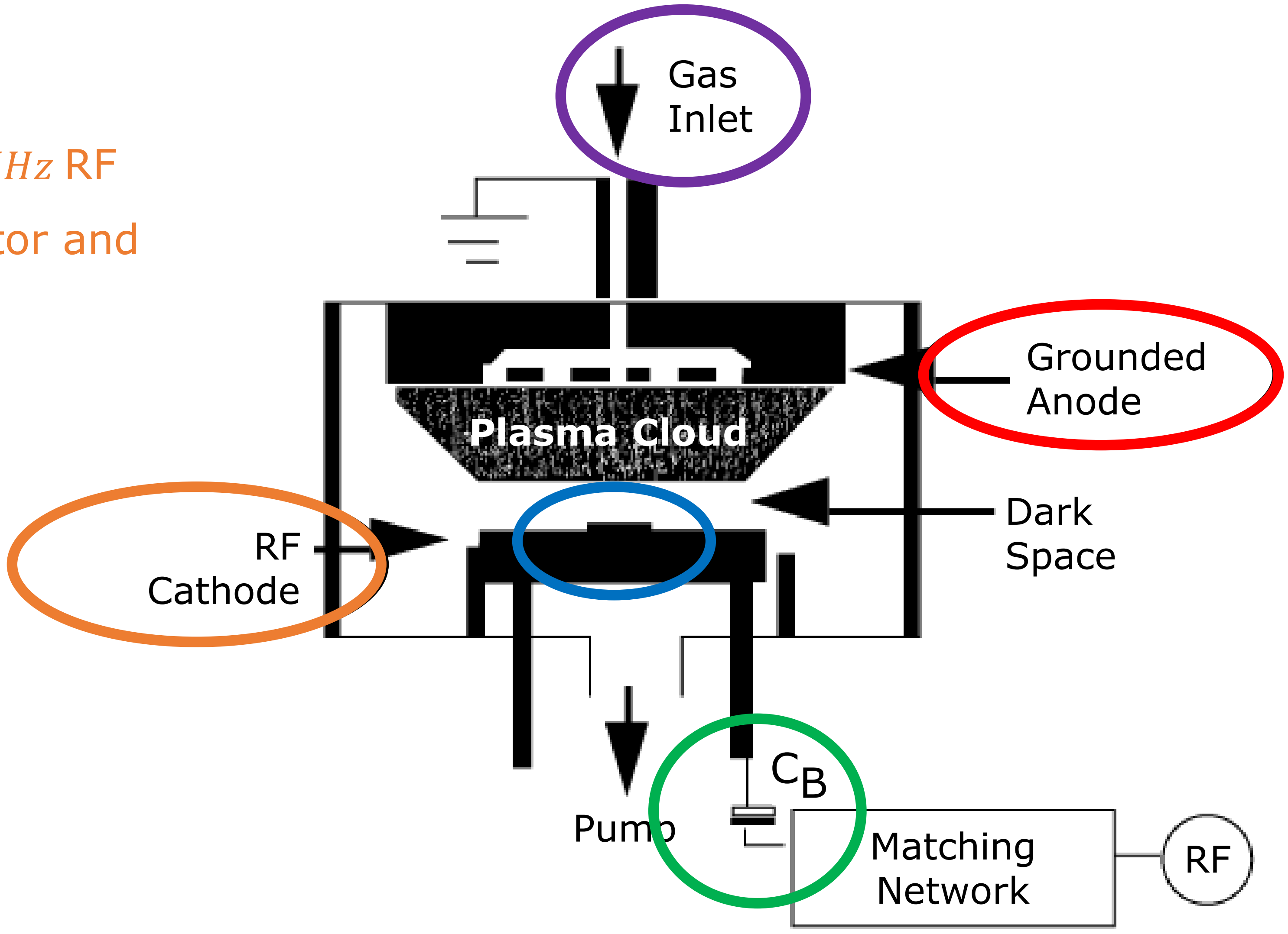
Since reactive ions are used as the etchant, such technique is usually called **Reactive Ion Etching (RIE)**.

Reactive Ion Etching: Parallel Plate RIE Reactor

- RIE uses one or more reactive gases as the etchants.
- Operating pressure: 10 mtorr – 100 mtorr to confine the plasma between two parallel plates.
- Substrates are normal to the gas flow and the RF field, resulting in a high degree of anisotropy because ions strike perpendicularly onto the surface.

Basic Theory of A Parallel Plate RIE System: Basic Components

- Two parallel electrode plates
- Top electrode plate is grounded
- Bottom electrode is driven by a $13.56\ MHz$ RF generator, connected through a capacitor and an impedance matching circuit
- The function of the capacitor is to block the electrode from discharging through the power supply
- The sample (substrate) is placed on the bottom electrode
- Etch gas is fed into the etch chamber which is kept under a vacuum evacuated environment



Basic Theory of A Parallel Plate RIE System: Operating Principles

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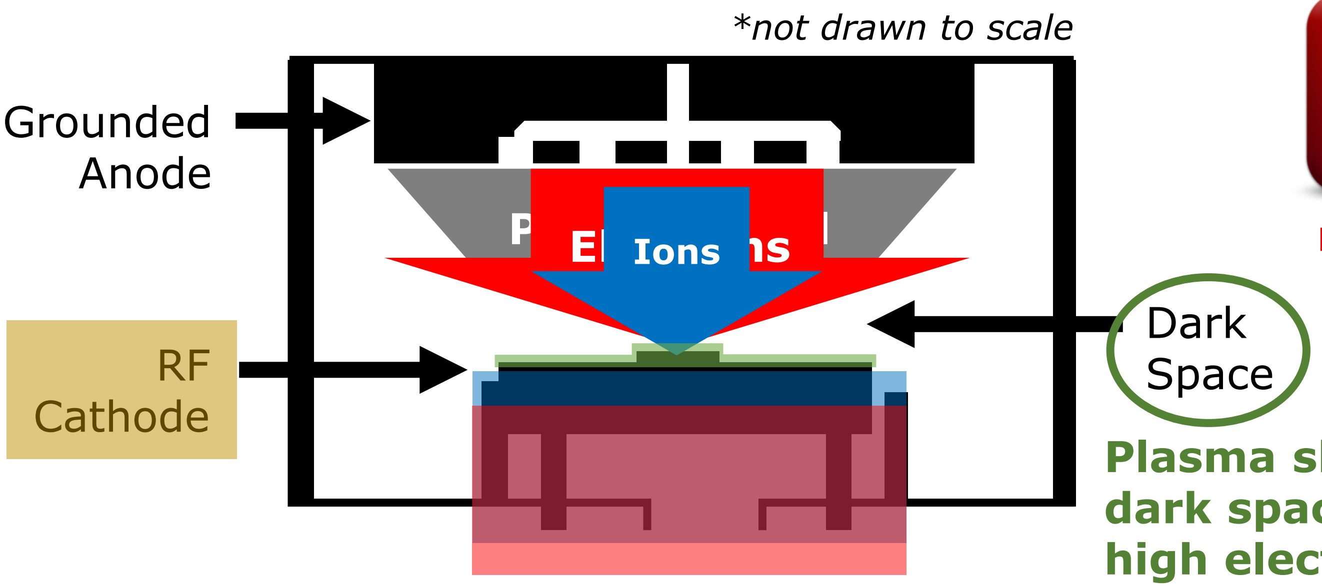
1. Electrons in chamber gained energy by applied RF power.

2. When the bottom electrode is positive, many highly mobile electrons are accelerated towards the electrode, causing a significant accumulation of negative charge.

3. When the bottom electrode is negative and heavy, immobile ions accelerate towards it. However, only relatively few of these ions strike the electrode as compared to the number of electrons in the previous cycle. Hence, in a steady state, this electrode is negative biased, and therefore is called a cathode.



Pause and observe carefully

Plasma sheath/ dark space with high electric field region

4. A high electric field region is then formed around the cathode. This region is known as the plasma sheath, or the dark space, where ion acceleration takes place before bombarding the electrode.

5. **Ions are accelerated** in dark space before bombarding the substrate.

Basic Theory of A Parallel Plate RIE System: Plasma Potential

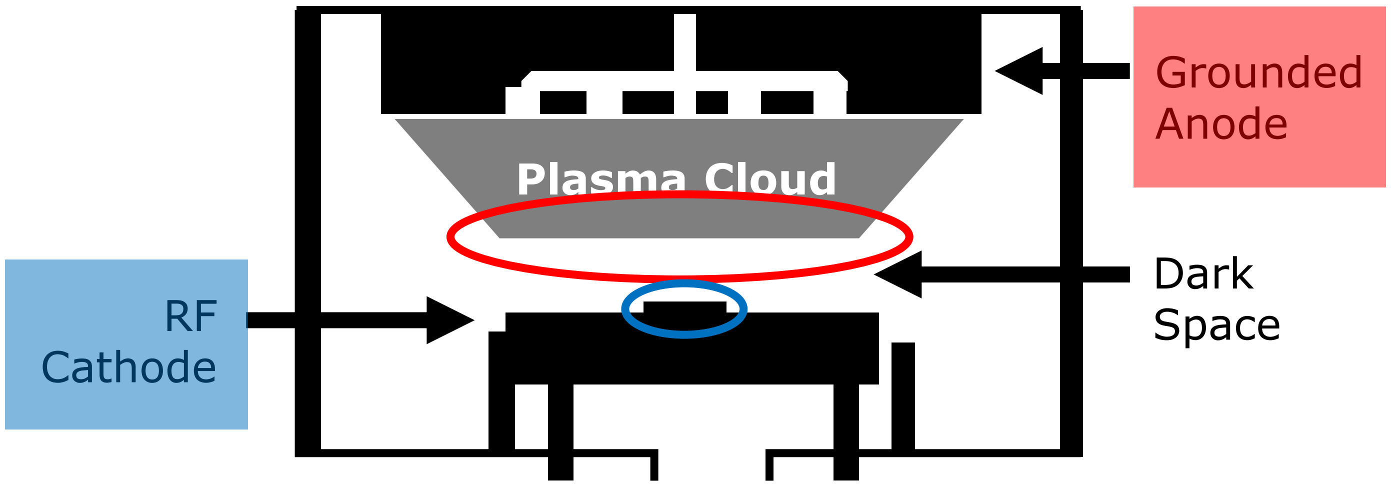
- The plasma potential is determined by the expression: $\boxed{|Vc| = Va\left(\frac{Aa}{Ac}\right)^4}$
- Vc = potential difference between the powered electrode (cathode) and the plasma
- Va = potential difference between the ground electrode (anode) and the plasma

$\frac{Aa}{Ac}$ = ratio of the respective electrode areas

Why must the anode area be bigger than the cathode area?

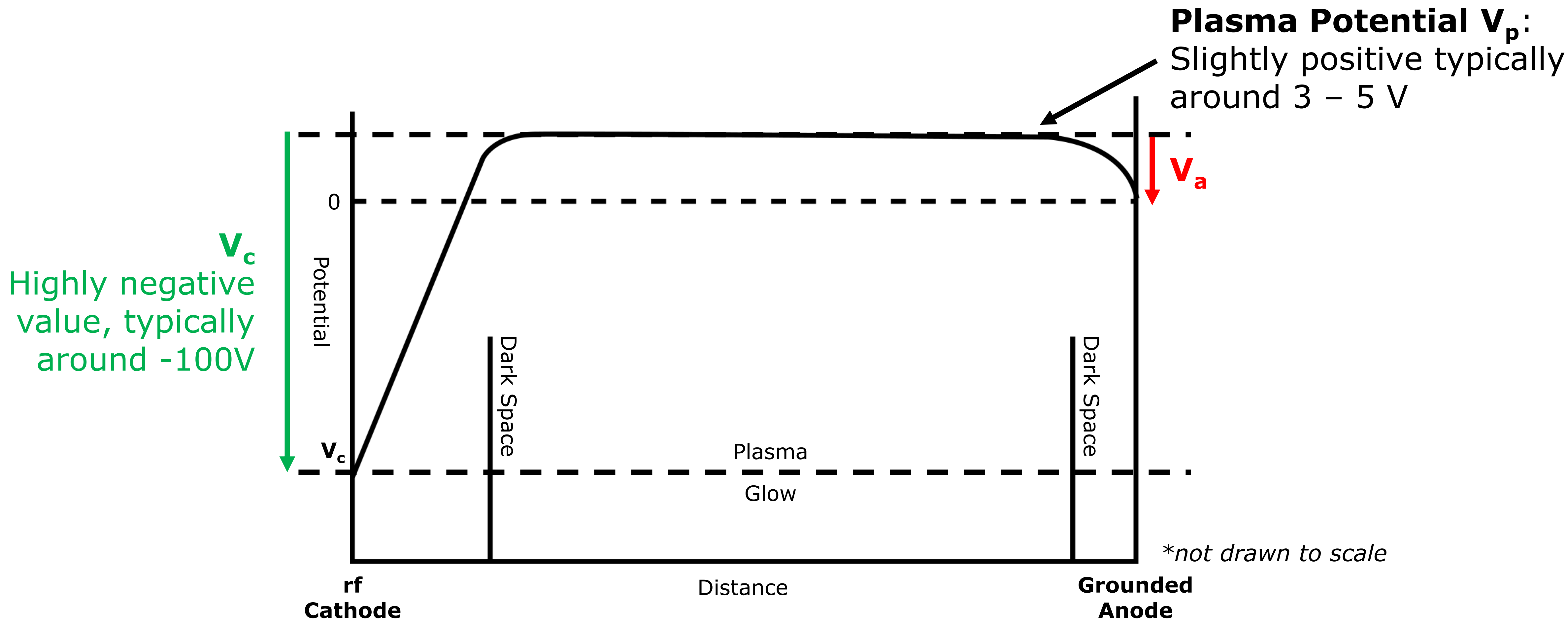
$$\uparrow |Vc| = Va\left(\frac{Aa}{Ac}\right)^{4\uparrow}$$

This will increase the energy of the bombarding ions, hence increasing the etch rate.



not drawn to scale

- The potential distribution between the electrodes is shown in the following graph:



Ion Acceleration and Physical Plasma Interaction in RIE System

- The acceleration of ions by the high field region (dark space) in RIE system yields high energy ion bombardment on the substrate, resulting in the physical etching on the substrate.

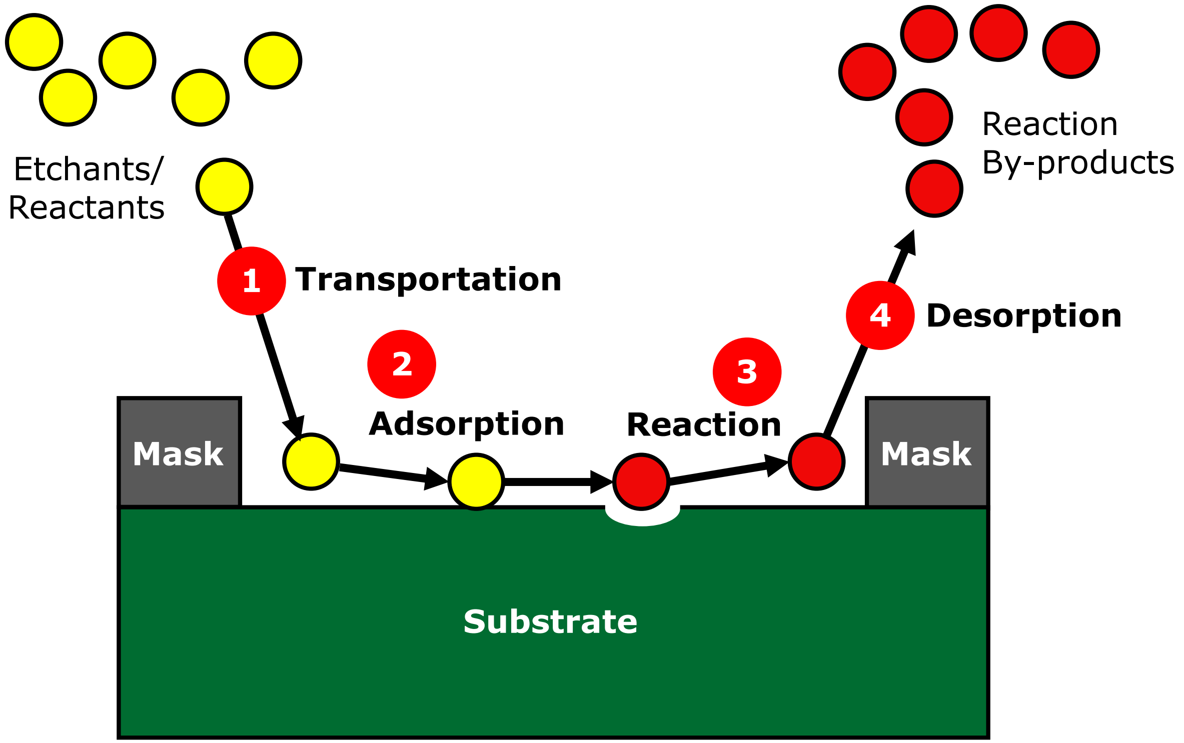
Next, let us look at the chemical interaction between reactive etchants and the substrate in RIE system.

RIE Mechanism

Four steps are involved in reactive ion etching mechanisms:

1. **Transportation**: The etchant (positive ions) accelerates to the substrate surface.
2. **Adsorption**: The etchant chemisorbs onto the surface of the substrate.
3. **Reaction** with the substrate and the formation of the volatile by- product (gaseous form).
4. **Desorption** of the volatile by-product away from the substrate.

The possible rate-limiting step in dry etching can either be step **(1), (2), (3), or (4)**.



<u>**Etch Rate-Limited Conditions**</u>

Transportation-limited condition: The rate of etchant transportation is significantly slower than the etchant-substrate reaction rate. The rate of step (1) and (4) determines the overall etch rate in dry etching.

Reaction-limited condition: The rate of etchant-substrate reaction rate is significantly slower than the rate of etchant transportation. The rate of step (2) and (3) determines the overall etch rate in dry etching.

Gases Used to Etch Films in Wafer Fabrication

Film	Etch Gases
Si	$CF_4,\ CF_4-O_2,\ CF_3Cl,\ CCl_4,\ SF_6-O_2,\ NF_3,\ ClF_3$
SiO_2	$C_2F_6,\ C_3F_8,\ CF_4-H_2,\ CHF_3$
Si_3N_4	$CF_4-O_2,\ C_2F_6,\ C_3F_8,\ CF_4-H_2$
Organics	$O_2,\ O_2-CF_4,\ O_2-SF_6$
Al	$CCl_4,\ CCl_4-Cl_2,\ BCl_3,\ BCl_3-Cl_2,\ SiCl_4$
W, WSi_2	$CF_4,\ C_2F_6,\ SF_6$

**For reference only*

- For etching of Si-based films, fluorocarbon (C_XF_Y)-based chemistry is used
- For etching of organic. films, oxygen-based chemistry is used.
- For etching of metal lines, chlorine-based or fluorine-based chemistry is used.

RIE Mechanism: Plasma Etching of Silicon/ Silicon Oxide

- In the case of RIE of SiO_2 in C_2F_6 plasma, the dissociation process may produce:

$$C_2F_6 \xrightarrow{e-dissociation} C_xF_y{}^a, C^b, F_z{}^c.$$

- Both carbon and fluorine can act as active etching species in this case, with carbon responsible for reaction with O_2 and fluorine with silicon.
- The following etching mechanisms are proposed (*ads* = *adsorption*):

Chemisorption: $$C_xF_y{}^a, C^b, F_z{}^c \rightarrow (C_xF_y)_{ads}, (C)_{ads}, (F_z)_{ads}[+electrons],$$

Reaction: $$(C_xF_y)_{ads}, (C)_{ads}, (F_z)_{ads} + SiO_2 \rightarrow w(SiF_4)_{ads}, (CO_z)_{ads},$$

Desorption: $$w(SiF_4)_{ads}, (CO_z)_{ads} \rightarrow w(SiF_4)_{gas}, (CO_z)_{gas}.$$

Where *w, x, y* and *z* here is equal to 1 or 2;

a, *b* and *c* can be either positively or negatively charged.

Plasma Etching of Silicon/ Silicon Oxide (Cont'd)

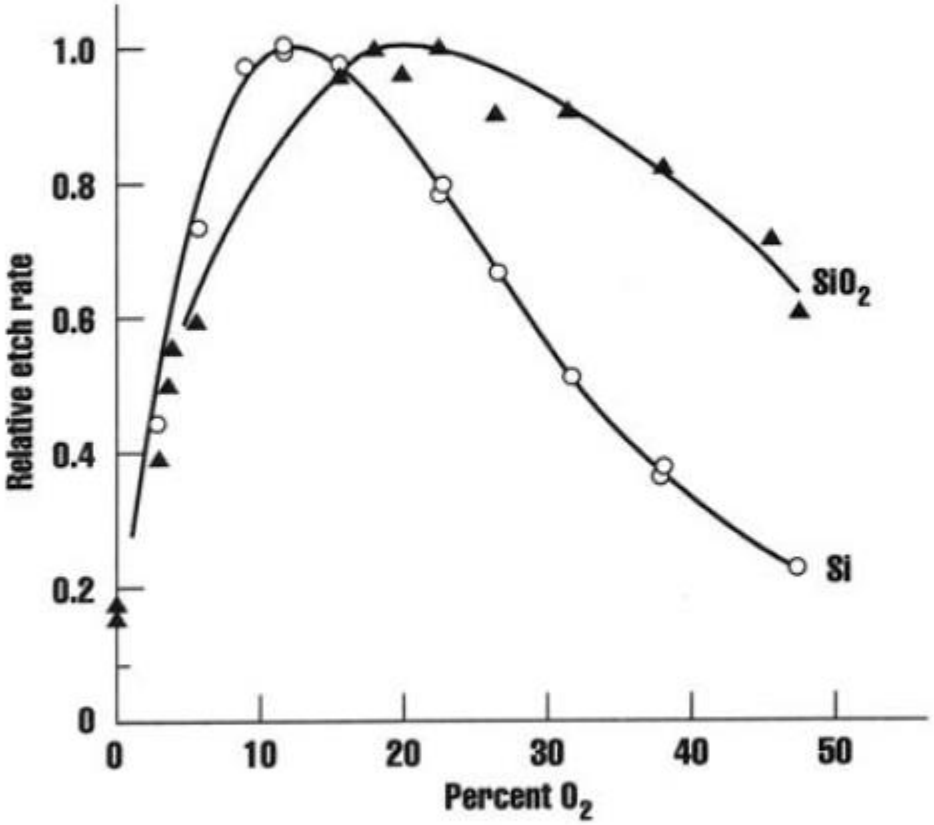
- When only CF_4 is used as the feed gas in RF plasma etch, no etching of Si or SiO_2 occurs.
- Etching starts after O_2 is added to the feed gas.
- Atomic F is the active etchant for Si and SiO_2 through the formation of the volatile SiF_4 and O_2:

$$Si + 4F \rightarrow SiF_4$$

$$SiO_2 + 4F \rightarrow SiF_4 + O_2$$

How does the O_2 content affect the etch rate?

Tailoring Gas Composition for RIE (Addition of O_2 Gas)



Etch Rate of Si and SiO_2 in CF_4 / O_2 Plasma

- Oxygen is added to CF_x plasma to increase the amount of reactive F species:

  $CF_2 + O \rightarrow COF + F$ (Highly probable due to the presence of O_2)

- Oxygen reacts with CF_3 and CF_2. Hence reducing the recombination rate of F and prevents the formation of the unreactive CF_4.

  $CF_2 + 2F \rightarrow CF_4$ (Less probable due to the above formation of **COF**)

- However, the etch rate will decrease if more O_2 is introduced, due to the dilution of CF_4 concentration.

Practice Question 1

Decide the appropriate effect in terms of increase (↑), or decrease (↓), if the electrode size of the RF generator in a plasma etch system is decreased.

a)	↑	↓	Ion energy
b)	↑	↓	DC bias
c)	↑	↓	Etch rate
d)	↑	↓	Selectivity

Pause and try out this question

Practice Question 2

What type of gas chemistry is generally chose for silicon plasma etching?

a) Fluorocarbon
b) Hydrocarbon
c) Silicon/carbon-based gases
d) Noble gases

Pause and try out this question

Practice Question 3

Why does the addition of O_2 change the etch rate in a CF_4-based plasma etch.

Oxygen is added to CF_4 plasma to increase the amount of reactive F species.

(O reacts with CF_3 and CF_2 and hence reduces the recombination of F)

Pause and try out this question

Factors Controlling Plasma Etch Rate

Factors Controlling Plasma Etch Rate

- Steady state pressure
- Average residence time
- Throughput/ gas load

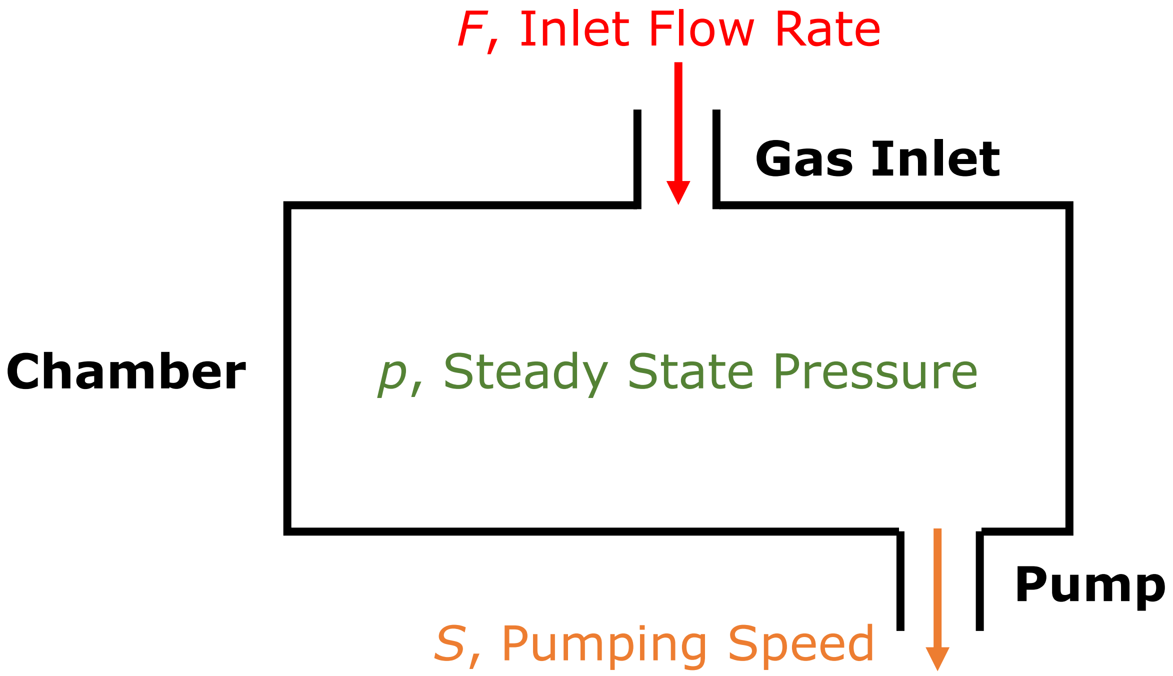
Factors Controlling Plasma Etch Rate: Steady State Pressure

The **steady state pressure (p)** in the system can be expressed as:

$$\boxed{p = \frac{F.760}{S} Torr}$$

Where F and S are the inlet flow rate and pumping speed in the same units (litre/second) $(1\ atm = 760\ torr)$.

Pumping speed S measures the volume of gas passing through the pump per second.

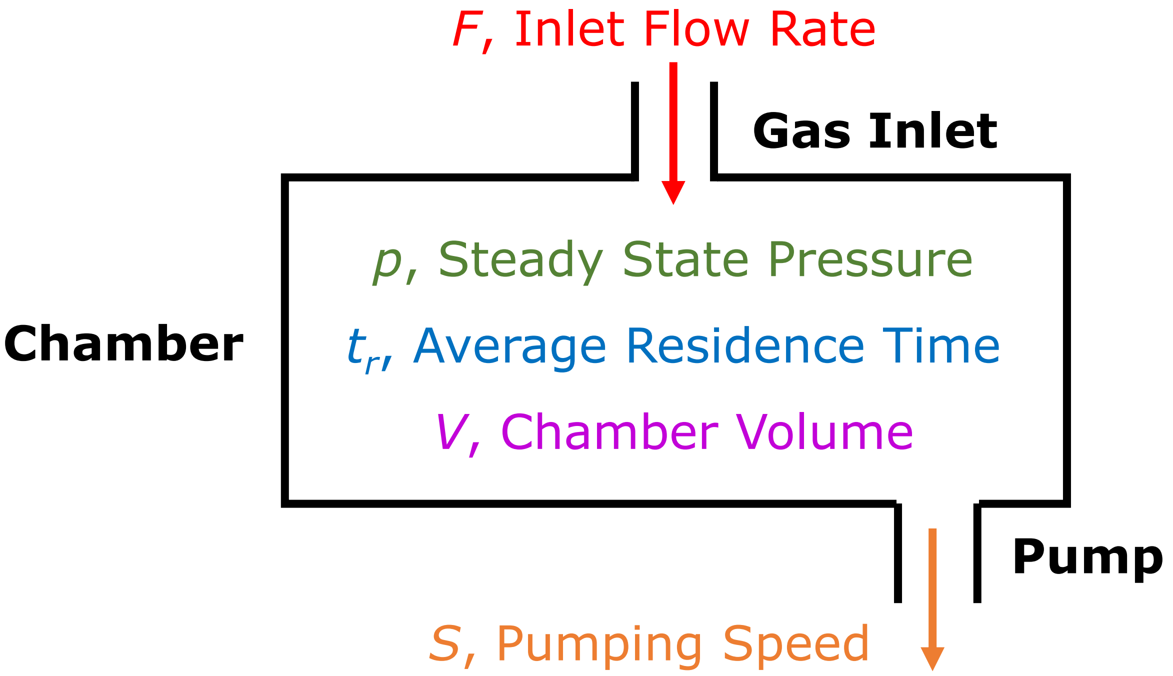


Flow rate and residence time:

- The **flow rate (F)** of the feed gas and the **reactor pressure (p)** determine the **residence time (t_r)** of the average molecule of the plasma.
- Residence time of a gas molecule is the **average time it remains in the process chamber before being pumped away.**
- Average residence time, t_r (in seconds)

$$t_r = \frac{V.p}{760.F}$$

Where V is the chamber volume.



By substituting: $p = \frac{F.760}{S} Torr$

Into: $t_r = \frac{V.p}{760.F}$

We obtain: $t_r = \frac{V}{S}$

- For a constant S, t_r does not vary with the changing pressure brought about by the change in flow rate (F). Hence, we should not assume that increasing F will increase the residence time and the corresponding etch rate.

Factors Controlling Plasma Etching Rates: Throughput/ Gas Load

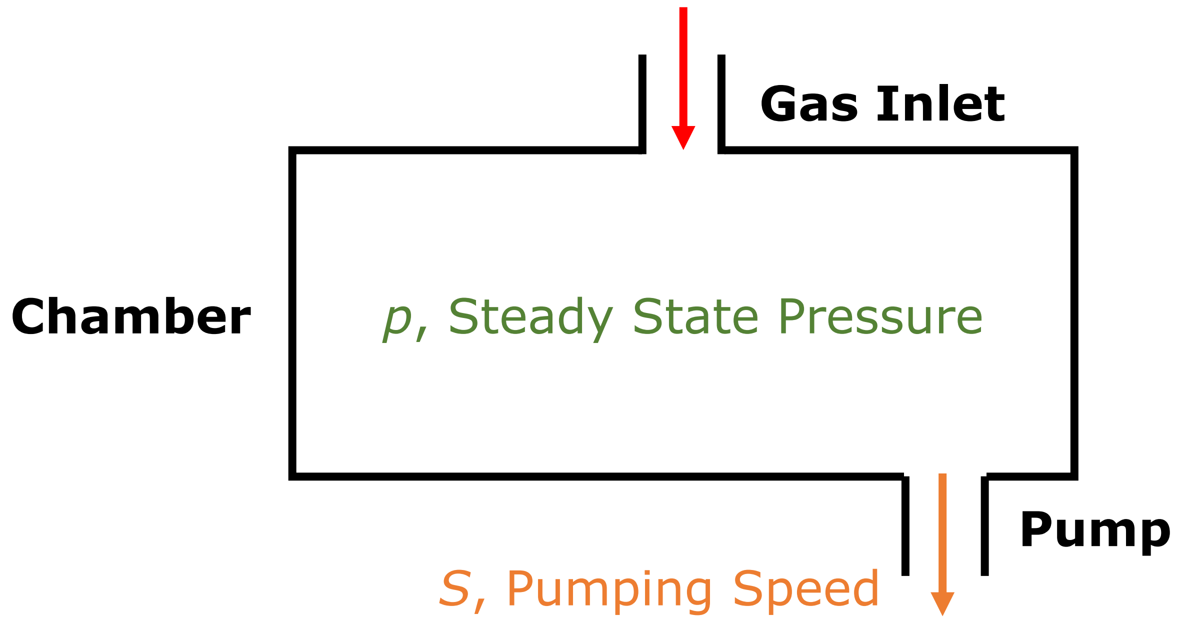
- **Throughput** or the gas load Q, equals to pS (**pressure times the pumping speed**):

$$Q = pS$$

- Hence, it is **proportional to the flux of molecules** passing through the pump.
- Units for throughput is torr litre/second (lt/s), but standard cc per minute (sccm) is more commonly used. Standard referring to standard temperature (°C) and standard pressure (1 atm, or 760 torr)

$$1 \text{ sccm} = \frac{10^{-3}[litres]x760[torr]}{60[s]} = 0.01266$$

1 torr litre / s = 78.9 sccm



Practice Question

A conventional 13.56 MHz parallel plate reactive ion etching (RIE) system was deployed to etch SiO_2 film with C_2F_6 plasma. The cathode plate of the RIE system has a diameter of 20 cm and a chamber volume of 20 litres. The etching was carried out at a cathode potential (V_c) of -450 V with a C_2F_6 flow rate of 25 m per second and a radio-frequency (RF) power of 100 W. The average residence time of the plasma is 1 second.

Pause and try out this question

Determine:

a) The power density of this process
b) The anode diameter, assuming the anode potential (Va) of 15 mV
c) The etch pressure of the chamber
d) The speed of the pump
e) Suggest ways to improve etch rate of the system

Practice Question

a) The power density of this process:

Power density = RF power/ cathode area

$$\frac{100W}{\pi\left(\frac{20cm}{2}\right)^2} = 0.318\,W/cm^2$$

b) The anode diameter, assuming the anode potential (V_a) of 15 mV:

$$|Vc| = Va\left(\frac{Aa}{Ac}\right)^4 \qquad \sqrt[4]{\frac{V_c}{V_a}}A_c = A_a \qquad \sqrt[4]{\frac{450}{0.015}}20^2 = (D_a)^2$$

$$D_a = 72.5\ cm$$

Practice Question

c) The etch pressure of the chamber:

$$t_r = \frac{V.p}{760.F}$$

$$p = \frac{760(0.025)(1)}{(20)}$$

$$p = 0.95\,Torr$$

d) Calculate the speed of the pump:

$$t_r = \frac{V}{S}$$

$$S = \frac{20}{1} = 20\,litre/s$$

e) Suggest ways to improve etch rate of the system:

- Use higher RF power/ higher cathode potential
- Increase anode area

Plasma Damage and General Issues in Etching

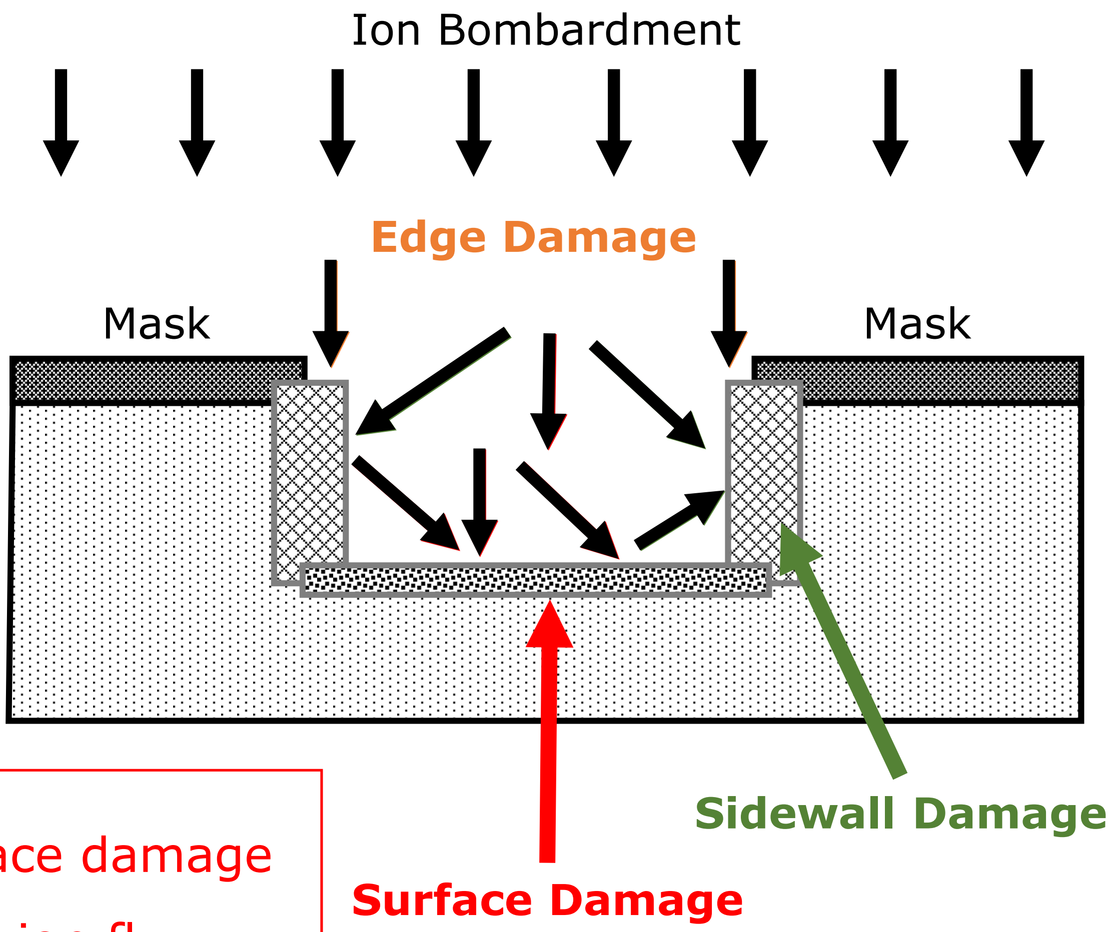
Plasma Damage

Plasma damage:

- High ion fluxes of $\mathbf{10^{15}}\ \boldsymbol{ion/cm^2}$ are delivered at energies of **300 to 700 eV** in plasma etching.
- The **high ion bombardment energy** causes **damage to the material**, and considerable **degradation** to the electrical and optical properties of devices.
- The degree of damage is **highly dependent on the accelerating potential and the mass of the ion species**.

Plasma Damage

For materials near to patterned edges, the rebound ions, sputtered material and chemical reactants may also cause damage to the edge.



Sidewalls suffer damage from the direct bombardment by directional ions and reactive radicals, and possibly deposition and ricocheting particles from the bottom surface.

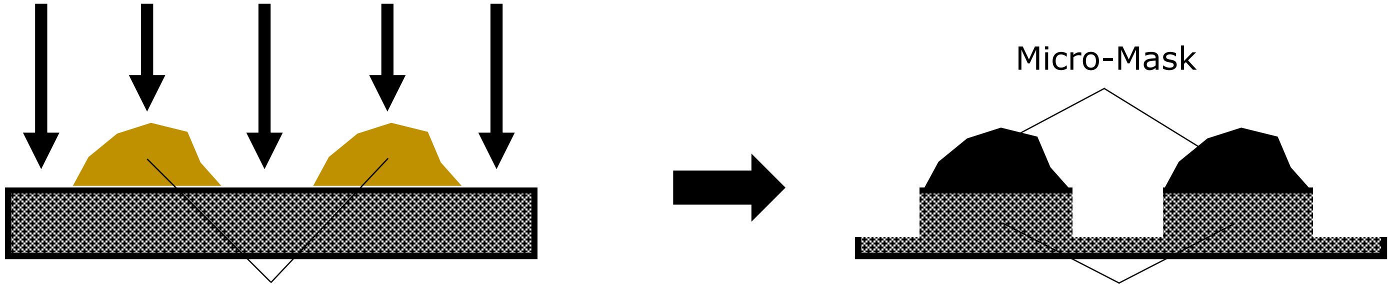
The principal source of surface damage may result directly from the ion flux.

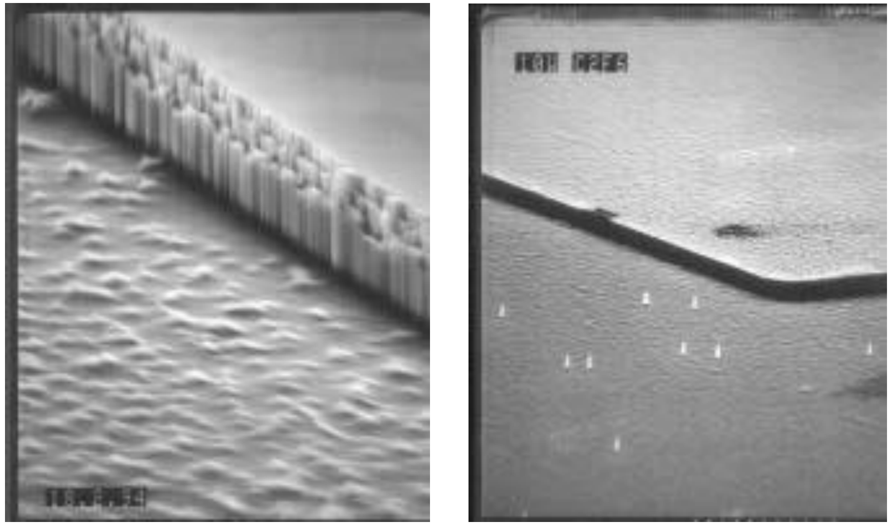
Plasma Damage

- Plasma damage has been observed to:
  a) Reduce the carriers mobility of semiconductors
  b) Deactivate dopants
  c) Increase the resistivity
- Annealing of samples using a RTP (Rapid Thermal Processor) or furnace at temperatures in the range of 450 to 800°C for a few seconds to a few minutes may partially or totally remove the damage.

Surface Contamination

- Contaminants such as fingerprints, dust particles, etc., may contaminate the semiconductor by leaving behind non-volatile by-products.
- These contaminants may deposit on the semiconductor surface and act as micro masks during the etching of the semiconductor.
- These micro-masks could inhibit the subsequent etching of the semiconductor and also cause the etched surface to be rough.





(a) (b)

a) *A rough surface due to contamination.*
b) *A reasonably clean surface has been obtained from the sample exposed to low power* C_2F_6.

General Issues Associated with Etching

- **Uniformity**: Across wafer
- **Etching rate**: Fast enough to be practical, and slow enough to be controllable
- **Selectivity**: Should be high
- **Anisotropy**: Directional dependence of etch rate
- **By-products**: Volatile or otherwise, easily removed

Practice Question 1

Define the following terms:

(a) Etch selectivity

(b) Anisotropy in etching

Why are they important in microfabrication?

Pause and try out this question

Practice Question 1

a) Etch selectivity:

- **Selectivity is the ratio of the etch rates between different materials, especially the material that needs to be etched compared with the material that we do not want to remove**.
- Smaller geometries require thinner layers of resist. High selectivity is necessary in most advanced processes to ensure critical dimension and profile control. The smaller the feature size of the process, the higher selectivity is needed.

b) Anisotropy in etching:

- **Anisotropy in etching is the ratio of vertical etching rate over horizontal etching rate**.
- With smaller geometries, the etch profiles have higher aspect ratios. It is difficult to get etchant chemicals in and reaction by-products out of the high aspect ratio openings. To overcome this, it is desirable to have directionality to drive the plasma into the high aspect ratio openings.

Comparison Between Wet and Dry Etching

Wet Etching	Dry Etching
Simple, inexpensive equipment	Elaborated equipment required (Higher cost)
Large batch process possible	
No proper etchant for specific materials (Si_3N_4)	Anisotropic etching (High downwards etching)
Minimum etching dimension is relatively large	Minimum etching dimension is small
Undercutting in isotropic etching	Less lateral etching, less undercutting

Pause and read carefully

Lesson Summary - Etching

Dry Etching

- Dry etching uses ionic (plasma) etchants to etch away the target materials.
- Plasma generation involves ionisation, recombination, excitation, relaxation and dissociation processes.
- Sputter etching uses inert ions (argon), whereas reactive ion etching uses reactive ions (C_2F_6).
- The operation of an RIE system is governed by the plasma potential and the area of the electrodes.
- Important parameters in dry etching include etchant gas flow rate, average residence time of the etchant gas, steady state pressure of the system chamber, and pumping speed of the etching system's pump.
- Plasma etching may cause sidewall damage, surface damage, and edge damage on the substrate.

Practice Question 2

Determine if the statements below about dry etch processes are either true or false

Pause and try out this question

a) Etch profiles of directional etch systems are generally isotropic. False
b) Dry etch provides good CD (critical dimension) control. True
c) Dry etch creates minimal resist lifting. True
d) Etch uniformity of dry etch is inferior to wet etch. False
e) Dry etch processes use less chemicals than wet etch processes. True
f) Plasma-induced damage is more common in wet etch processes. False
g) The complexity and cost of dry etch equipment is higher. True

Practice Question 3

Pause and try out this question

a) Describe the basic components of a plasma dry etch system.

b) Explain what is a reactive plasma and how it is generated in a DC glow discharge?

c) What are the advantages and disadvantages of reactive ion etching versus sputter etching? Cite an example of when one might want to use sputter etching rather than RIE?

d) In the plasma of a RIE system, consider an argon atom that is ionized during a collision in the plasma. Over a given mean free path, one of the particles will achieve a much higher speed. Explain, with a diagram, how does that affects the potential (voltage) of the plasma relative to that of either electrode?

e) What are the general issues associated with etching?

Practice Question 3

a) The basic components of a dry etch system include a reaction chamber where the etching takes place, an RF power supply to ignite the plasma, a gas flow control system and a vacuum system to remove etch-by products and gases.

b) Reactive plasma describes a discharge process in which ionization and fragmentation of gases take place and produce chemically reactive species. Such species are reactive both in gas phase and with solid surface. These reactive species are used to interact and etch or remove the surfaces that are not masked by the lithography pattern. Electron collision are inelastic and will result in ionized species or excited neutral species in the plasma via ionization, relaxation, recombination, etc

c) RIE gives more selectivity; sputtering etches almost everything, at about the same rate. Use sputter etching when etching multilayer stack of different materials on the substrate, when etching substrate a little doesn’t matter.

Pause and read carefully

Practice Question 3

d) Over a given mean free path, electron achieves a much higher speed and thus travels much farther than the ion. Since most of these particles are created in the plasma, more electrons than ions leave the plasma and as a result, the plasma is at a positive potential relative to either electrode.

e)

- **Uniformity**: Across wafer
- **Etching rate**: Fast enough to be practical, and slow enough to be controllable
- **Selectivity**: Should be high
- **Anisotropy**: Directional dependence of etch rate
- **By-products**: Volatile or otherwise, easily removed

Pause and read carefully