Plasma Etching
Outline

- **Plasma vs. Wet Etching**
- **The Plasma State**
  - **Plasma composition, DC & RF Plasma**
- **Plasma Etching Principles and Processes**
- **Equipment**
- **Advanced Plasma Systems**

Terminology

Etching - the process by which material is removed from a surface

Mask Layer - Used to protect regions of the wafer surface. Examples are photoresist or an oxide layer

Wet Etching - substrates are immersed in a reactive solution (etchant). The layer to be etched is removed by chemical reaction or by dissolution. The reaction products must be soluble and are carried away by the etchant solution.

Dry Etching - Substrates are immersed in a reactive gas (plasma). The layer to be etched is removed by chemical reactions and/or physical means (ion bombardment). The reaction products must be volatile and are carried away in the gas stream.

Anisotropic - etch rate is not equal in all directions.

Isotropic - etch rate is equal in all directions.

Selectivity - the ratio of etch rate of film to etch rate of substrate or mask.

Aspect Ratio - ratio of depth to width of an etched feature.

Why Plasma Etching?

Advanced IC Fabrication with small geometries requires precise pattern transfer

Geometry in the < 1.0 micrometer range is common

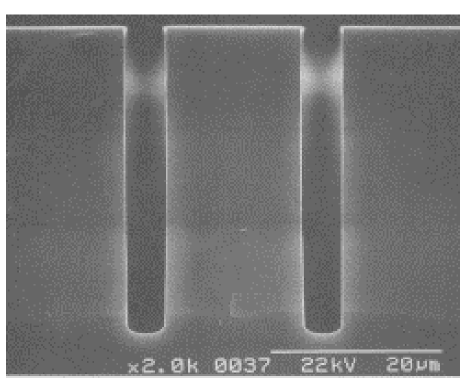
Line widths comparable to film thickness

Some applications require high aspect ratio

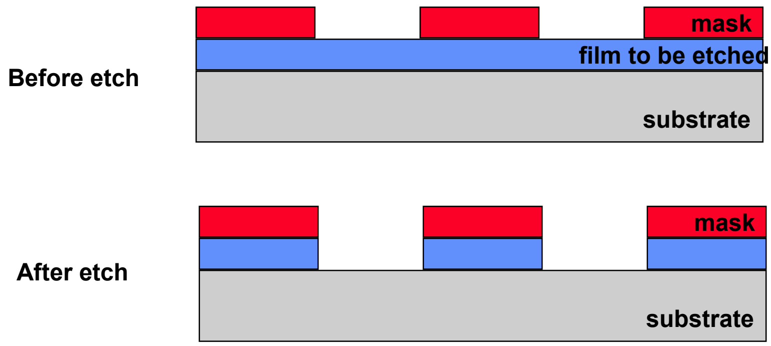
Some materials wet etch with difficulty

Disposal of wastes is less costly

Anisotropic Etch, High Aspect Ratio



Ideal Etching Process



No process is ideal, but some plasma etches are close.

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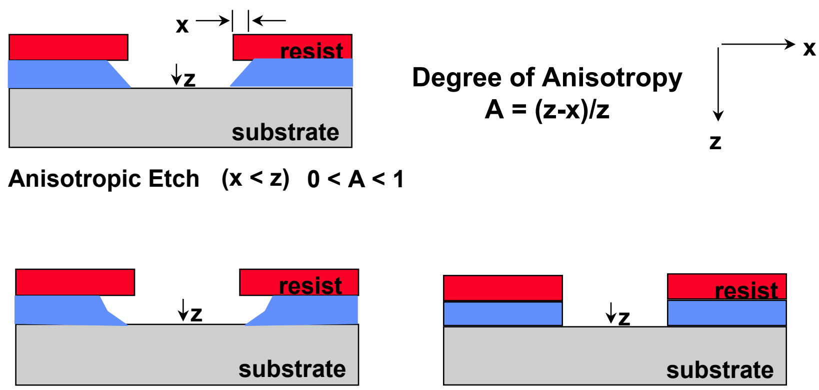
Directionality of Etching



Anisotropic Etch (x < z) 0 < A < 1

Isotropic Etch (x = z) A = 0

Vertical Etch (x = 0) A = 1
(Perfectly anisotropic)

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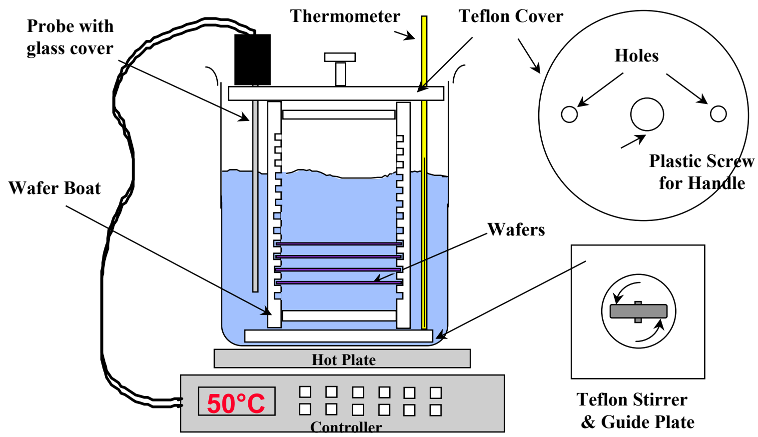
Wet Etching



Generally Wet Etching is Isotropic

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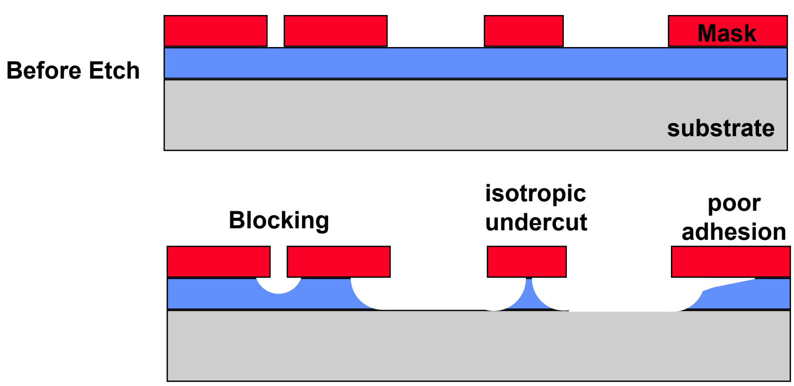
Wet Etching Problems



After Isotropic Etch

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Wet Etching Characteristics

- **Advantages:**
  - **Simple equipment**
  - **High throughput (batch process)**
  - **High selectivity**
- **Disadvantages:**
  - **Isotropic etching leads to undercutting**
  - **Uses relatively large quantities of etch chemicals, must immerse wafer boats, must discard partially used etch to maintain etch rate**
  - **Hot chemicals create photoresist adhesion problems**
  - **Small geometries difficult, line with > thickness, etch block caused by surface tension**
  - **Critical Etch time, dimensions change with etch time, bias develops**
  - **Chemical costs are high**
  - **Disposal costs are high**

Wet Etch Chemistries

- **Silicon (Nitric Acid and Hydrofluoric Acid and water)**
  - **Si +HNO3 + H2O --> SiO2 + HNO2 +H2 (+6HF) --> H2SiF6 + HNO2 + 2H2O + H2**
- **SiO2 (HF Water and NH4F)**
  - **SiO2 + 6HF --> H2 +SiF6 +2H2O**
- **Si3N4 (Dilute Hot Phosphoric (180C) H3PO4)**
- **Al (HPO4) +HNO2 +Acedic CH3COOH + H2O**
  - **Nitric oxidizes Al --> Al2O3 and HPO4 dissolves Al2O3**

Dry Etching Characteristics

- **Advantages:**
  - **No photoresist adhesion problems**
  - **Anisotropic etch profile is possible**
  - **Chemical consumption is small**
  - **Disposal of reaction products less costly**
  - **Suitable for automation, single wafer, cassette to cassette**
- **Disadvantages:**
  - **Complex equipment, RF, gas metering, vacuum, instrumentation**
  - **Selectivity can be poor**
  - **Residues left on wafer, polymers, heavy metals**
  - **Particulate formation**
  - **CFC's**

Dry Etching Mechanisms

- **Generate etchant species**
- **Diffusion to Surface**
- **Adsorption (and Migration)**
- **Reaction**
- **By-product Desorption**
- **Diffusion of By-product to Bulk Gas**

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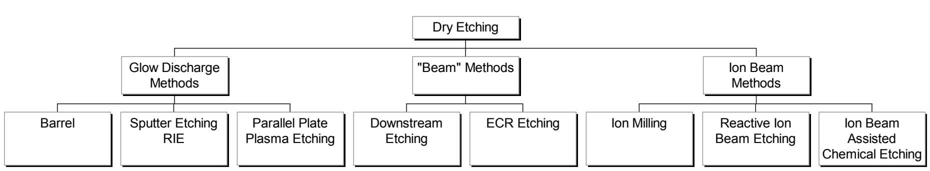
Dry Etching Methods

- **Dry Etching -- uses gas reactant species to etch film**
  - **Plasma Etching -- typically high pressure, no ion bombardment (substrate placed on grounded electrode)**
  - **Reactive ion etching -- typically lower pressures, ion bombardment (substrate placed on powered electrode**
  - **Ion beam methods -- plasma is generated in a separate chamber and ions are accelerated towards the substrate (independently control flux of radicals and ions)**
  - **Beam methods -- plasma is generated in a separate chamber and mainly neutrals active species (radicals) are directed towards substrate.**

Dry Ethcing Nomenclature



Pressure Range

0.2-2.0 Torr   0.01-0.2 Torr   0.1-1.0 Torr 10^{-3}-10^{-4} Torr 10^{-4}-10^{-1} Torr

Ion Energy

low   high   minimal   High but adjustable

Definitions

- **<u>Plasma</u> - partially ionized gas containing an equal number of positive and negative charges, as well as some other number of none ionized gas particles**
- **<u>Glow discharge</u> - globally neutral, but contains regions of net positive and negative charge**
- Most thin film processes utilize glow discharges, but “plasmas” and “glow discharges” are often used interchangeably

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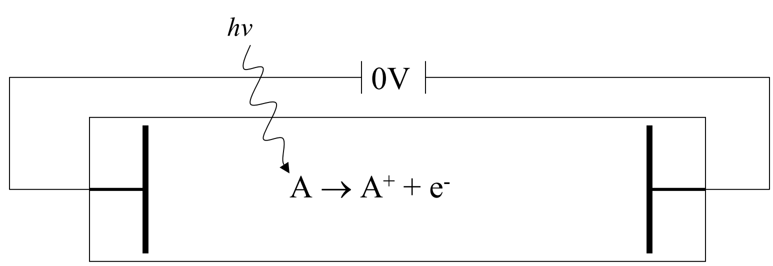
DC Glow Discharge

- **Before application of the potential, gas molecules are electrically neutral and the gas at room temperature will contain very few if any charged particles. Occasionally however, a free electron may be released from a molecule by the interaction of, for example, a cosmic ray or other natural radiation, a photon, or a random high energy collision with another particle.**



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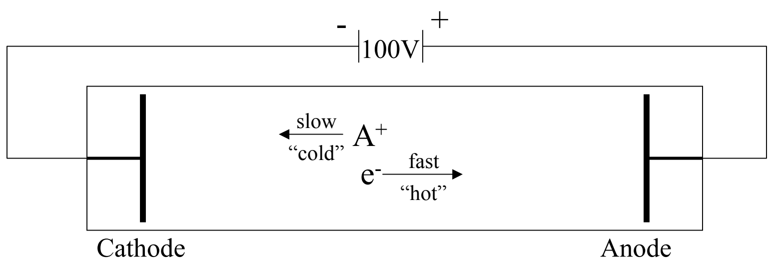
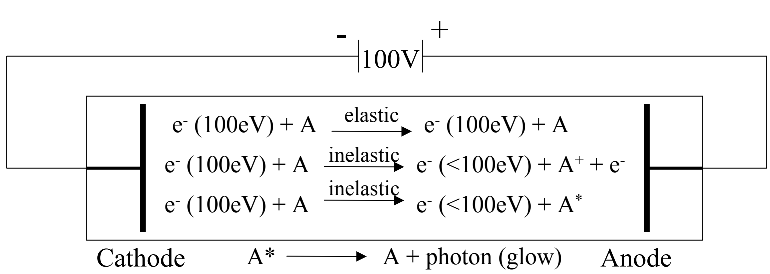
DC Glow Discharge

- **When a large voltage is applied between the electrodes, say 100 V/cm, any free electrons which may be present are rapidly accelerated toward the anode. They quickly attain high velocity (kinetic energy) because THEY HAVE SUCH LOW MASS. Since kinetic energy can be related to temperature, the electrons are "hot" - they achieve extremely high temperatures because of their low mass, in an environment of heavy, slow-moving "cold" gas molecules.**



DC Glow Discharge

- **Electrons begin to collide with gas molecules, and the collisions can be either elastic or inelastic.**
  - **Elastic collisions deplete very little of the electron's energy and do not significantly influence the molecules because of the great mass difference between electrons and molecules: Mass of electron = 9.11 e-31 Kgm, Mass of Argon = 6.64e20 Kgm.**
  - **Inelastic collisions excite the molecules of gas or ionize them by completely removing an electron. (The excitation - relaxation processes are responsible for the glow)**



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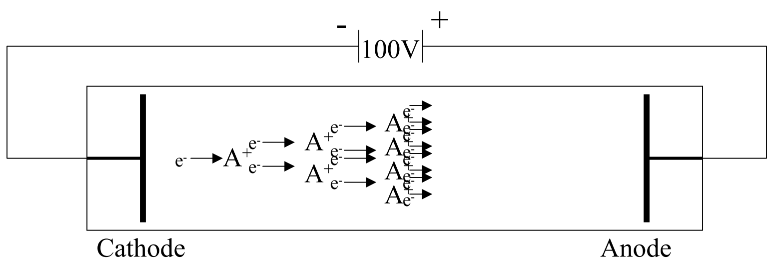
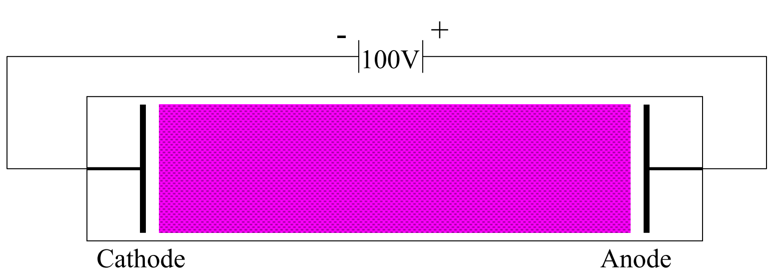
DC Glow Discharge

- **Newly produced electrons are accelerated toward the anode and the process** cascades **(Breakdown).**



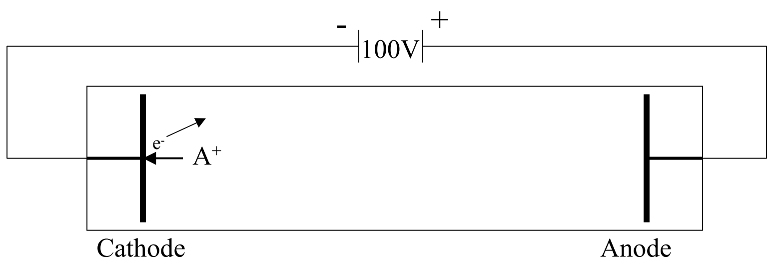
DC Glow Discharge

- **With sufficient voltage, the gas rapidly becomes filled with positive and negative particles throughout its volume, i.e. it becomes ionized.**



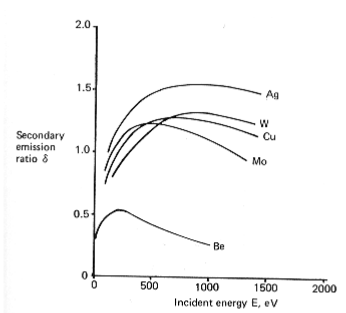
DC Glow Discharge

- **Positive ions are accelerated toward the negative electrode (cathode). Collision with the cathode causes the emission of** secondary electrons **which are emitted from the cathode into the plasma.**

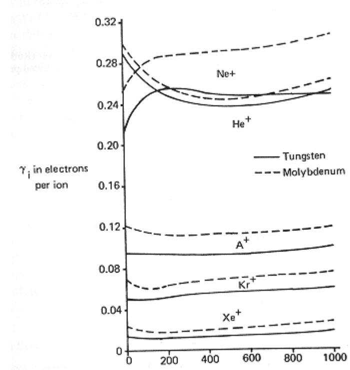


Secondary Electron Coefficient

- **Secondary Electron Coefficient (δ) vs Incident <u>Electron</u> Energy**

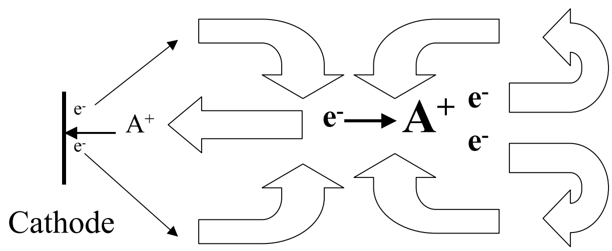


- **Secondary Electron Coefficient (γ_i) vs Incident <u>Ion</u> Energy**



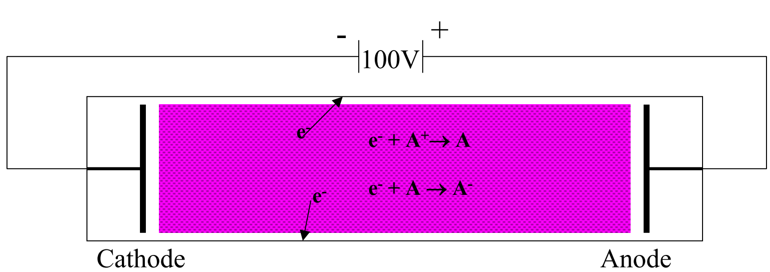
DC Glow Discharge

- **Free electrons from secondary emission and from ionization are accelerated in the field to continue the above processes, and a steady state self-sustaining discharge is obtained.**



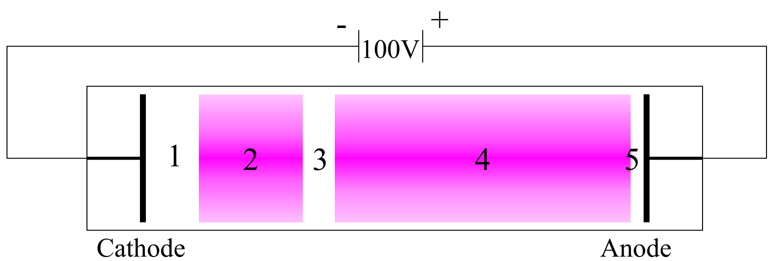
DC Glow Discharge

- **Electrons are lost by: (a) Drift and diffusion to the chamber walls, (b) recombination with positive ions, (c) attachment to neutral molecules to form negative ions.**

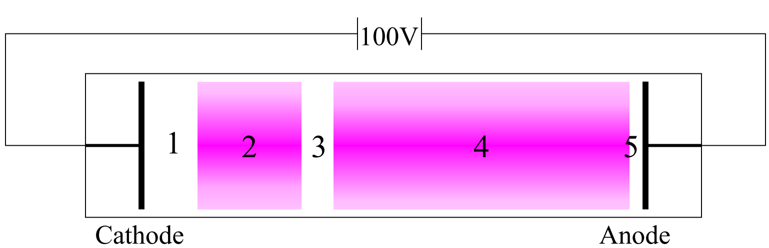


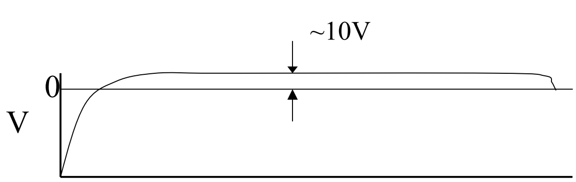
DC Glow Discharge Regions

- **The glow discharge, overall, must always remain neutral, although portions of it may be charged negatively or positively.**
- **Glow Discharge Regions**
  - **1 -- Cathode Dark Space (Crooke's Dark Space)**
  - **2 -- Negative Glow**
  - **3 -- Faraday Dark Space**
  - **4 -- Positive Column**
  - **5 -- Anode Dark Space**



Current and Potential Distributions in a DC Glow Discharge





Most of the voltage drop is across the cathode dark space

DC versus RF Plasmas

- **Insulating materials will not sustain a plasma**
  - **Ion current charges the insulator positively and ultimately extinguishes the plasma (ie. Can not bleed off charge)**
- **Use rf power to deposit insulating materials**

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RF Plasma

- **At frequencies > 100kHz electrons respond and ions do not**
  - **Typical rf frequency - 13.56 MHz (designated by FCC)**
- **High mobility of electrons causes a dc "self bias" to develop on target after the first ac cycles(~1/2 rf peak-to-peak)**

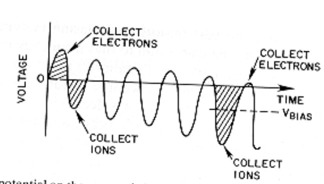

Fig. 9. The potential on the powered electrode of Fig. 8b as a function of time for the first several rf cycles.

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The RF Plasma

1. AC voltage overcomes the problem of charge which accumulates on a dielectric in the DC system.

The positive charge which accumulates due to ion bombardment during one half of the AC cycle can be neutralized by electron bombardment during the next half cycle. The frequency of AC must be high enough so the half period will be shorter than the charge-up time of the dielectric. Although this time will vary due to conditions and dielectric materials, for most applications the frequency must be above **100 KHz.**

2. Although there are a number of differences in the practical operation of AC plasmas, the principles of DC glow discharges can be applied to AC. One simply considers the AC as a rapidly reversing DC plasma.

At low frequency both electrons and ions can follow the field, so that a glow discharge is the same as DC, except that the polarity reverses twice each cycle. At high frequency the massive ions cannot respond to the frequency changes, whereas electrons can. By far the most common RF frequency used is 13.56 MHz, allowed by the FCC.

The RF Plasma, cont'd

3. At high frequency the electrodes experience a high electron current in the first few cycles, and become charged negatively with respect to the plasma.

4. This negative charge attracts a cloud of ion (ion sheath) around each electrode, with the electrons being restricted to oscillation in the region between the sheaths. The electrons create more ions and electrons by collisions in this region, whereas the ions in the sheath provide a continuous bombardment of the electrodes.

Magnetrons

- **Magnetic fields change trajectory of electrons in a magnetic field**
  - **Imposing a magnetic field effectively increases the distance an electron travels, this in turn increases the ionization rate (and subsequently the sputtering rate)**

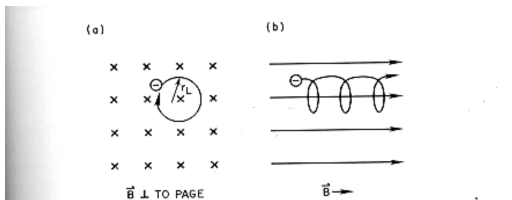

Fig. 23. (a) The motion of an electron in a magnetic field oriented perpendicular to the page. (b) The same motion viewed from the side. The motion along the direction of the magnetic field line is unaffected by the field.

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Various Magnetron Configurations

- **Planar Magetron**

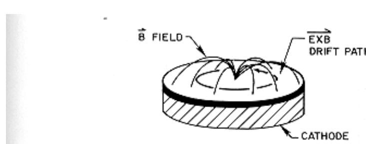

Fig. 30. A circular planar magnetron cathode, showing the shape of the magnetic field and the resulting drift path. Not shown is the plasma (close to the cathode) or the power supplies and anode.

- **Enhanced rate region**

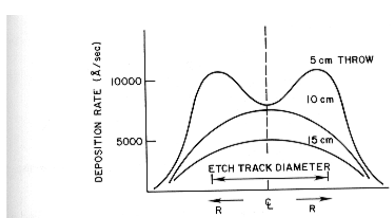

Fig. 33. The deposition profile on a sample in front of a magnetron cathode as a function of sample distance.

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Various Magnetron Configurations

- **S-gun**

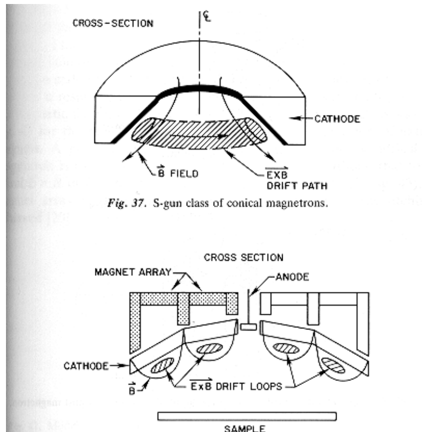

Fig. 37. S-gun class of conical magnetrons.

Fig. 38. An S-gun type of magnetron with two $\vec{E} \times \vec{B}$ drift paths on the same axis.

Collision Processes

High Energy Electrons Collide with Gas Molecules and Create New Species

Ionization - An electron is completely removed from a gas molecule or atom, to make a positive ion. (Negative ions are quite rare in plasmas.)

Electronic Excitation - This accounts for the glow. When electrons collide with atoms or molecules, they excite or energize electrons to higher energy levels. When these electrons fall back to lower levels, they emit energy usually in the form of photons of visible light.

Molecular Fragmentation - Electron collisions break up molecules into fragments which as a result have unsatisfied chemical bonding and are chemically reactive. These are called radicals.

Radicals - have no net charge, and therefore are not accelerated by the field or are not attracted by charged particles. They have a long lifetime compared to charged particles.

Production of Active Species

Simple Ionization:

$Ar + e- \text{-->} Ar^+ + 2e-$

$O_2 + e- \text{-->} O_2^+ + 2e-$

Dissociative Ionization:

$CF_4 + e- \text{-->} CF_3^+ = F + 2e-$

Dissociative Ionization with Attachment:

$CF_4 + e- \text{--} CF_3^+ + F- + e-$

Molecular Dissociation, Radical Formation:

$O_2 + e- \text{-->} 2O + e-$

$CF_3Cl + e- \text{-->} CF_3 + Cl + e-$

$CF_4 + e- \text{-->} CF_3 + F + e-$

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Plasma Composition

A typical plasma contains:

Neutral Molecules at a density of	**10e16/cm3**
Radicals	**10e14/cm3**
Electrons	**10e8/cm3**
Positive ions	**10e8/cm3**

There are a million times more radicals than ions or electrons. Radicals form more easily and their lifetime is much longer.

Ions don't etch, radicals do. Ions affect the process by energetic (physical) bombarding of the surface, influencing the chemical processes of etching.

Radicals are responsible for the dry etching process. They are chemically active and react with the surfaces to produce volatile products.

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Loss Mechanisms

In a plasma, unstable particles are continuously generated. The concentrations of ions, radicals, active atoms, & electrons increase until their loss rate is equal to the generation rate, forming a steady-state plasma.

Recombination of ions and electrons: They attract each other and are annihilated.

Drift, diffusion to walls: Electrons are lost at conductive surfaces, chamber walls or electrodes. Ions are lost (converted to neutral particles) by contact with conductive surfaces, especially positive electrode.

Recombination of radicals: 2O => O_2

Chemical reaction: 4F + Si => SiF4 (Fluorine radical combines with silicon wafer to produce silicon tetrafluoride gas. This is a typical dry etching process.)

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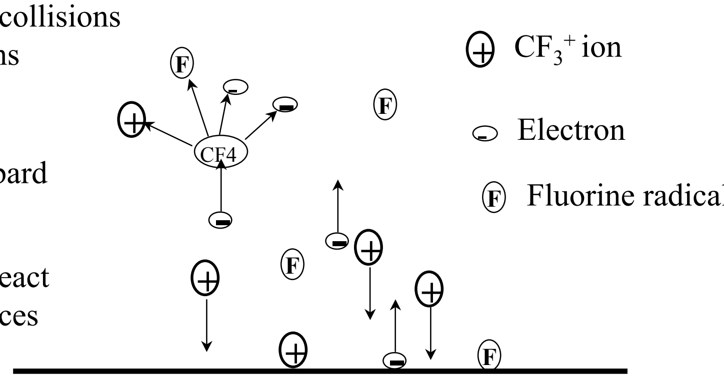
Ion Bombardment at Surfaces

Electron collisions create ions

Ions bombard surfaces

Radicals react with surfaces



Negatively charged surface

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GEC Cell

SF6
CF4
CHF3
O2
H2

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Dry Etching Spectrum

Pressure		Ion Energy
Low <50 mTorr ↓	**Physical (Sputtering)** Directional Poor Selectivity Radiation Damage Possible	↑ High
100 mTorr	**Reactive Ion Etching** Physical and Chemical Variable Anisotropy Variable Selectivity	
400 mTorr High	**Chemical Plasma Etching** Fast, Isotropic High Selectivity Low radiation Damage	Low

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Basic Principle of Plasma Etching

CF4 is inert gas (Freon 14)

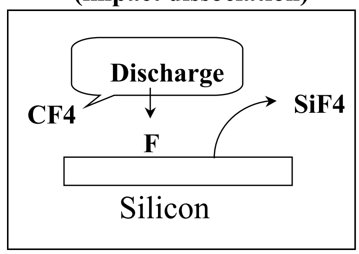
add electron impact:

$CF_4 + e \Rightarrow CF_3^+ + F + 2e$ (Dissociative Ionization)

$CF_4 + e \Rightarrow CF_3 + F + e$ (impact dissociation)

To produce chemically reactive fluorine radicals. Then at the surface:

$Si + 4F \Rightarrow SiF_4$ (gas)



Reactive Ion Etching

- **Three Mechanisms proposed for ion induced chemical reactions that lead to enhanced etching**
  - **Mauer et al. -- Chemically enhanced physical sputtering: SiF_x radicals of a fluorinated Si surface has an increased sputter yield versus pure Si surface.**
  - **Flamm and Donnelly -- Damage induced chemical reaction: lattice damage induced by ion bombardment causes the reaction rate of incident gaseous species to be enhanced**

Reactive Ion Etching

- **Coburn and Winters -- spontaneous versus ion enhanced etching**
  - **spontaneous etching -- 3 dimensional layer growth of volatile thin film, and subsequent desorption**
  - **ion enhanced etching -- ion damaged surface is more reactive, volatile species ejected from surface due to ion bombardment**
  - **XeF_2 - Ar^+ - Si System**

Generate etchant species
Diffusion to Surface
Adsorption (Surface Damage -- higher reactivity)
Reaction (Increase Temp)
By-product Desorption (Ion Collisions)
Diffusion of By-product to Bulk Gas

Silicon Etching

CF4 is Freon 14 F/C ratio is 4

CF4 + e- --> CF3 + F + e-

F radicals adsorb on silicon surface; SiF4 desorbs

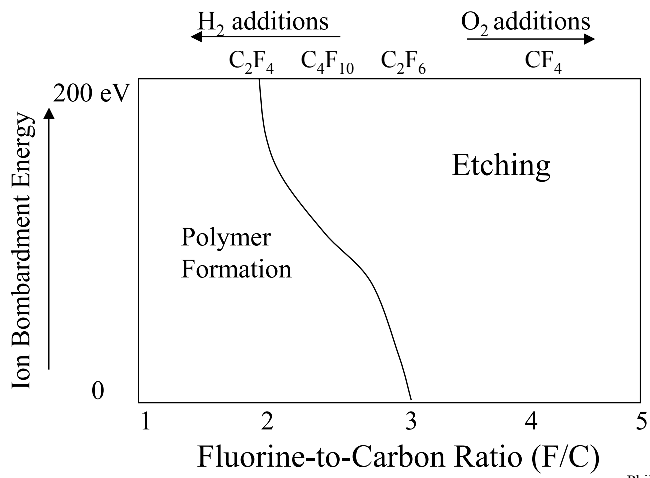
CF3 radicals also adsorb

CF3 + F --> CF4 desorbs

The presence of carbon on the surface reduces the amount of fluorine available to etch silicon. Carbon will leave the surface by combining with F reducing fluorine, carbon can remain on the surface forming C-F polymers which in turn inhibits etching. High F/C ratio favors etching.

Dry Etching Chemistries

- **Si materials (Si, SiO_2, Si_3N_4) etch in Fluorine Chemistries (SiF_2 and SiF_4 volatile species)**
- **<u>Fluorine-to-Carbon Ratio Model</u>**
  - **Silicon etch rate**



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Polymer Formation

It is known that flourocarbon gases such as CHF3, CF4, C3F8 etc. produce unsaturated compounds in the plasma, leading to polymer formation and deposition on the wafer surface and electrodes. Polymer formation and the boundary between polymerization and etching conditions depend upon the fluorine to carbon (F/C) ratio. Addition of oxygen to the plasma chemistry increases F/C ratio and reduces polymer formation. The addition of oxygen, unfortunately also increases the removal rate of photoresists. Energetic ion bombardment will shift the polymerization-etching boundary to lower F/C ratios.

PROBLEMS WITH POLYMERS:
Deposits can form on all surfaces of the chamber, affecting reproducibility of the etch process.
Polymers are a source of particulate contamination.
Cleaning of chambers must be performed regularly in order to prevent build up. This represents reduced up-time.

ADVANTAGES OF POLYMERS:
Properly controlled polymer deposition can allow anisotropic etching with otherwise purely chemical isotropic etch chemistries.

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Added Gases

Hydrogen - reduces fluorine concentration by combination to form HF

Oxygen - Increases fluorine concentration by combining with carbon (CO, CO_2) which would otherwise bond to fluorine (reacts with CF_3 to liberate F)

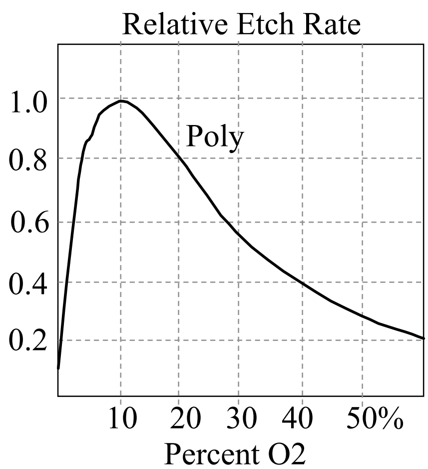
Argon - Inert (heavy) gas which can be added to ion enhance the etching process (I.e. reactive ion etch). Because it is inert, this does not effect the chemistry of the plasma.

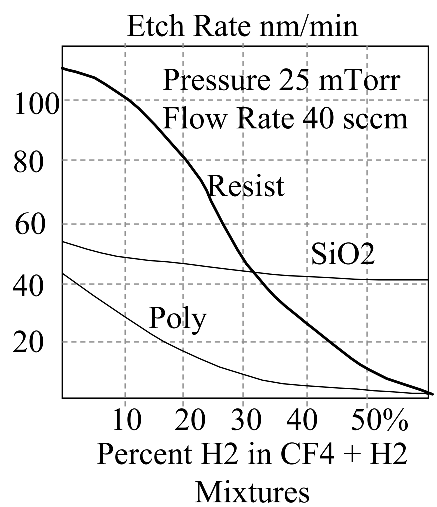
Si - SiO_2 Selectivity

- Adding O_2 **can increase etch rate if Si (ie increases F/C ratio by reacting with Carbon. By decreasing the carbon content, the oxide etch rate decreases and subsequently increases the Si etch selectivity over oxide.**
- Addition of H_2 **decreases the effective F/C ratio (by reacting with F to form HF). This decreases the formation of SiF_4 and subsequently decreases the etch rate of both Si and SiO_2.**
  - **The lower F/C ratio will enhance polymerization on silicon surfaces and inhibit etching.**
  - **On SiO_2 surfaces, the presence of O_2 in the film locally reacts with C (to form CO and CO_2) and minimizes polymerization.**
  - **Subsequently the Si etch rate decreases, relative to the SiO_2 etch rate which improves the selectivity of SiO_2 versus Si.**

Gas	C:F Ratio	SiO_2:Si Selectivity
CF_4	1:4	1:1
C_2F_6	1:3	3:1
C_3F_8	1:2.7	5:1
CHF_3	1:2	10:1

Etch Rates vs Added Gas Concentration





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Polymer Formation

It is known that flourocarbon gases such as CHF3, CF4, C3F8 etc. product unsaturated compounds in the plasma, leading to polymer formation and deposition on the wafer surface and electrodes. Polymer formation and the boundary between polymerization and etching conditions depend upon the fluorine to carbon (F/C) ratio. Addition of oxygen to the plasma chemistry increases F/C ratio and reduces polymer formation. The addition of oxygen, unfortunately also increases the removal rate of photoresists. Energetic ion bombardment will shift the polymerization-etching boundary to lower F/C ratios.

PROBLEMS WITH POLYMERS:
Deposits cam form on all surfaces of the chamber, affecting reproducibility of the etch process.
Polymers are a source of particulate contamination.
Cleaning of chambers must be performed regularly in order to prevent build up. This represents reduced up-time.

ADVANTAGES OF POLYMERS:
Properly controlled polymer deposition can allow anisotropic etching with otherwise purely chemical isotropic etch chemistries.

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Silicon Dioxide Etching Mechanism

C3 and F radicals adsorb. C bonds with oxygen at the surface F bonds with Si. By-products are CO, CO2, COF2, SiF4. The addition of H2 removes F from the system by forming stable HF gas. Addition of H2 therefore decreases the effective F/C ratio and increases selectivity of SiO2 with respect to silicon. As H2 is increased, it begins to consume fluorine H + F = HF This slows the formation of SiF4 and slows the removal of Silicon. Polymerization will be promoted on all surfaces, which tends to inhibit etching. On horizontal surfaces however, ionic bombardment provides enough energy cause the carbon/hydrogen to combine with surface oxygen. Released CO and H2O expose the surface silicon which is removed by combining with released fluorine radicals. Silicon will not be etched because of the absence of oxygen at the surface.

Commercial Etching Processes

Material	Kind of Gas Plasma	Remark
Si	CF_4, $CF_4 + O_2$, CCl_2F_2	
poly-Si	CF_4, $CF_4 + O_2$, $SF_6 + O_2$, $CF_4 + N_2$	doped or undoped
SiO_2	CF_4, $CF_4 + H_2$, HF*	*selective
	CCl_2F_2, C_3F_8**, $C_2F_6 + H_2$**	**diode system
Si_3N_4	CF_4, $CF_4 + O_2$	
Mo	CF_4, $CF_4 + O_2$	
W	CF_4, $CF_4 + O_2$	
Au	$C_2Cl_2F_4$	
Pt	$CF_4 + O_2$, $C_2Cl_2F_4 + O_2$, $C_2Cl_3F_3 + O_2$	
Ti	CF_4	
Ta	CF_4	
Cr	Cl_2, CCl_4, CCl_4 + Air	evaporate or sputter
Cr_2O_3	Cl_2 + Ar, CCl_4 + Ar	oxidation method
Al	CCl_4, CCl_4 + Ar, BCl_3	
Al_2O_3	CCl_4, CCl_4 + Ar, BCl_3	
GaAs	CCl_2F_2	

Ion-assisted Anisotropic Etching

Two mechanisms are proposed to explain the phenomenon of ion assisted anisotropy. Anisotropic etching is believed to result from a combination of physical and chemical removal processes. The ratio of vertical etch rate to horizontal etch rate may be increased either by reducing the horizontal rate or by increasing the vertical rate.

ION INDUCED DAMAGE MECHANISM:
In this model, bombarding ions have sufficient energy to break crystal bonds, making the film more accessible and the surface more reactive to the active chemical etchants. At the sidewalls, where there is little ion bombardment, the etching process proceeds at the nominal chemical etch rates.

SURFACE INHIBITOR MECHANISM:
In some etch chemistries, the surface exposed to the plasma is likely to become coated with a chemisorbed film of etchant radicals and unsaturated species, which polymerize and adhere tenaciously to the material being etched. The resulting polymer coating inhibits the chemical reactions necessary to etch. Ion bombardment can cause the polymers to desorb, exposing horizontal surfaces to the etching gas. Vertical surfaces experience little or no bombardment, therefore etching in the horizontal direction can be completely blocked.

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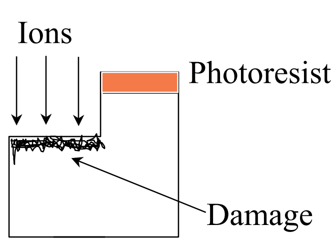
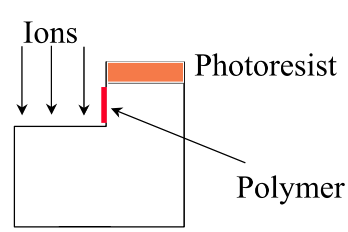
Ion-assisted Anisotropic Etching

SURFACE DAMAGE



speeds chemical reaction on horizontal surfaces.

SURFACE INHIBITOR



slows chemical reaction on vertical surfaces.

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Aluminum Etching

Special Problems:

1. Aluminum is not etched by fluorine, because AlF_3 is not volatile. Chlorine or bromine are used, which are highly corrosive to equipment.
2. $AlCl_3$, the etch product, is highly corrosive to the remaining aluminum film, and must be removed quickly after plasma etching.
3. Native aluminum oxide is an etch resistant barrier, which is removed by Hydrogen plasma reduction and/or by sputtering by bombardment with Argon at high energies.
4. Aluminum often has a few percent of Silicon or Copper. Silicon is removed by the Chlorine, Copper is not and requires a special process.

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Copper Etching

Special problems:

1. Copper does not form any volatile compounds with known plasma etch gases, and therefore cannot be RIE etched.
2. Copper can be sputter etched, but this technique has no selectivity.
3. Contamination of the fab with copper is serious concern.

The Damascene process has become an attractive enabling method for patterning copper by CMP.

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Dry Etching Parameter Space

- **Adjustable System Parameters**
  - **Reactor**
  - **Material of Chamber Walls**
  - **Material of Electrodes**
  - **Geometry (grounded versus powered electrode area)**
  - **Platform Temperature**
  - **Geometry of Gas Flow**
  - **Pumping Speed**
  - **Power**
  - **Frequency**
  - **Gas Supply**
  - **Composition**
  - **Flow rate**
  - **Pressure**
  - **Residence Time**

Dry Etching Parameter Space

- **Observable Wafer Parameters**
  - **Uniformity**
  - **Etch Rate**
  - **Selectivity (mask and underlying film)**
  - **Loading Effect**
  - **Profile (ie side-wall angle)**
  - **Temperature of Substrate Surface**
  - **Damage**
  - **Contamination**

Uniformity

- **Gas Flow Uniformity over Wafer**
- **Etch product formation/Flow rate of etch gas ≥ 0.1**
  - **example 3 inch Si wafer at 500A/min in CF_4 plasma:**
    - **etch product = 5e19 SiF_4/minute (2sccm)**
    - **Minimun CF_4 flow rate = 20sccm**
- **Residence Time (τ)**
  - **$\tau = (VP)/(760F)$**
    - **where V=volume of the reactor (cm^3), P=steady state pressure (torr), F=flow rate (sccm)**
- **Dissociation Rate of Reactive Species (D)**
  - **~5x the total ion current**
    - **example ion current = 0.1mA, D = 5e15 molecules/(cm^2-s)**

Uniformity

- **Electrode interactions**
  - **Non-uniform etchant species**
    - **electrode reaction < wafer reaction**
    - **electrode reaction > wafer reaction**
  - **Re-deposition of involatile by-product**
  - **Electrical**
    - **impedance variations**
    - **secondary electron coefficient differences**
  - **Edge effects**
    - **sheath thickness**
    - **enhanced sputtering**
  - **Temperature variations (poor local contact)**

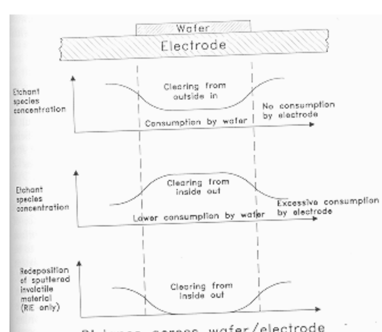

Fig. 10. Chemical and physical effects leading to the "bull's-eye effect" (nonuniform etching across a wafer). (Reproduced by permission from Ref. 22.)

Loading and Selectivity

- **"Loading effects" -- etch rate depends on the surface area of the material to be etched**
- **Selectivity**
  - **Carbon Blocking -- SiO_2/Si system (F/C ratio model)**
  - **Volatility -- mask or underlying layer does not form volatile etch product (ie resist ashing in O_2 does not ethc Si, SiO_2, Al etc., Si and SiO_2 etching in Fluorine chemistry does not etch Al)**
  - **Thermodynamics -- compare free energies for reactions (large negative ΔH usually etches much faster than positive ΔH)**

Contamination and Damage

- **Sputtering**
  - **Cathode -- energetic bombardment at cathode can deposit cathode material on substrate (coat electrode with SiO_2 or teflon)**
  - **Vacuum chamber -- metals such as Fe, Ni, Cr, Al, Cu and Zn can degrade devices (leakage or deep level traps)**
  - **Carbon Implantation**

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Contamination and Damage

- **Polymeric Residues**
  - **C/F model for polymerization versus etching**

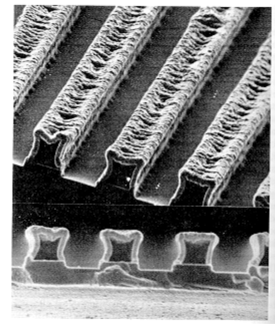

Fig. 12. SEM micrographs of Teflon-like residues outlining the original photoresist profiles, which were dissolved in acetone. This thick conformal coating was deposited in a system that had previously been heavily contaminated by polymers formed by etching at relatively high pressures in CHF_3. (Periodicity of grating = 5 μm.)

- **Radiation Damage**
  - **Energetic ions, photons and electrons**
    - **dielectric leakage**
    - **SiO_2/Si fixed and mobile charge**
    - **Interface state build-up**

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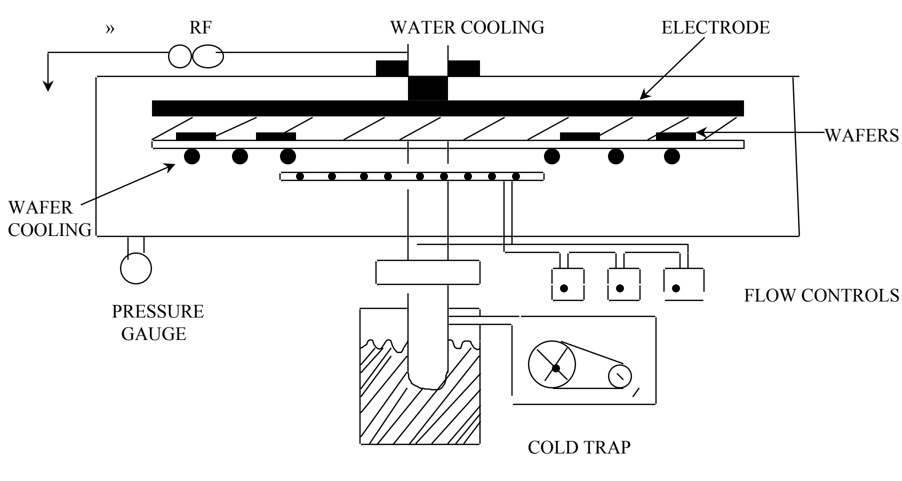
Planar Parallel Plate Plasma Etcher



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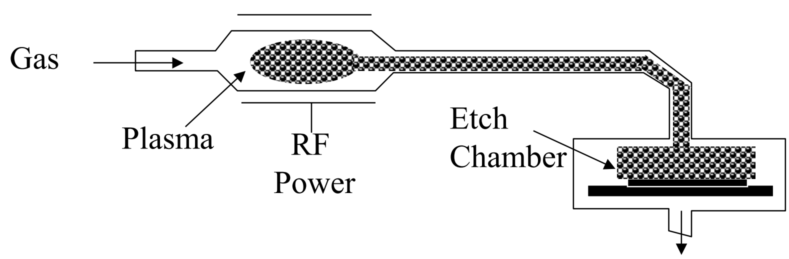
Downstream etchers

Plasma is formed in a cavity which is separated from the etching chamber. Wafers are shielded from bombardment. Only radicals reach wafers. Etching is completely chemical and isotropic
High selectivity achievable; Si:SiO2 = 50:1 Plasma may be generated by RF or by microwave



Advanced Plasma Systems

Submicron features may require unusually low pressures for acceptable etching. Conventional plasma systems etch very slowly because of the low plasma density. Advanced systems utilize various techniques to increase the plasma density at low pressures.

Techniques to increase plasma density:

- Magnetic field to confine electrons
- Microwave excitation of electrons
- Downstream system to control ion energy

Examples:

- Electron Cyclotron Resonance (ECR)
- Magnetically Enhanced RIE (MERIE)
- Reactive Ion Beam Etching (RIBE)

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