Chapter 9, Etch

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Objectives

Upon finishing this course, you should able to:

- Familiar with etch terminology
- Compare wet and dry etch processes
- List four materials need to be etched during IC processing and list the main dry etch etchants
- Describe etch process in IC fabrication
- Become aware of hazards in etch processes

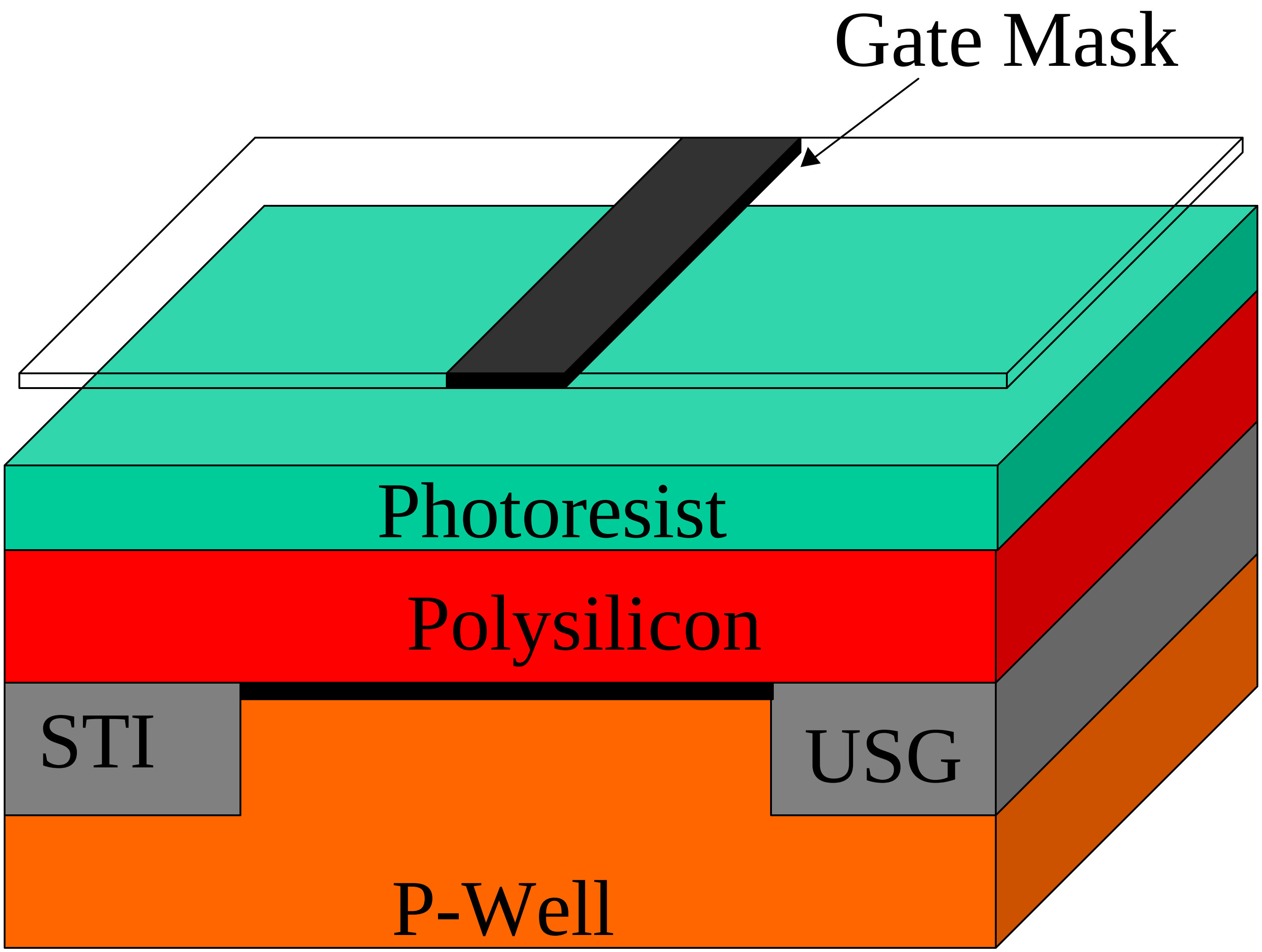
Outline

- Introduction
- Terminology
- Wet and dry etch
- Plasma basics
- Plasma etch processes

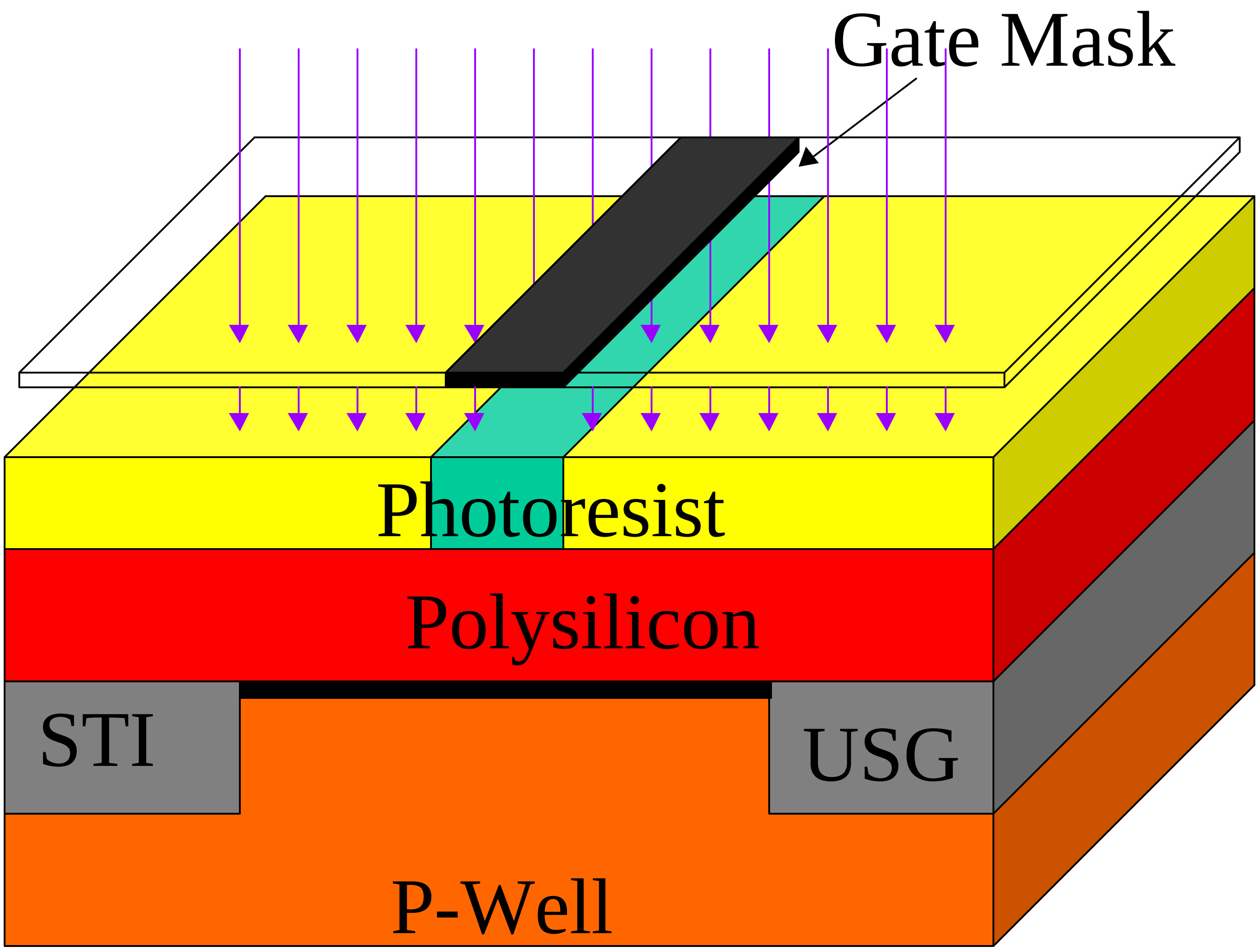
Definition of Etch

- Process that removes material from surface
- Chemical, physical or combination of the two
- Selective or blanket etch
- Selective etch transfers IC design image on the photoresist to the surface layer on wafer
- Other applications: Mask making, Printed electronic board, Artwork, etc.

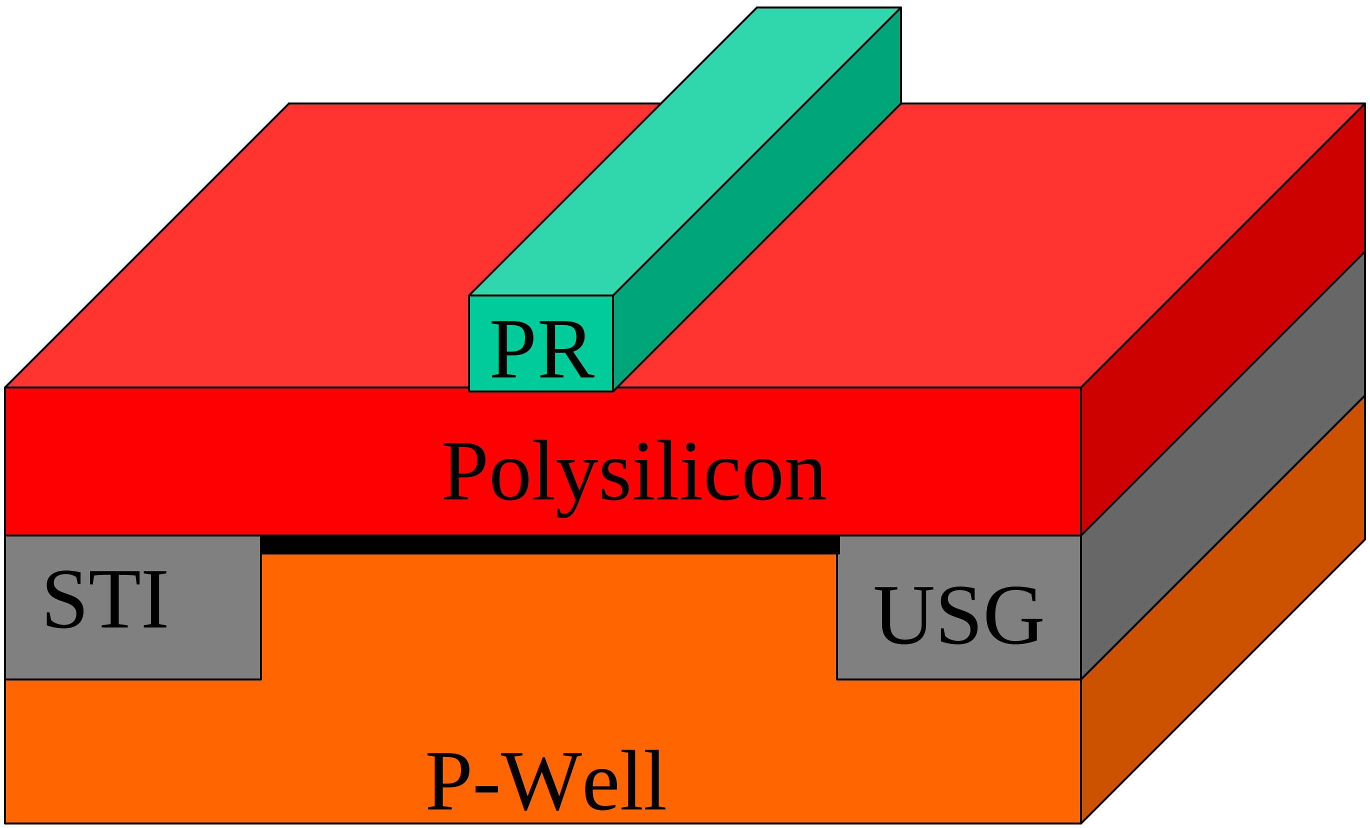
Gate Mask Alignment



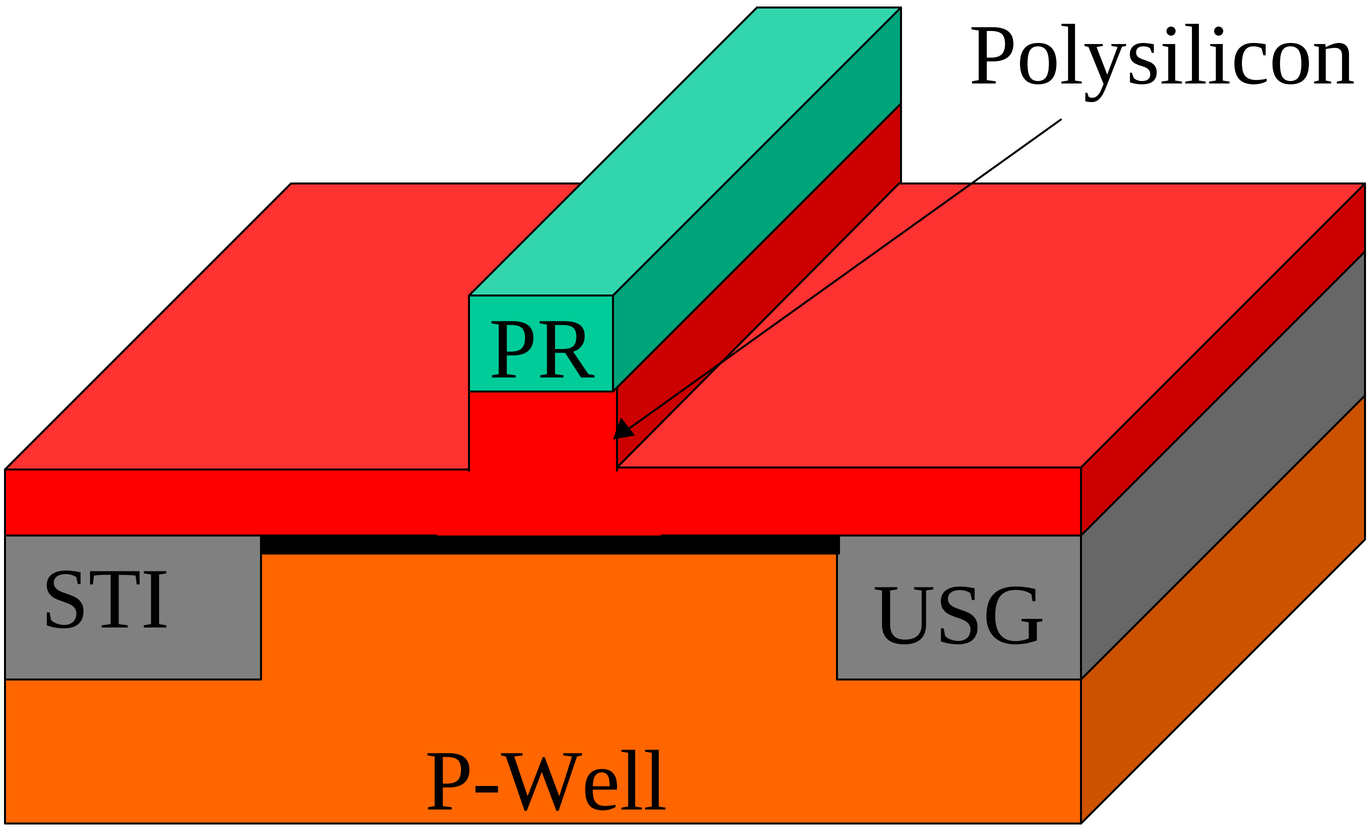
Gate Mask Exposure



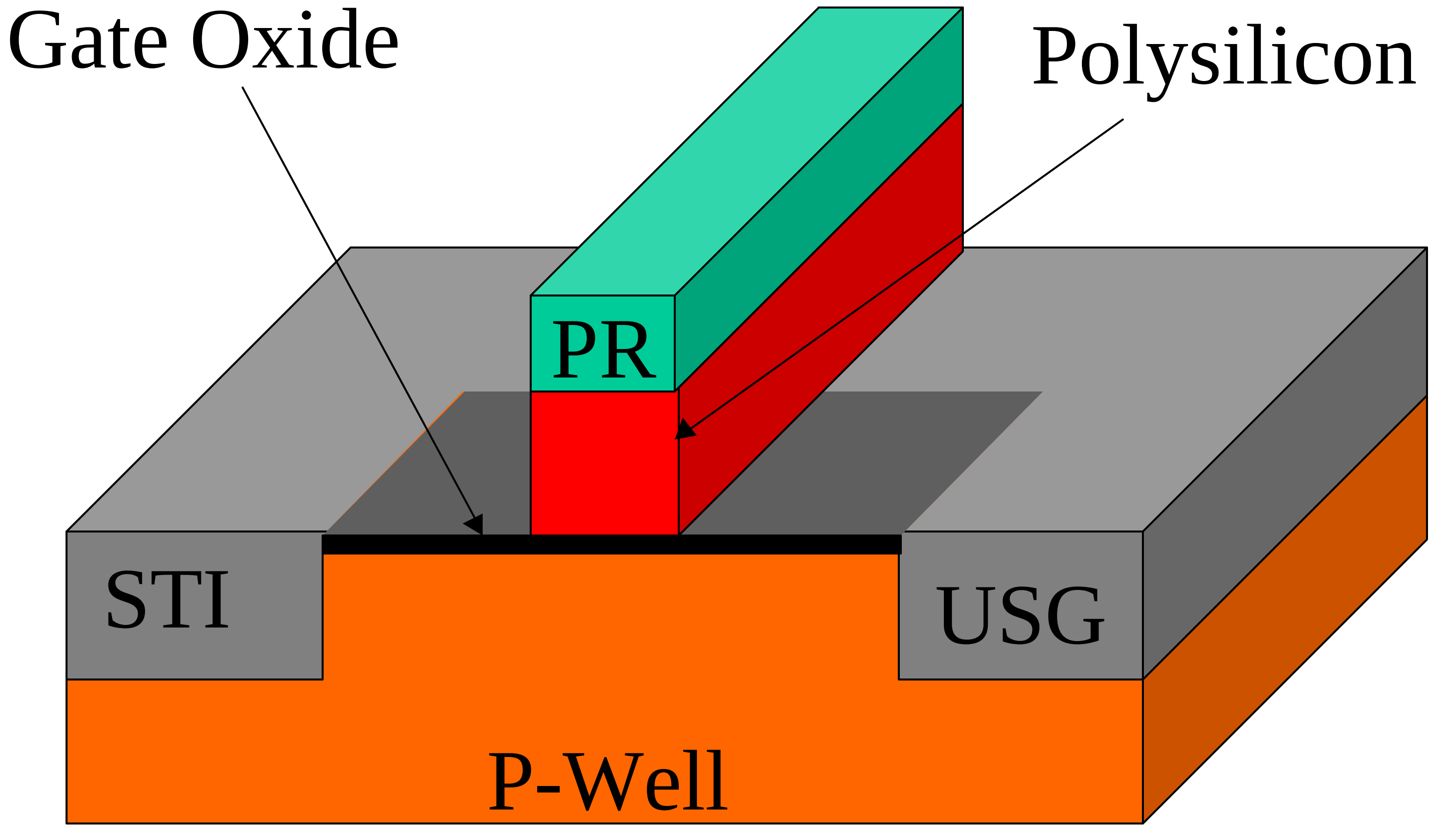
Development/Hard Bake/Inspection



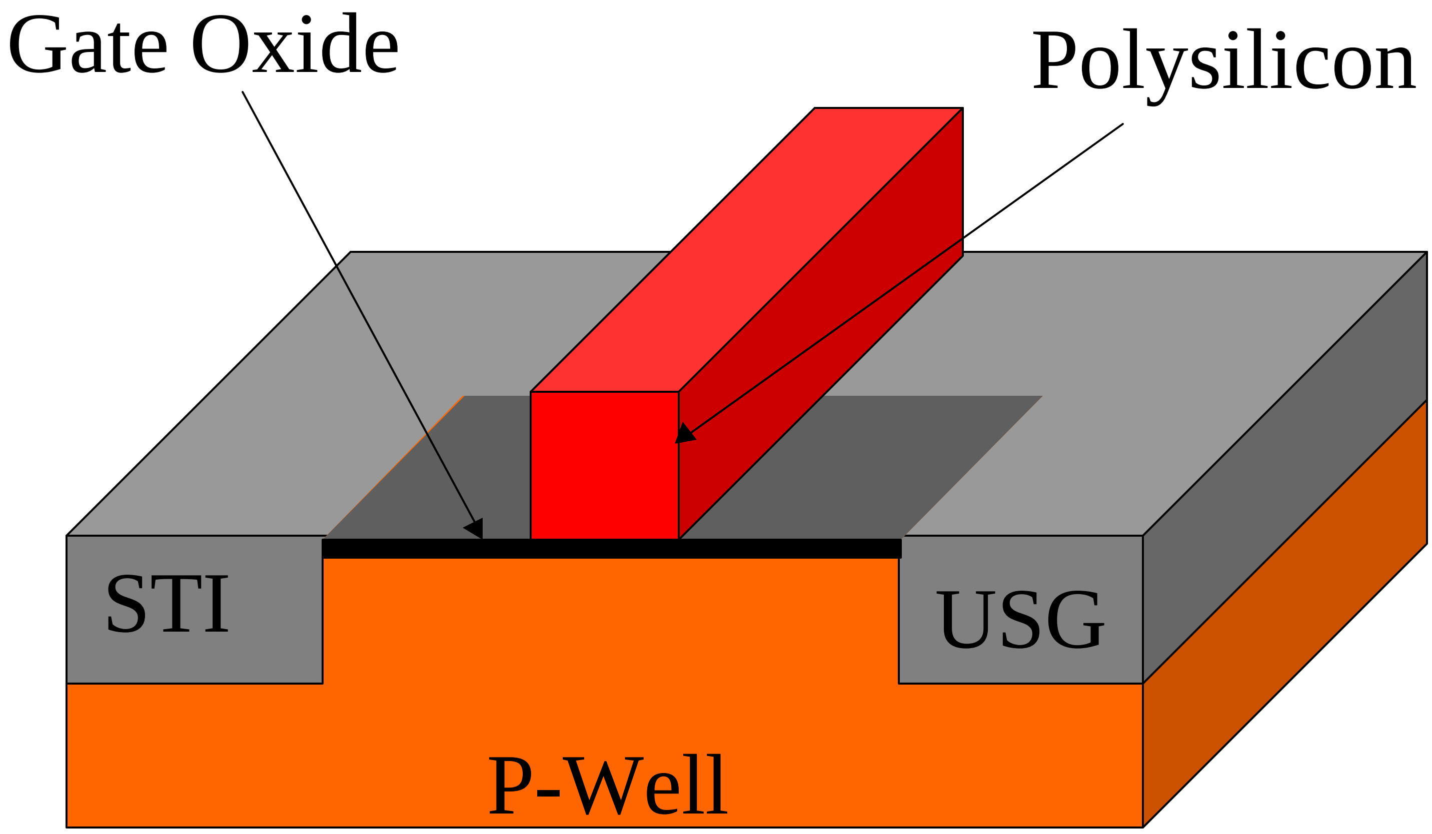
Etch Polysilicon



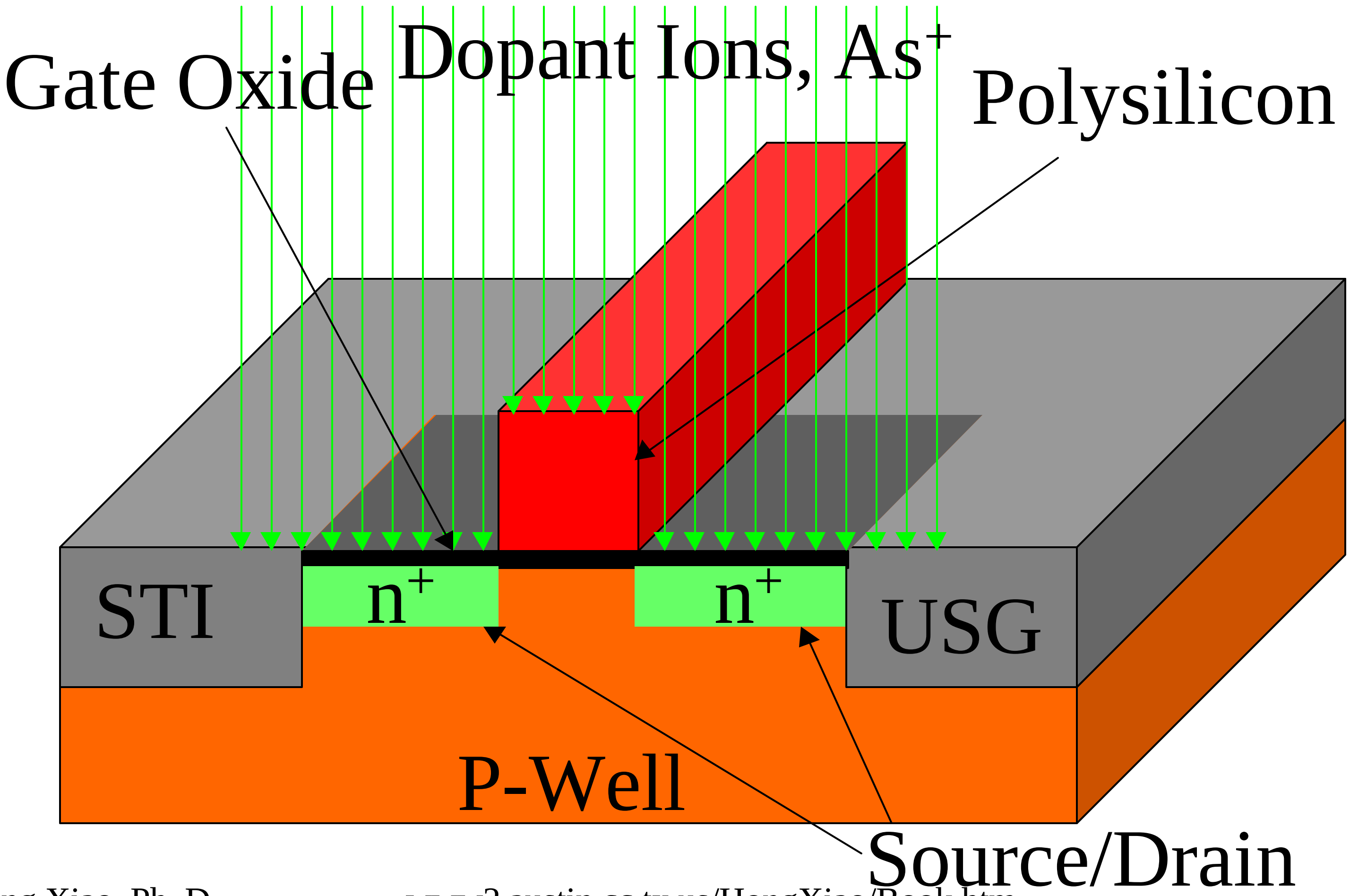
Etch Polysilicon, Continue



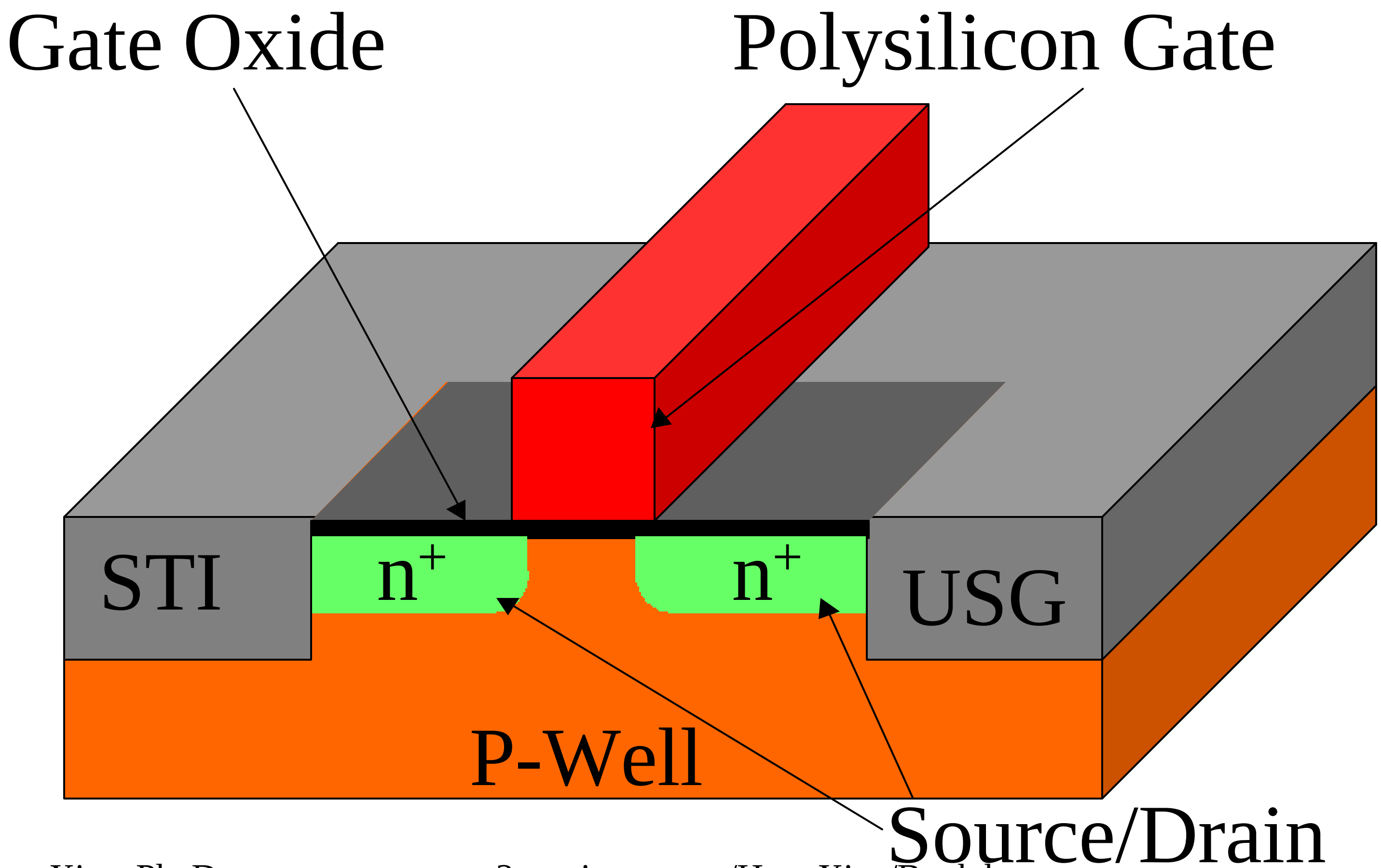
Strip Photoresist



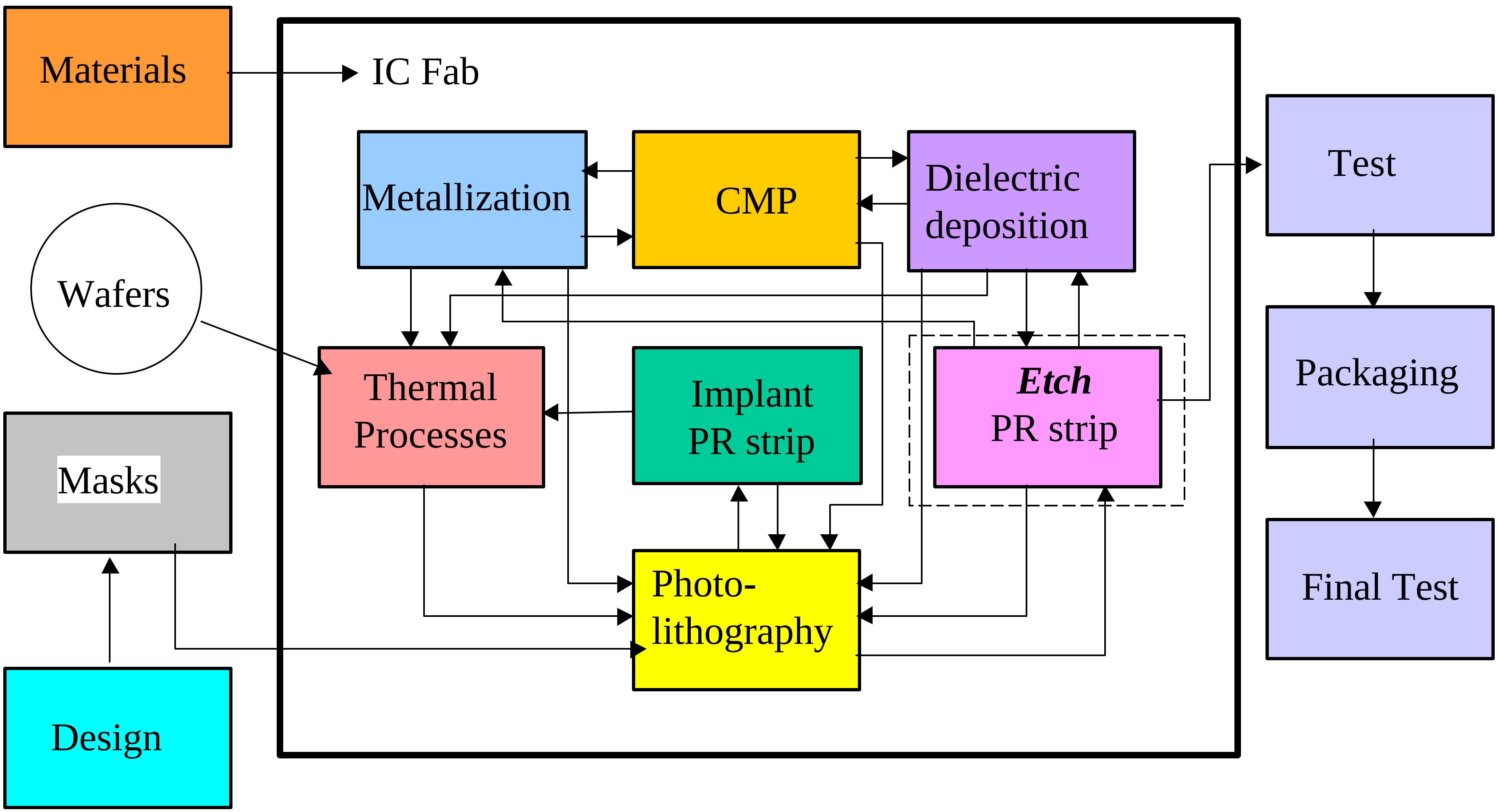
Ion Implantation



Rapid Thermal Annealing



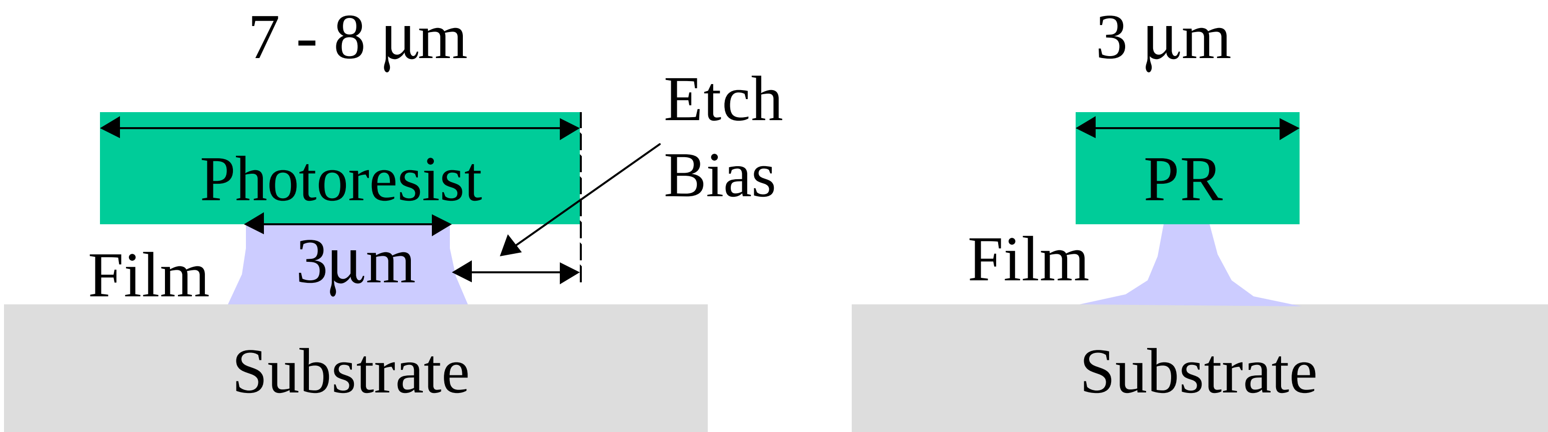
Wafer Process Flow



Applications of Etch

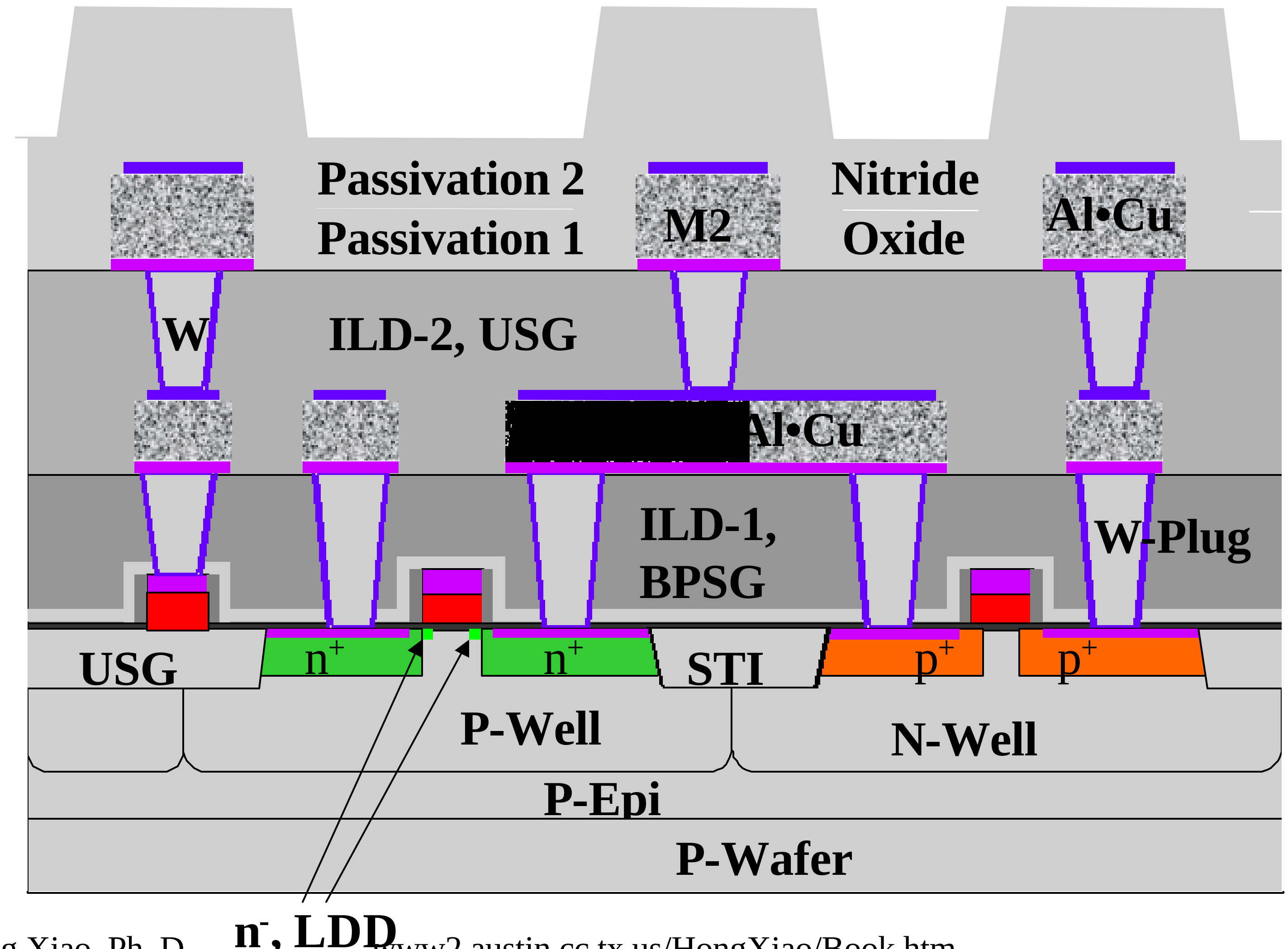
- IC Fabrication
- Mask making
- Printed electronic board
- Art work
- Nameplate
- Glassware

Wet Etch Profiles



- Can’t be used for feature size is smaller than 3 μm
- Replaced by plasma etch for all patterned etch

CMOS Cross-Section

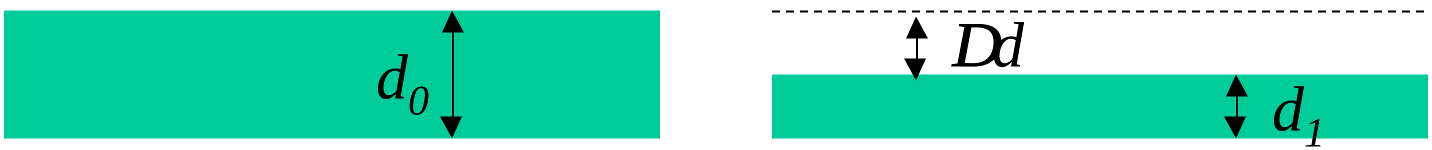


Etch Terminology

- Etch rate
- Selectivity
- Etch uniformity
- Etch profile
- Wet etch
- Dry etch
- RIE
- Endpoint

Etch Rate

Etch rate measures of the how fast the material is removed from wafer surface.



Before etch After etch

$$\text{Etch Rate} = \frac{Dd}{t} \quad (\text{Å/min})$$

$Dd = d_0 - d_1$ (Å) is thickness change and t is etch time (min)

Etch Rate

$$\text{Etch rate} = \frac{\text{thickness change after etch}}{\text{etch time}}$$

PE-TEOS PSG film, 1 minute in 6:1 BOE at 22 °C,

Before etch, t = 1.7 μm, After wet etch, t = 1.1 μm

$$\text{ER} = \frac{17000-11000}{1} = 6000\ \text{Å/min}$$

Etch Uniformity

- Etch uniformity is a measure of the process repeatability within the wafer (WIW) and wafer to wafer (WTW)
- Thickness measurements are made before and after etch at different points
- More measure points, higher the accuracy
- Standard deviation definition are normally used
- Different definitions give different results

Standard Deviation Non-uniformity

N points measurements

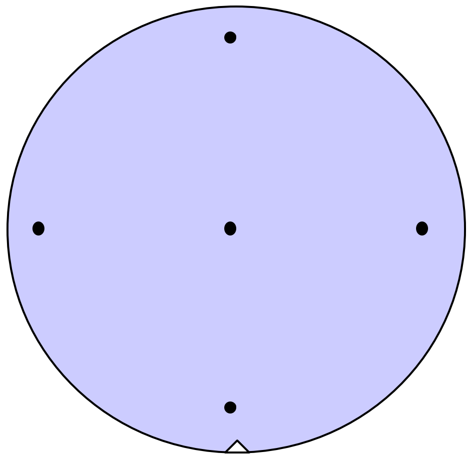
$$s = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_3 - \bar{x})^2 + \cdots + (x_N - \bar{x})^2}{N-1}}$$

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots + x_N}{N}$$

Max-Min Uniformity

Etch non-uniformity (NU) can be calculated by using following equation (called Max-Min uniformity, good for classroom exercise):

$$NU(\%) = (E_{max} - E_{min})/ 2E_{ave}$$



E_{max} = Maximum etch rate measured

E_{min} = Minimum etch rate measured

E_{ave} = Average etch rate

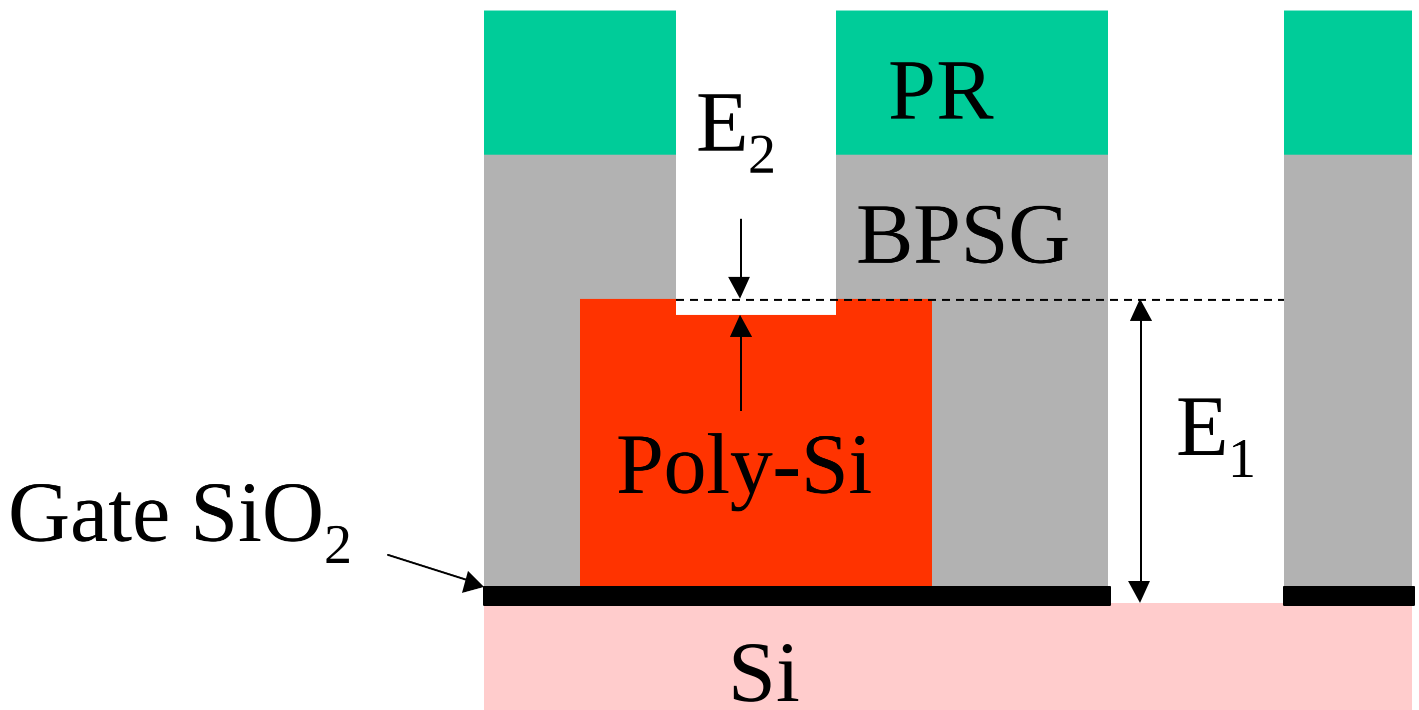
Selectivity

- Selectivity is the ratio of etch rates of different materials.
- Very important in patterned etch
- Selectivity to underneath layer and to photoresist

$$S = \frac{E_1}{E_2}$$

Selectivity

- Selectivity of BPSG to Poly-Si: $S = \dfrac{E_1}{E_2}$



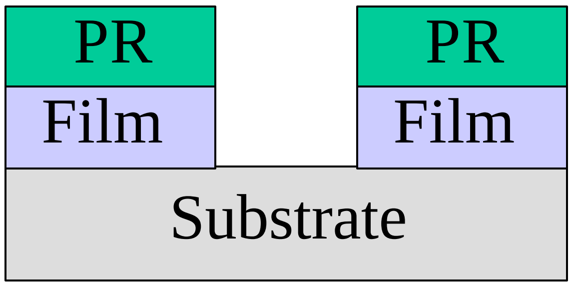
Selectivity

$$\text{Selectivity} = \frac{\text{Etch rate 1}}{\text{Etch rate 2}}$$

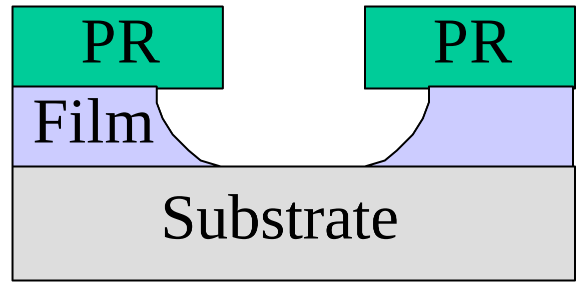
Etch rate for PE-TEOS PSG film is 6000 Å/min, etch rate for silicon is 30 Å/min, PSG to silicon

$$\text{Selectivity} = \frac{6000}{30} = 200:1$$

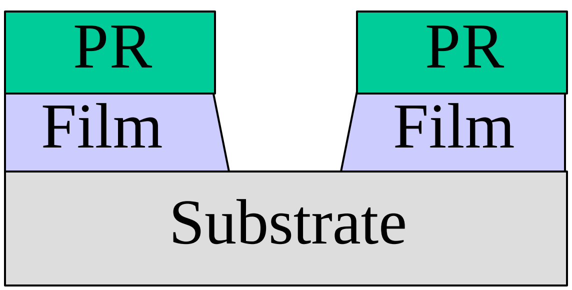
Etch Profiles



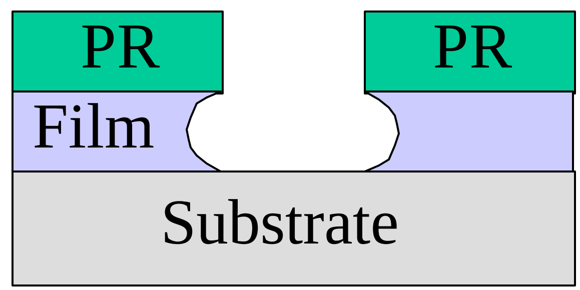
Anisotropic



Isotropic

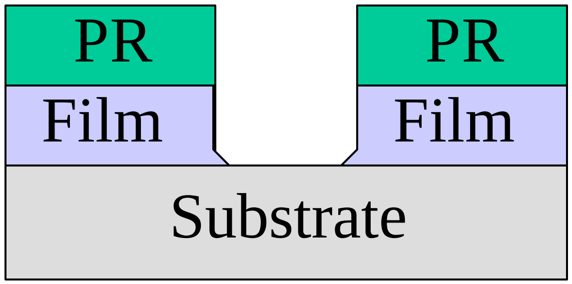


Anisotropic, tapered

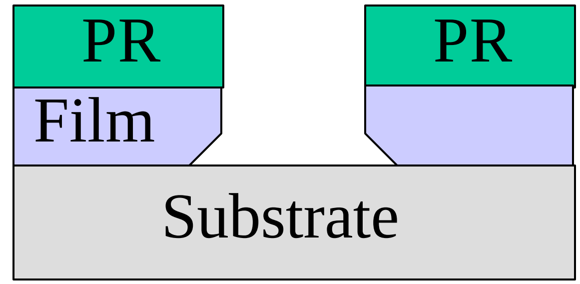


Anisotropic, Undercut

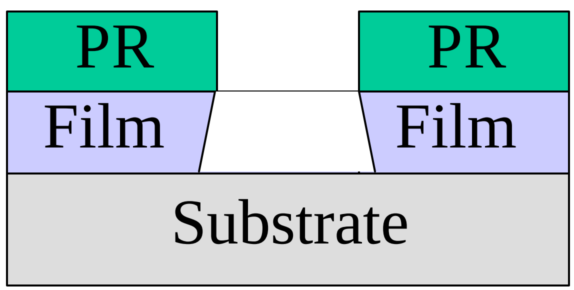
Etch Profiles



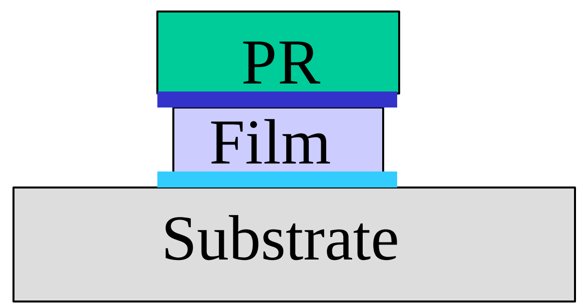
Anisotropic, Foot



Undercut, reversed foot



Undercut, reversed tapered



Undercut, I-beam

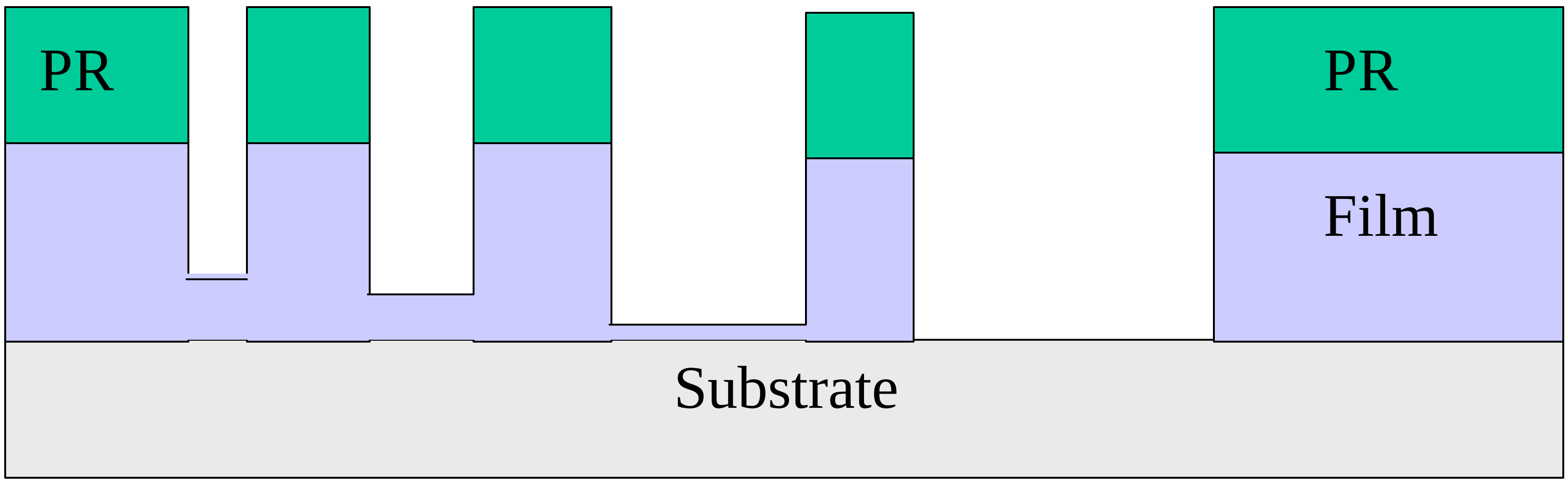
Loading Effects: Macro Loading

- ER of a wafer with a larger open area is different from the wafer with a smaller open area
- Mainly affects the batch etch process,
- Has a minimal effect on the single wafer process

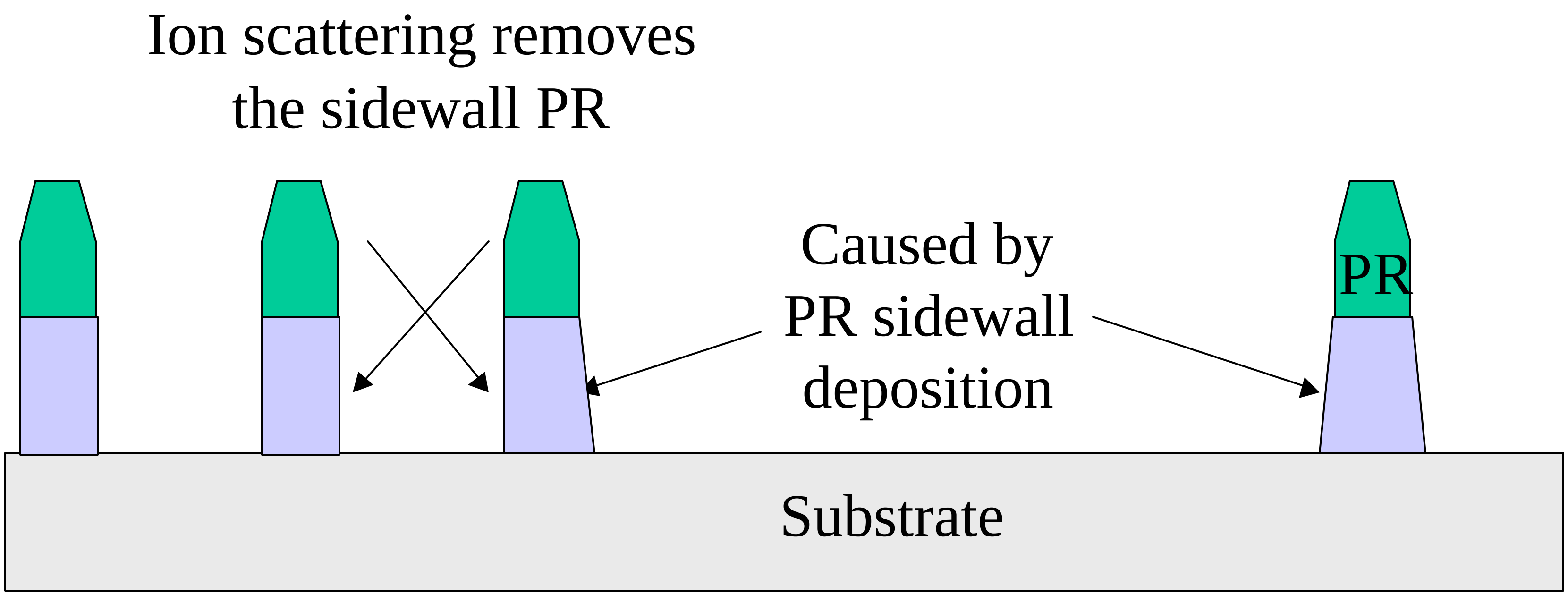
Loading Effects: Micro Loading

- Smaller hole has a lower etch rate than the larger holes
- Etchants are more difficult to pass through the smaller hole
- Etch byproducts are harder to diffuse out
- Lower pressure can minimize the effect.
- Longer MFP, easier for etchants reaching the film and for etch byproducts to get out

Micro Loading



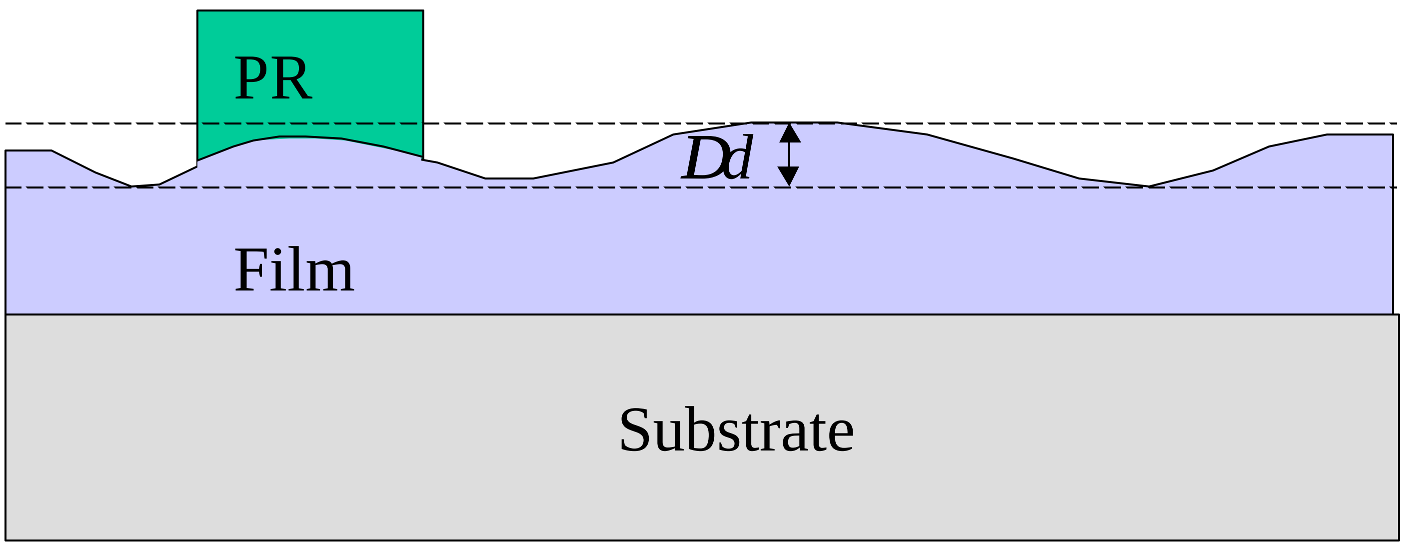
Profile Micro Loading



Over Etch

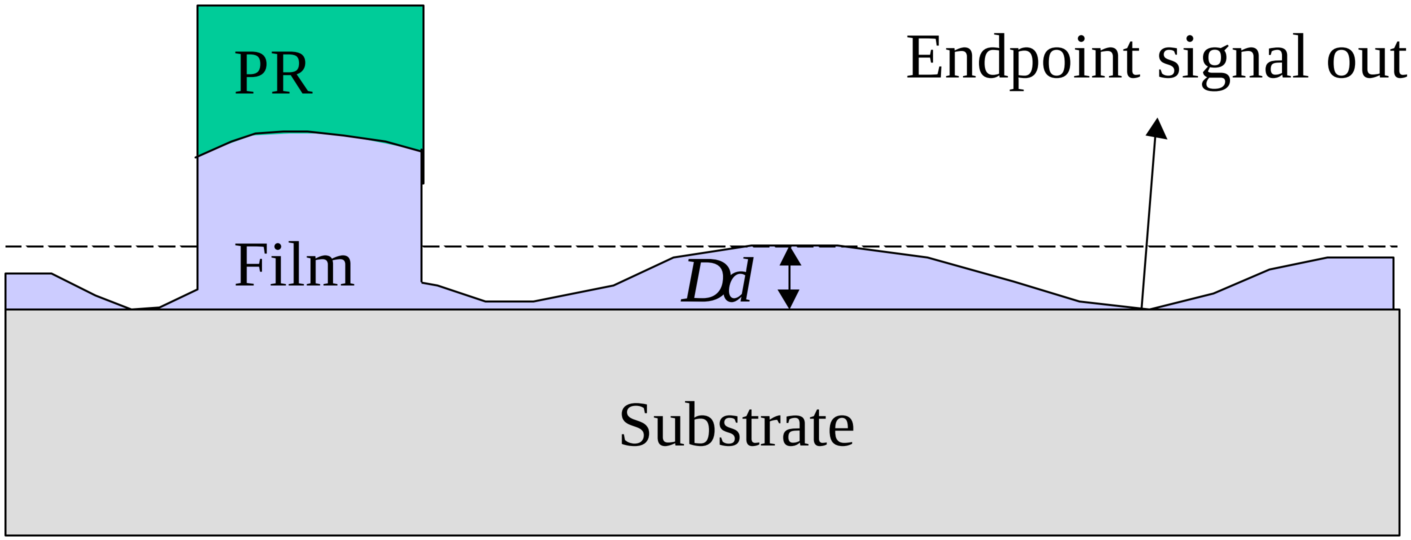
- Film thickness and etch rate is not uniform
- Over etch: removes the leftover film
- Selectivity of etched film and substrate
- RIE uses optical endpoint to switch from main etch to over etch

Start Etch Process



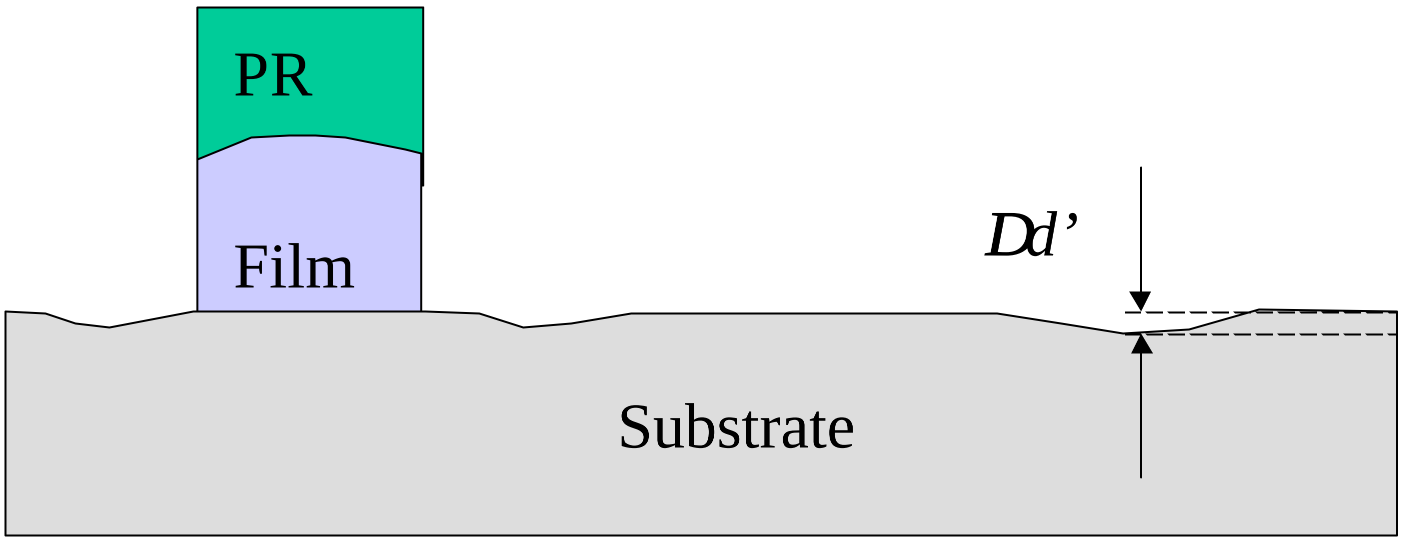
Start main etch

Main Etch Endpoint



Before over etch

After Overetch

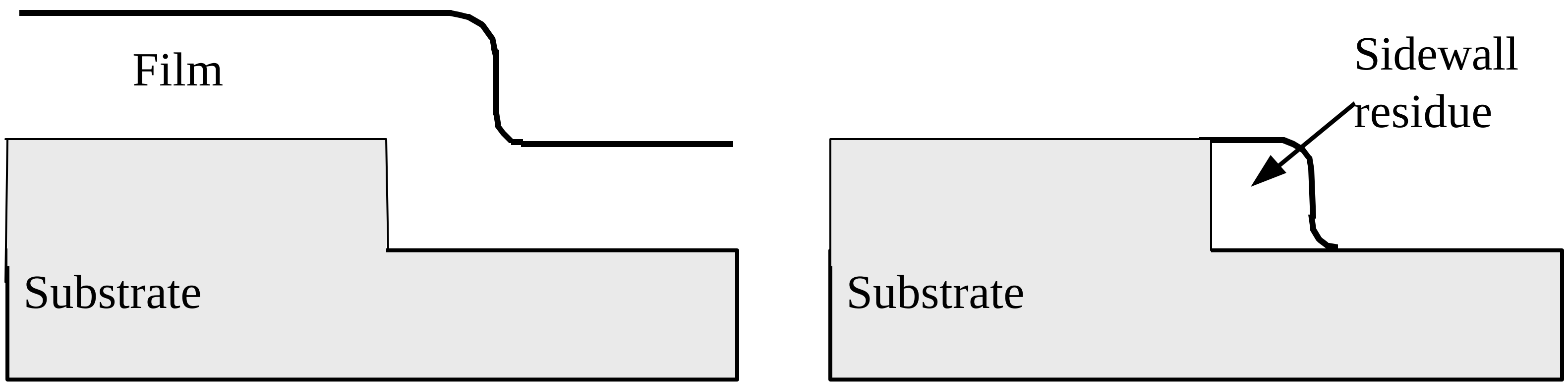


After over etch

Residues

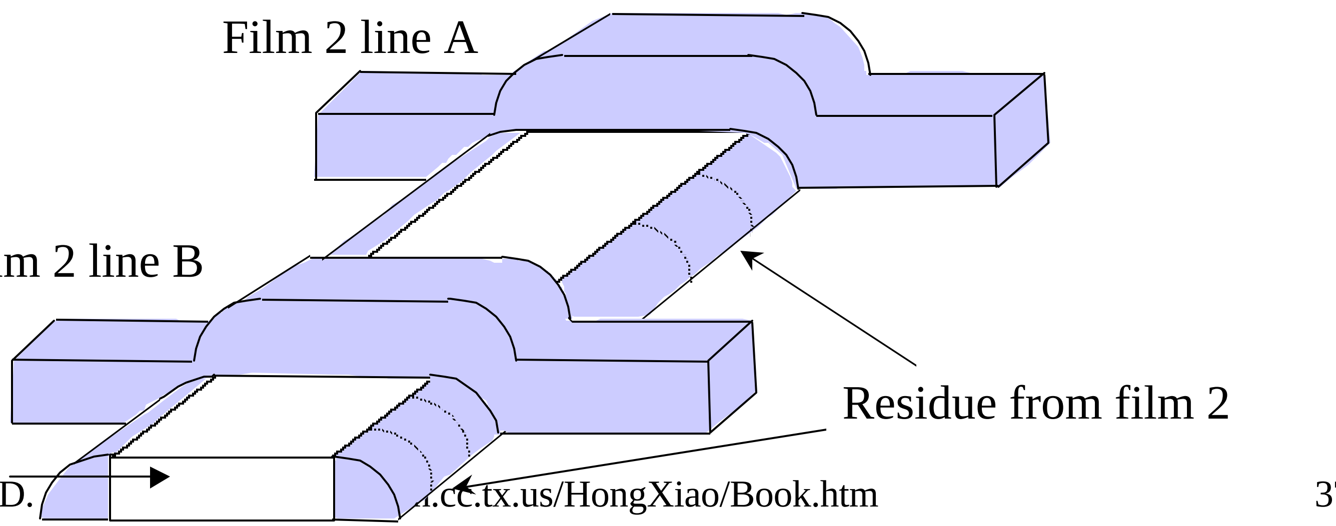
- Unwanted leftovers
- Causes
  - insufficient over etch
  - non-volatile etch byproducts

Insufficient Over Etch

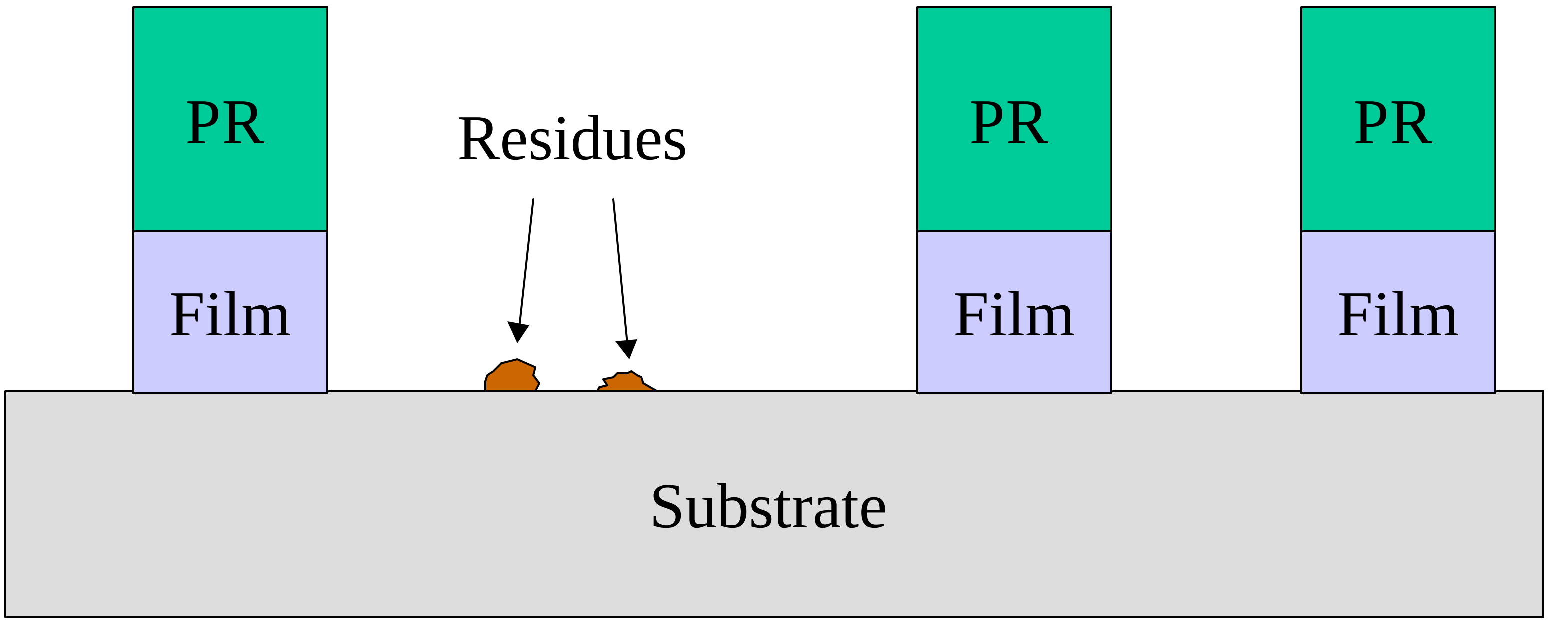


Before etch

Insufficient over etch



Non-volatile Residue on Surface



Residues

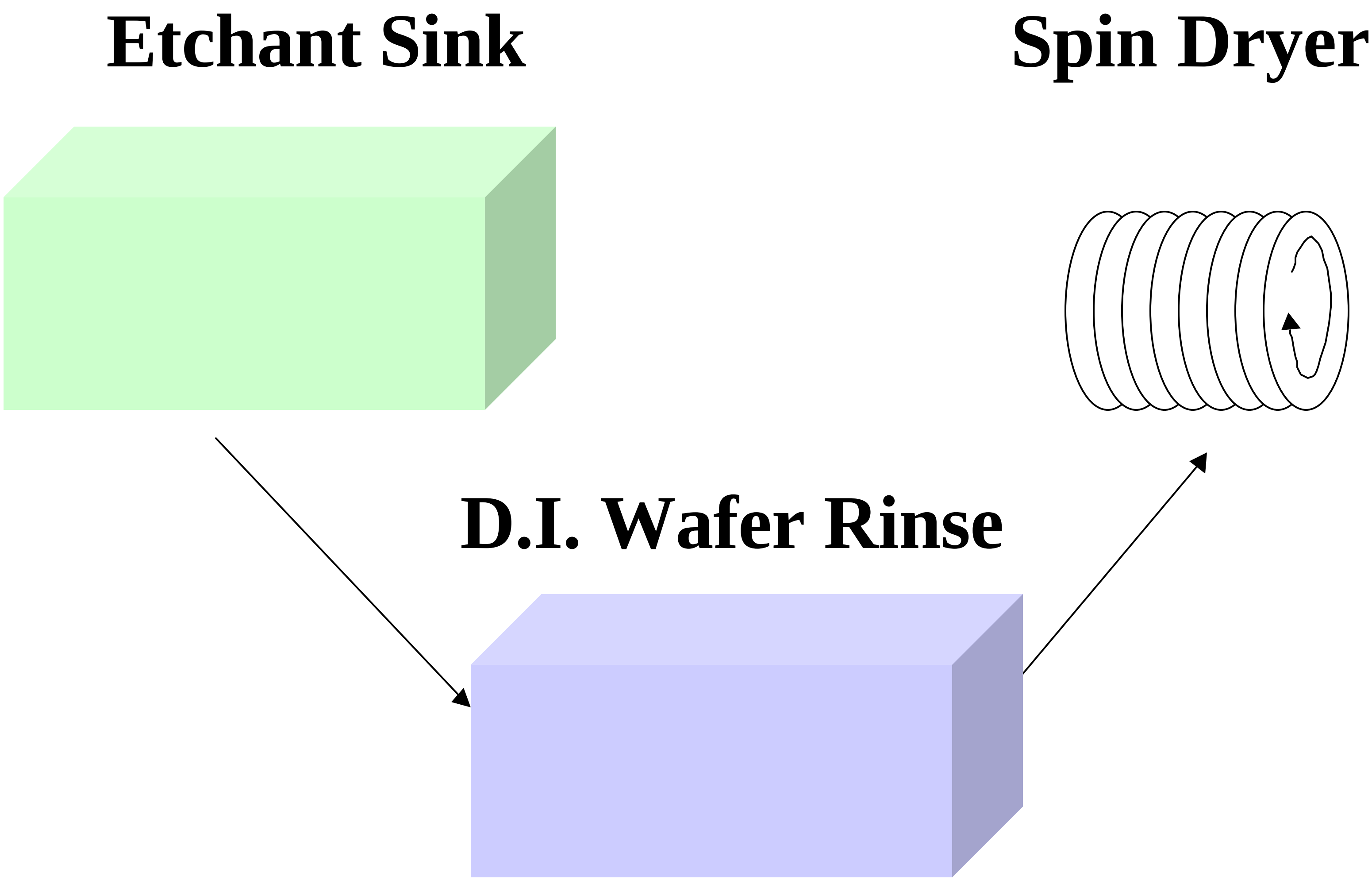
- Adequate over etch
- Removal of non-volatile residues
  - Sufficient ion bombardment to dislodge
  - Right amount of chemical etch to scoop
- Oxygen plasma ashing: Organic residues
- Wet chemical clean: inorganic residues

Wet Etch

Wet Etch

- Chemical solution to dissolve the materials on the wafer surface
- The byproducts are gases, liquids or materials that are soluble in the etchant solution.
- Three basic steps, etch, rinse and dry

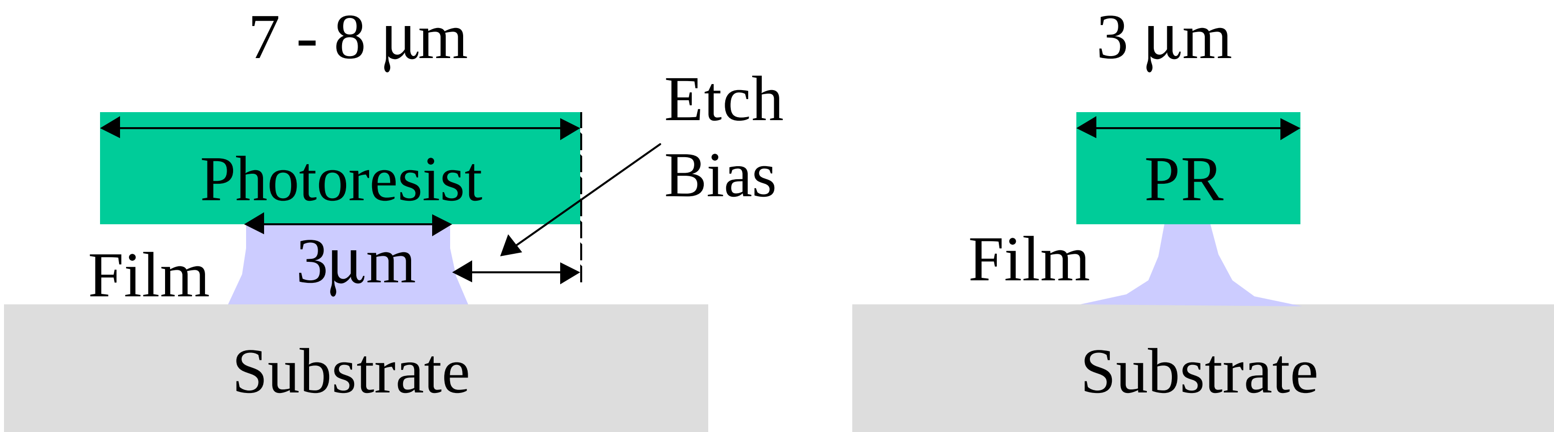
Basic Wet Etch Process Steps



Wet Etch

- Pure chemical process, isotropic profile
- Was widely used in IC industry when feature size was larger than 3 micron
- Still used in advanced IC fabs
  - Wafer clean
  - Blanket film strip
  - Test wafer film strip and clean

Wet Etch Profiles



- Can't be used for feature size is smaller than 3 μm
- Replaced by plasma etch for all patterned etch

Applications of Wet Etch

- Wet etch can not be used for patterned etch when CD < 3 μm
- High selectivity
- It is widely used for strip etch process, such as nitride strip and titanium strip, etc.
- Also widely used for CVD film quality control (buffered oxide etch or BOE)
- Test wafers strip, clean, and reuse

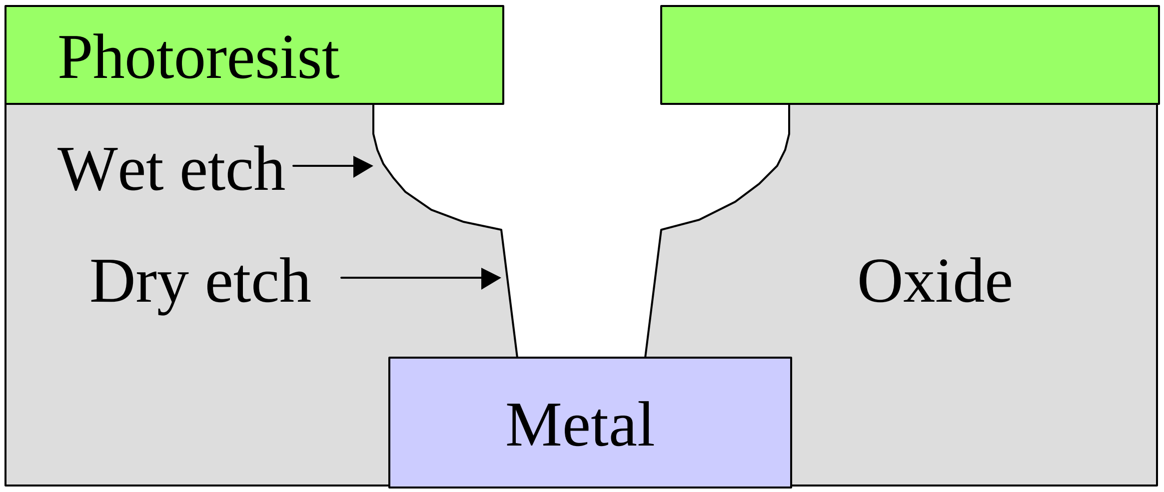
Wet Etching Silicon Dioxide

- Hydrofluoric Acid (HF) Solution
- Normally diluted in buffer solution or DI water to reduce etch rate.

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

- Widely used for CVD film quality control
- BOE: Buffered oxide etch
- WERR: wet etch rate ratio

Wide Glass Contact

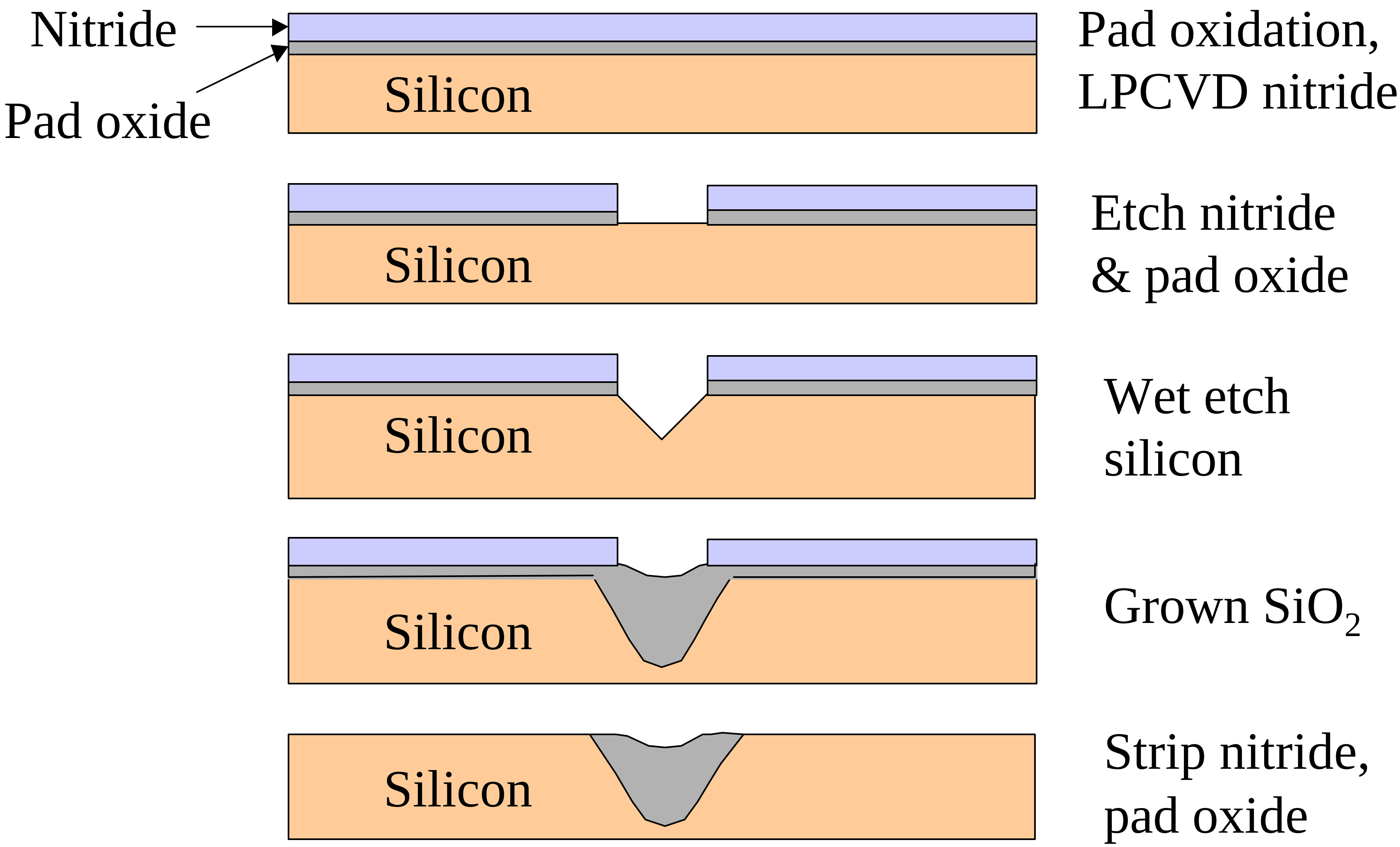


Wet Etching Silicon or Poly

- Silicon etch normally use mixture of nitric acid (HNO_3) and hydrofluoric acid (HF)
- HNO_3 oxidizes the silicon and HF removes the oxide at the same time.
- DI water or acetic acid can be used to dilute the etchant, and reduces the etch rate.

$$\mathbf{Si + 2HNO_3 + 6HF \rightarrow H_2SiF_6 + 2HNO_2 + 2H_2O}$$

Isolation Formation



Wet Etching Silicon Nitride

- Hot (150 to 200 °C) phosphoric acid H_3PO_4 Solution
- High selectivity to silicon oxide
- Used for LOCOS and STI nitride strip

$$Si_3N_4 + 4\,H_3PO_4 \rightarrow Si_3(PO_4)_4 + 4NH_3$$

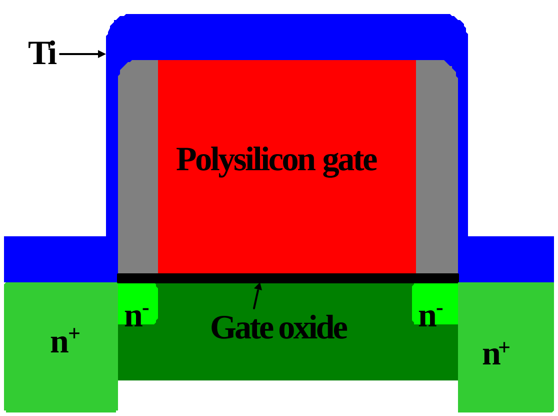
Wet Etching Aluminum

- Heated (42 to 45°C) solution
- One example: 80% phosphoric acid, 5% acetic acid, 5% nitric acid, and 10 % water
- Nitric acid oxidizes aluminum and phosphoric acid removes aluminum oxide at the same time.
- Acetic acid slows down the oxidation of the nitric acid.

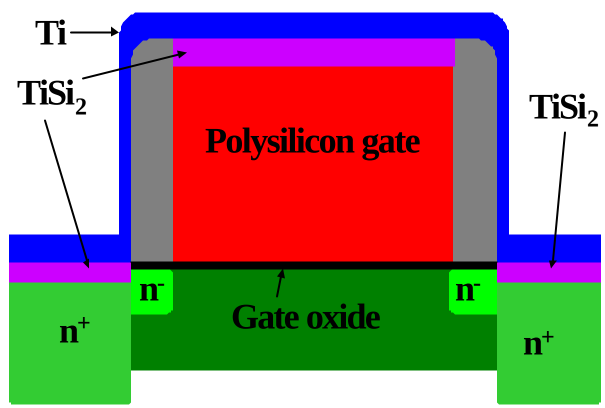
Wet Etching Titanium

- 1:1 mixture of hydrogen peroxide (H_2O_2) and sulfuric acid (H_2SO_4)
- H_2O_2 oxidizes titanium to form TiO_2
- H_2SO_4 reacts with TiO_2 and removes it simultaneously
- H_2O_2 oxidizes silicon and silicide to form SiO_2
- H_2SO_4 doesn't react with SiO_2

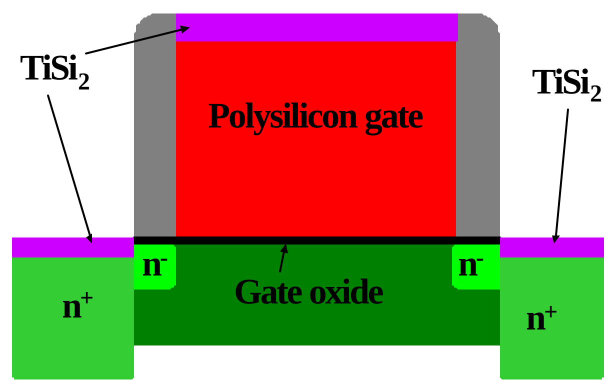
Self-aligned Titanium Silicide Formation



Titanium deposition



Silicide annealing



Titanium wet striping

Factors that Affect Wet Etch Rate

- Temperature
- Chemical concentration
- Composition of film to be etched

Wet Chemical Hazards

- HF
- H_3PO_3
- HNO_4

- Corrosive
- Oxidizer
- Special hazard

Wet Chemical Hazards

- HF
- Don’t feel when contact
- Attack bone and neutralize by calcium
- Acute pain

- Never assume. Treat all unknown clear liquid as HF in IC fab.

Advantages of Wet Etch

- High selectivity
- Relatively inexpensive equipment
- Batch system, high throughput

Disadvantages of Wet Etch

- Isotropic Profile
- Can't pattern sub-3μm feature

- High chemical usage
- Chemical hazards
  - Direct exposure to liquids
  - Direct and indirect exposure to fumes
  - Potential for explosion

Plasma Etch

Introduction

- Gas in, gas out
- Plasma generates free radicals and ion bombardment
- RIE (Reactive Ion Etch)
  - combined chemical and physical etch
- Most patterned etches are RIEs

Comparison of Wet and Dry Etch

	Wet Etch	**Dry Etch**
Etch Bias	Unacceptable for < 3μm	Minimum
Etch Profile	Isotropic	Anisotropic to isotropic, controllable
Etch rate Selectivity	High High	Acceptable, controllable Acceptable, controllable
Equipment cost	Low	High
Throughput	High (batch)	Acceptable, controllable
Chemical usage	High	Low

Plasma Basics

- A plasma is an ionized gas with equal numbers of positive and negative charges.
- Three important collisions:
  - *Ionization* generates and sustains the plasma
  - *Excitation-relaxation* causes plasma glow
  - *Disassociation* creates reactive free radicals

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%.

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

Mean Free Path (MFP)

- Effect of pressure:

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

- Higher pressure, shorter MFP
- Lower pressure, longer MFP

Vacuum and Plasma

- Pressure too high, MFP will be too short
- Ionization usually require at least 15 eV
- Electrons can’t get enough energy to ionize if MFP is too short
- Need vacuum and RF to start and maintain stabilize plasma

Ion Bombardment

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

Ion Bombardment

- Electrons are moving much faster than ions
- Electrons reach electrodes and chamber wall first
- Electrodes are charged negatively, repel electrons and attract ions
- Charge difference near the surface forms sheath potential
- Sheath potential accelerates ions towards the electrode and causes ion bombardment

Ion Bombardment

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

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

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

Ion Bombardment Control

- RF power is the main knob to control etch rate
  - Increasing RF power, increases etch rate
  - usually reduces selectivity
- RF power also used to control film stress for PECVD processes
  - Increasing RF power increase compressive stress

Self-Bias

- Different size electrodes
- No net charge build up in plasma
- Charge fluxes on both electrodes are the same
- Smaller electrode has higher charge density
- Larger DC bias between plasma and smaller electrode

Etch Processes

Chemical	RIE	Physical

Blocking Mechanism	**Damaging Mechanism**
Silicon Etch	Oxide Etch
Poly Etch	Nitride Etch
Metal Etch	

Chemical Etch

- Purely chemical reaction
- By products are gases or soluble in etchants
- High selectivity
- Isotropic etch profile
- Examples:
  - Wet etch
  - Dry strip

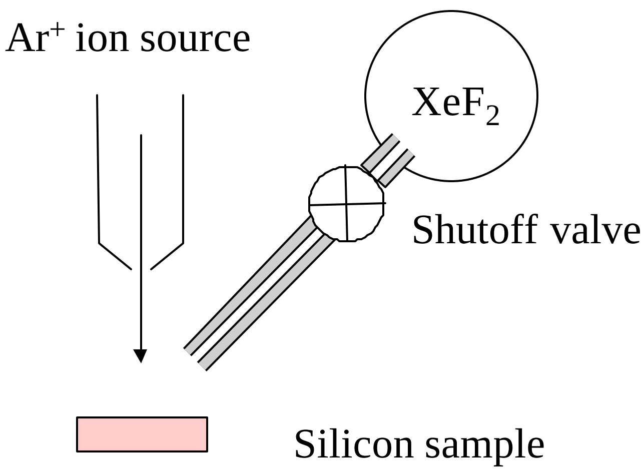
Physical Etch

- Bombardment with inert ions such as Ar^+
- Physically dislodging material from surface
- Plasma process
- Anisotropic profile
- Low selectivity
- Example:
  - Argon sputtering etch

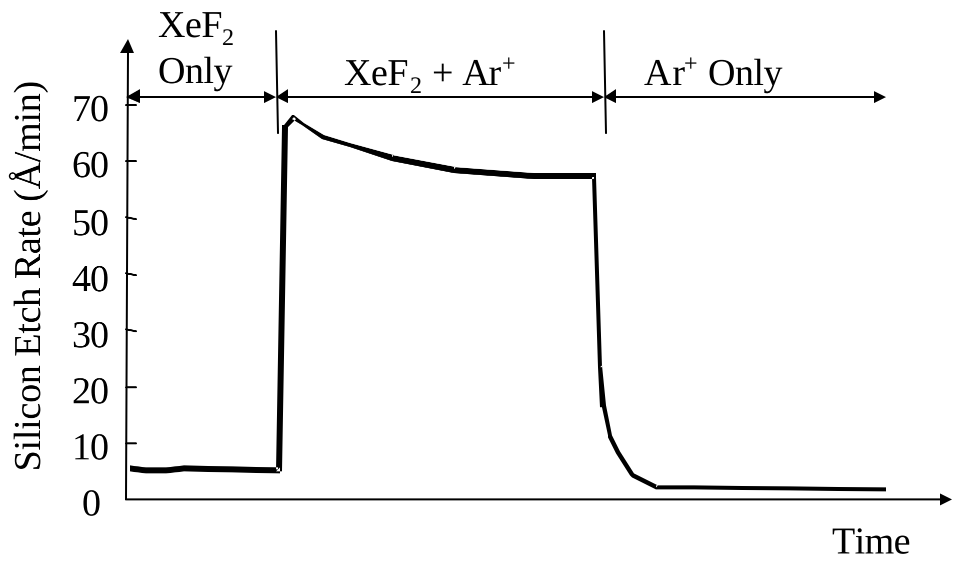
Reactive Ion Etch (RIE)

- Combination of chemical and physical etch
- Plasma process, ion bombardment plus free radicals
- Misleading name, should be called ion assistant etch (IAE)
- High and controllable etch rate
- Anisotropic and controllable etch profile
- Good and controllable selectivity
- All patterned etches are RIE processes in 8” fabs

RIE Experiment



Experiment arrangement

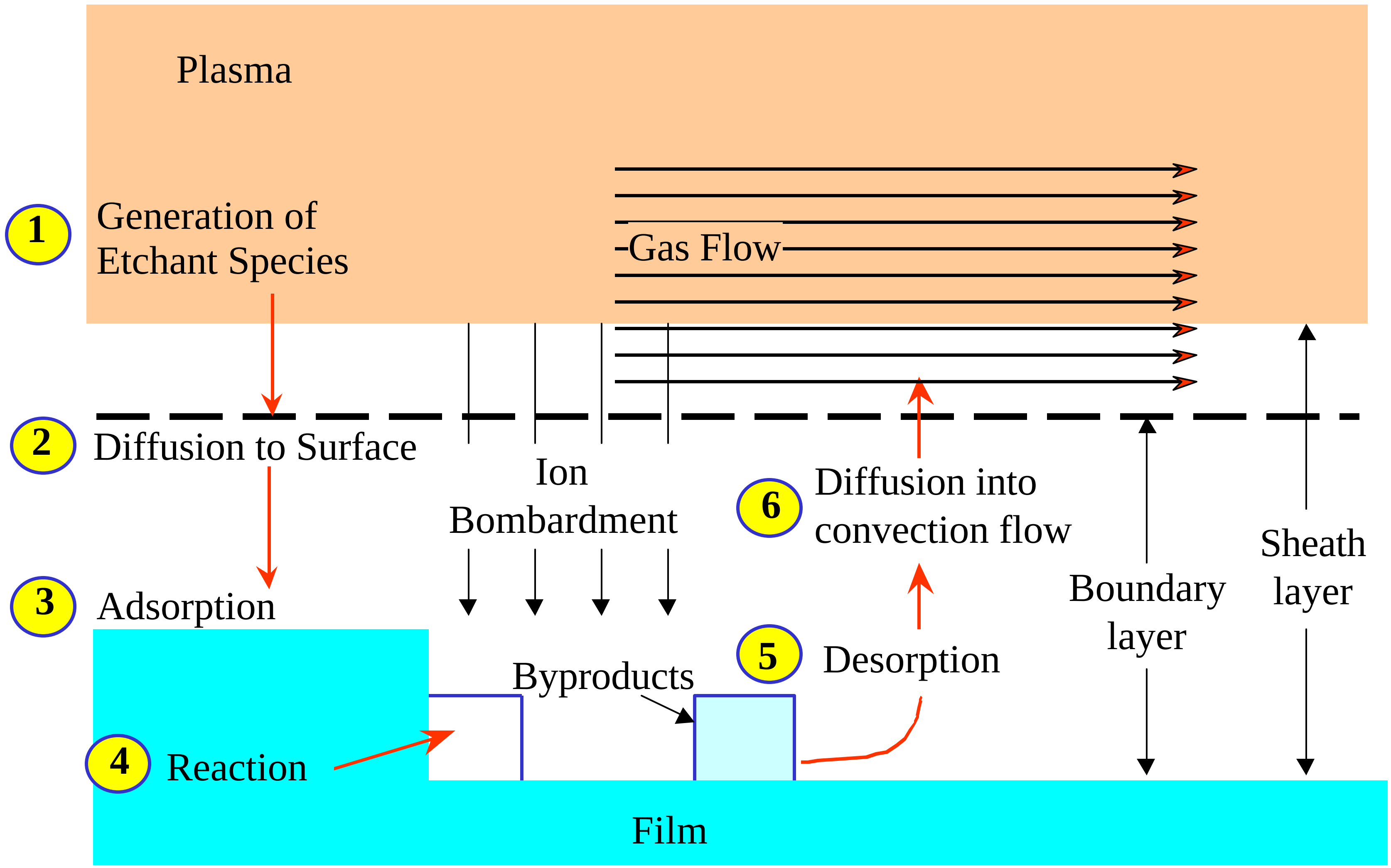


Experiment results

Three Etch Processes

	Chemical Etch	**RIE**	**Physical Etch**
Examples	Wet etch, strip, RP etch	Plasma patterned etches	Argon sputtering
Etch rate	High to low	High, controllable	Low
Selectivity	Very good	Reasonable, controllable	Very poor
Etch profile	Isotropic	Anisotropic, controllable	Anisotropic
Endpoint	By time or visual	Optical	By time

Etch Process Sequence



Etch Profile Control

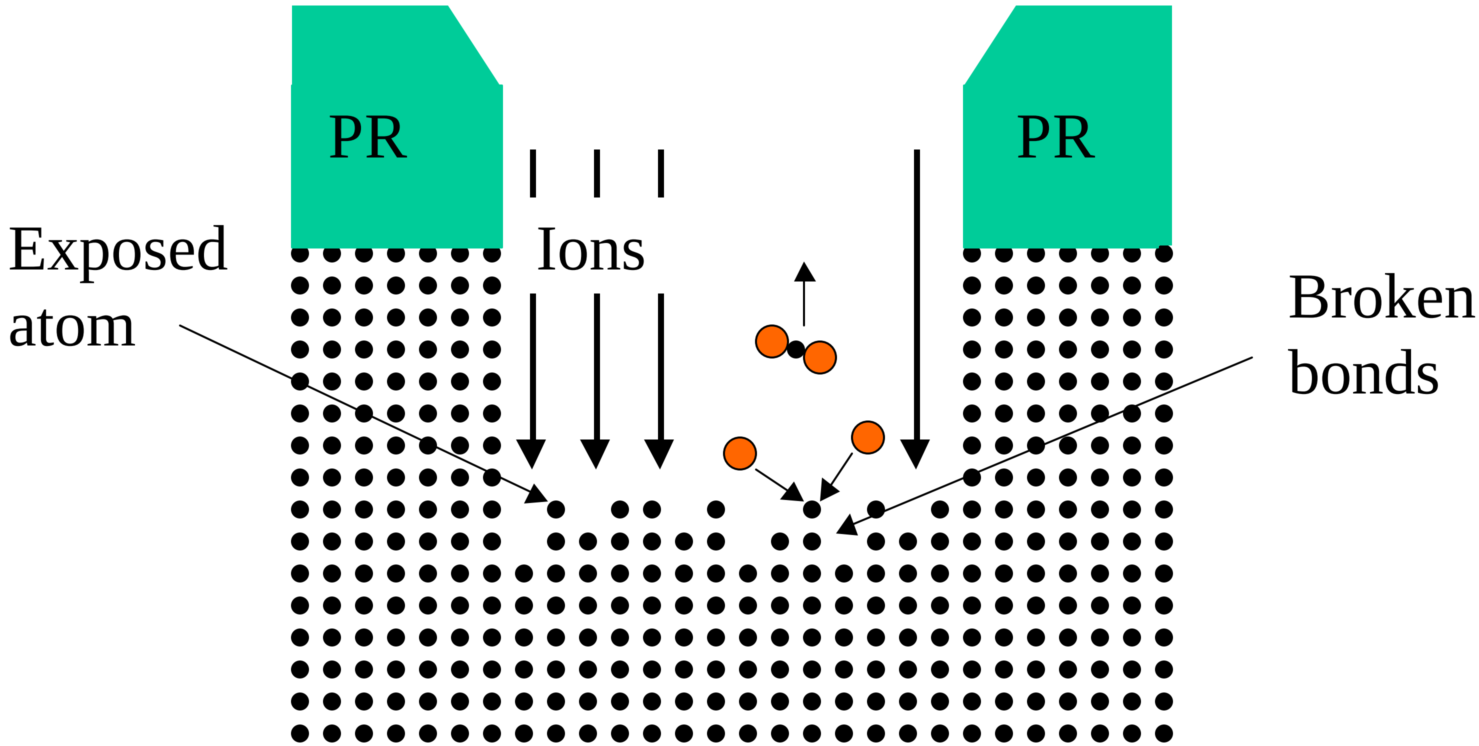
Damaging	**Blocking**
Oxide	Epi-silicon
Nitride	Polysilicon
	Metal

Anisotropic profile control can be achieved by using ion bombardment from plasma

Damaging Mechanism

- Heavy ion bombardment damages chemical bonds
- Exposed surface atoms are easier to react with etchant free radicals
- Ion bombardment is mainly in vertical direction
- Etch rate on vertical direction is much higher than on horizontal direction $\rightarrow$ anisotropic etch

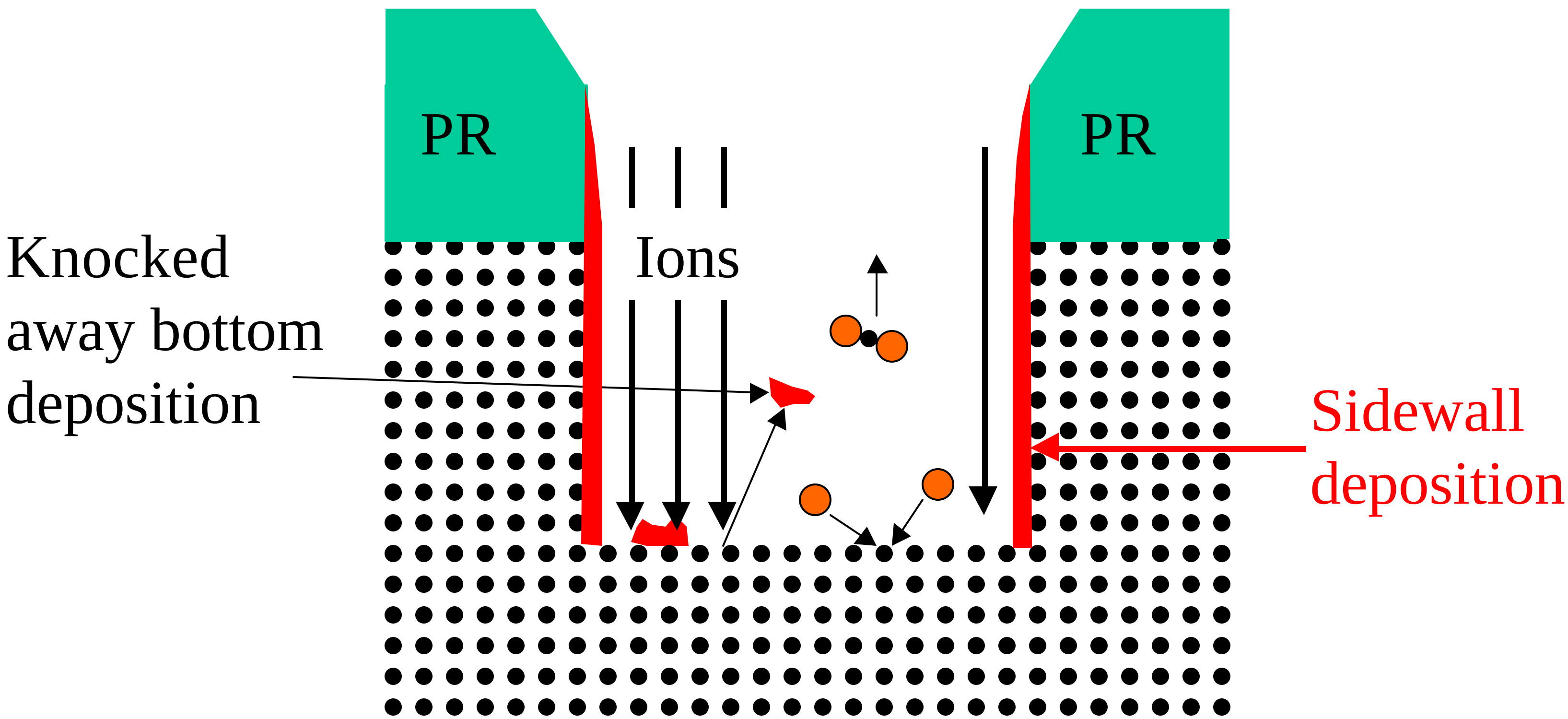
Damage Mechanism



Blocking Mechanism

- Chemicals deposit on the surface
- Sputtered photoresist and/or byproducts of etch chemical reaction
- Ion bombardment is mainly in vertical direction
- It prevents deposition to buildup on bottom
- Deposition on sidewall blocks etch process
- Etch process is mainly in vertical direction

Blocking Mechanism



Etched Atom or molecule

Etchant free radical

Etch Byproduct

Etch Mechanisms and Their Applications

Pure Chemical Etch	Reactive Ion Etch (RIE)		Pure Physical Etch
	Blocking mechanism	Damaging mechanism	
No ion bombardment	Light ion bombardment	Heavy ion bombardment	Only ion bombardment
PR strip	Single crystal silicon etch		
Ti strip	Polysilicon etch	Oxide etch	Sputtering etch
Nitride strip	Metal etch	Nitride etch	

Benefits of Using Plasma For Etch Process

- High etch rate
- Anisotropic etch profile
- Optical endpoint

Plasma Etch Chambers

- Batch system
- Single wafer system
- High density plasma system
  - IPC
  - ECR
  - Helicon

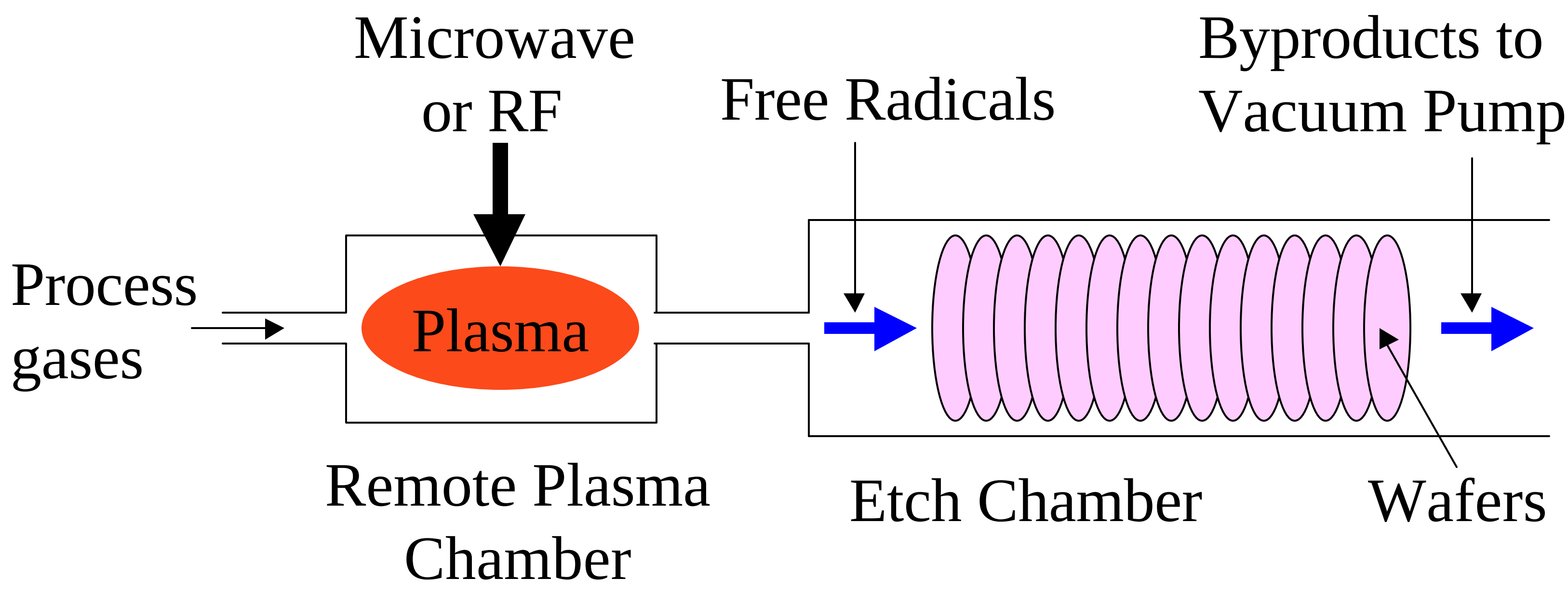
Batch Systems

- High throughput
- Older systems
- Smaller diameter, <150 mm or 6 inch
- Downstream etcher and barrel etch system
  - Both are pure chemical etch, no ion bombardment

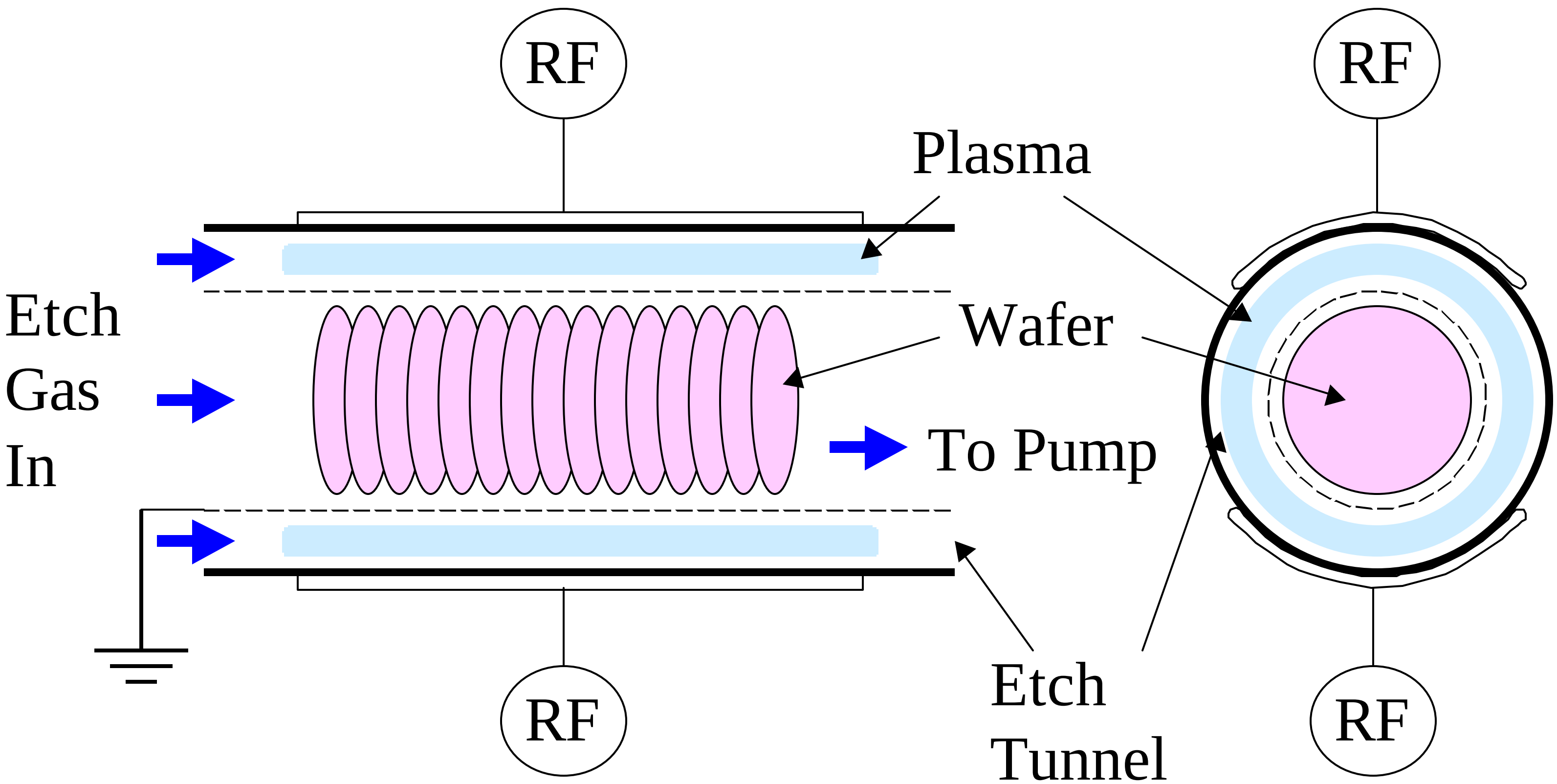
Etch Chamber

- Lower pressure, longer MFP, less collisions
- High ion energy, less ion scattering and better anisotropy etch profile
- Lower pressure also helps to remove the etch byproducts
- Etch chambers usually operate at lower pressure

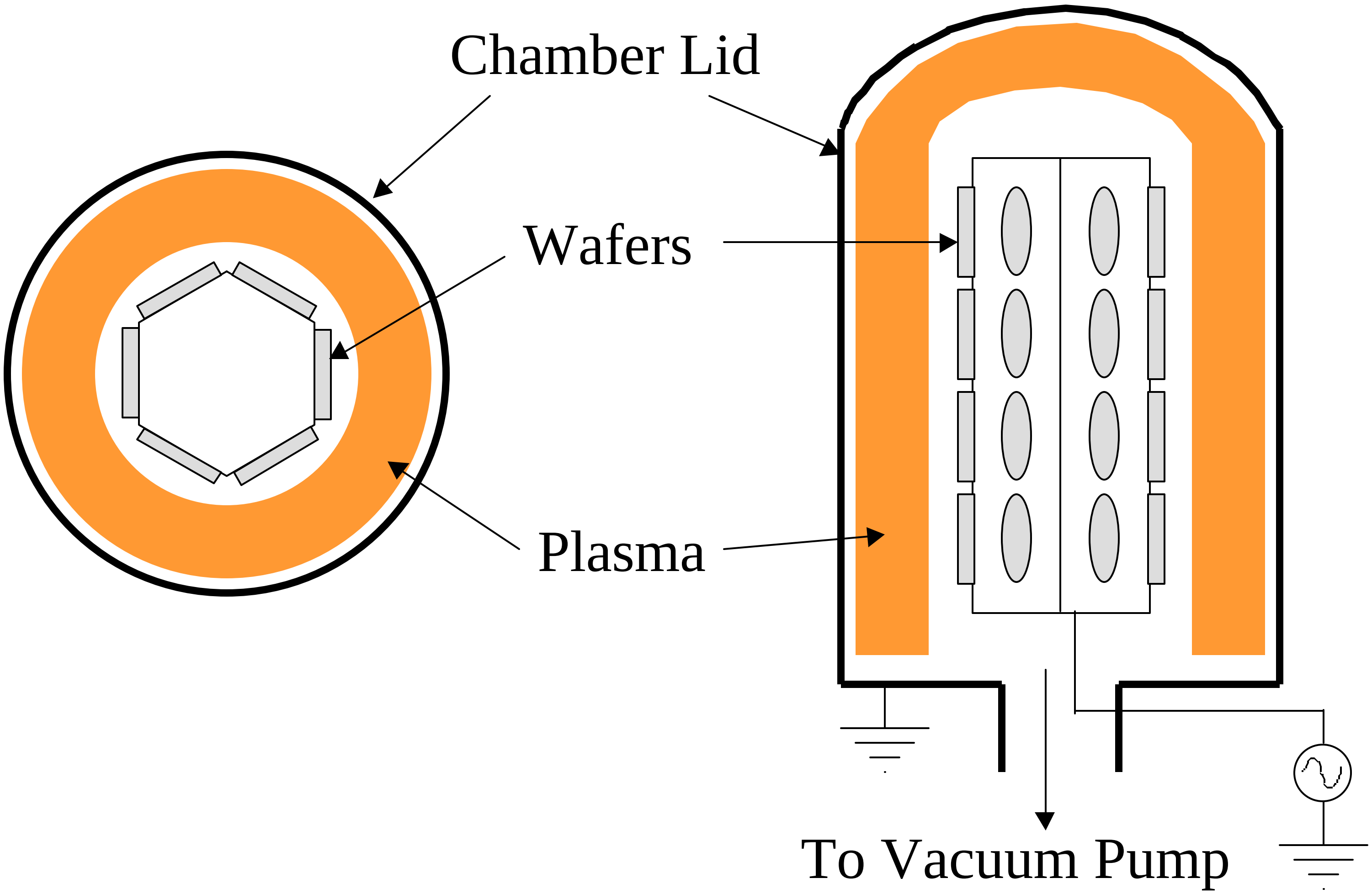
Down Stream Plasma Etcher



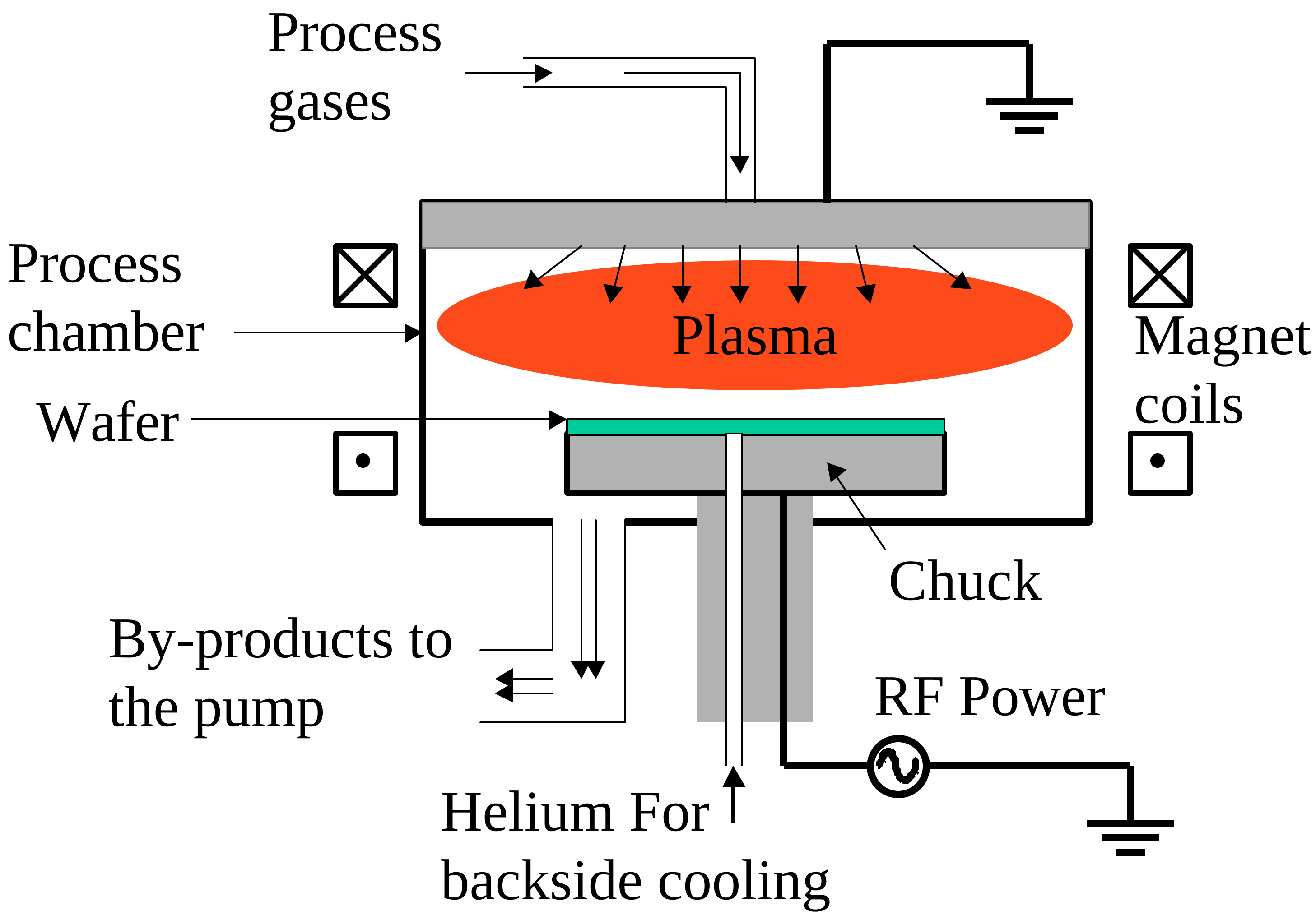
Barrel Etch System



Batch RIE System



Schematic of an RIE System



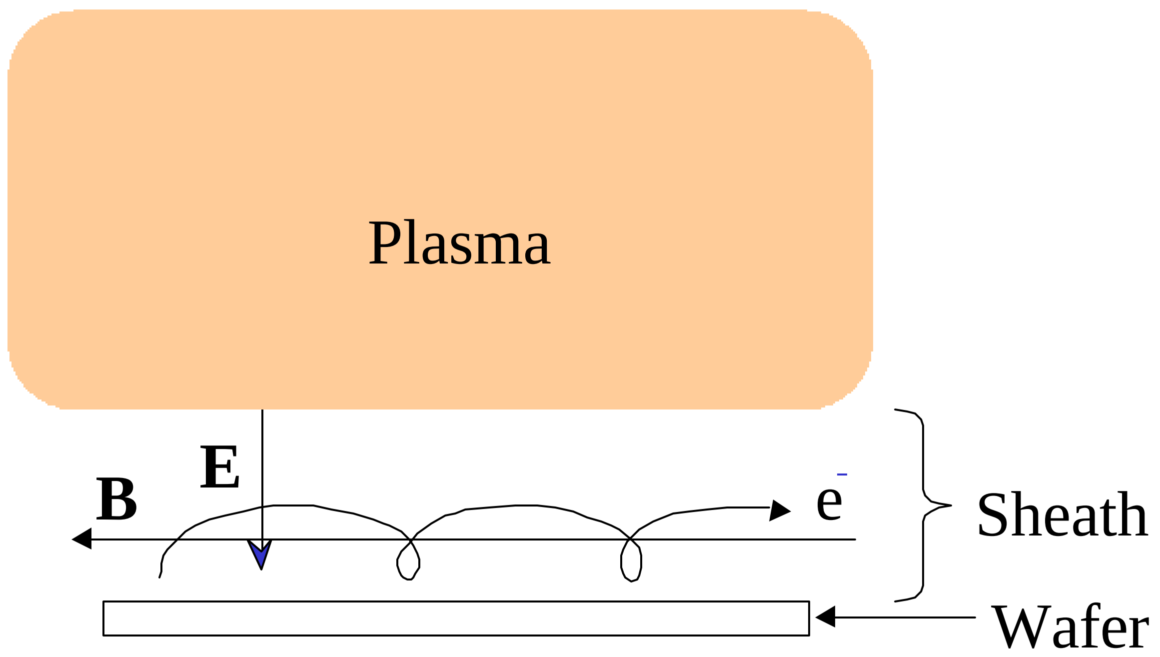
Purpose of Magnets

- Long MFP, insufficient ionization collisions
- In a magnetic field, electron is forced to spin with very small gyro-radius
- Electrons have to travel longer distance
- More chance to collide
- Increasing plasma density at low pressure

Effect of Magnetic Field on DC Bias

- Magnetic field increasing electron density in sheath layer
- Less charge difference in sheath region
- Lower DC Bias
- Effects on ion bombardment
  - increasing ion density
  - reducing ion energy

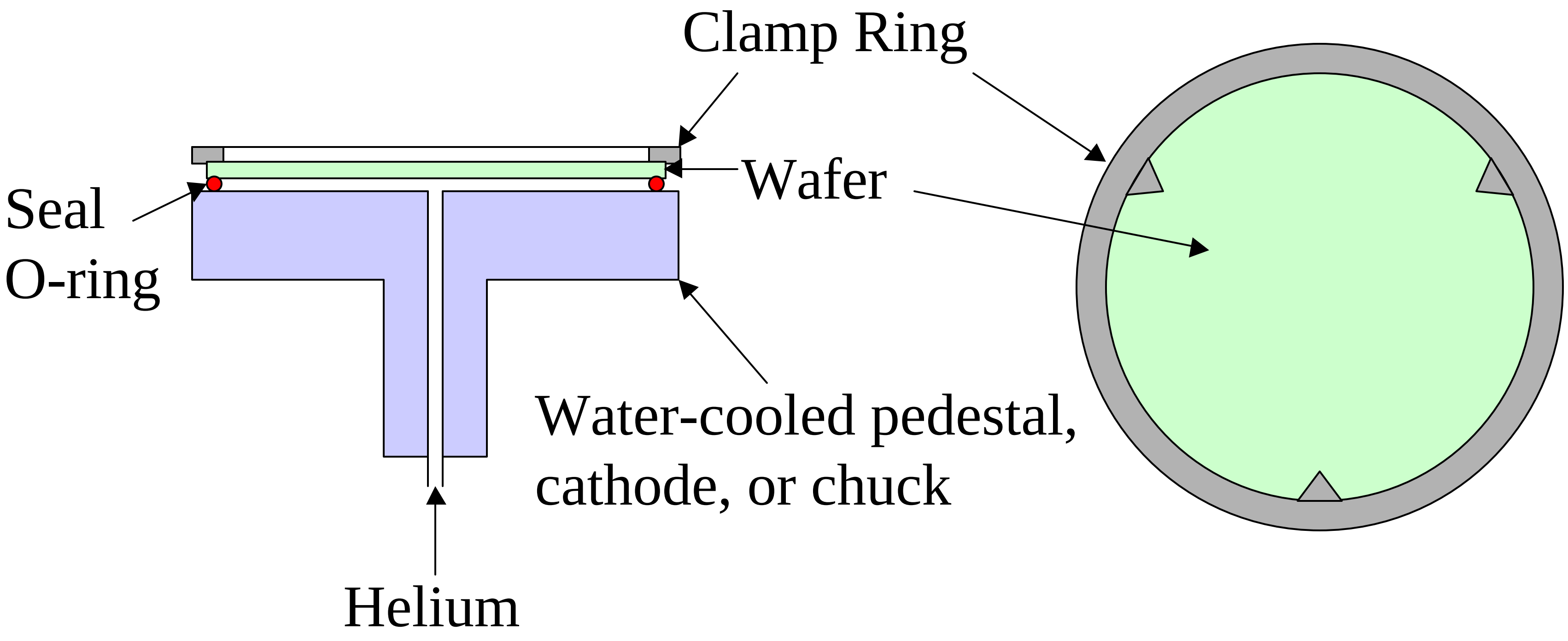
Effect of Magnetic Field on DC Bias



Wafer Cooling

- Ion bombardment generate large amount heat
- High temperature can cause PR reticulation
- Need cool wafer to control temperature
- Helium backside cooling is commonly used
- Helium transfer heat from wafer to water cooled chuck

Clamp Ring

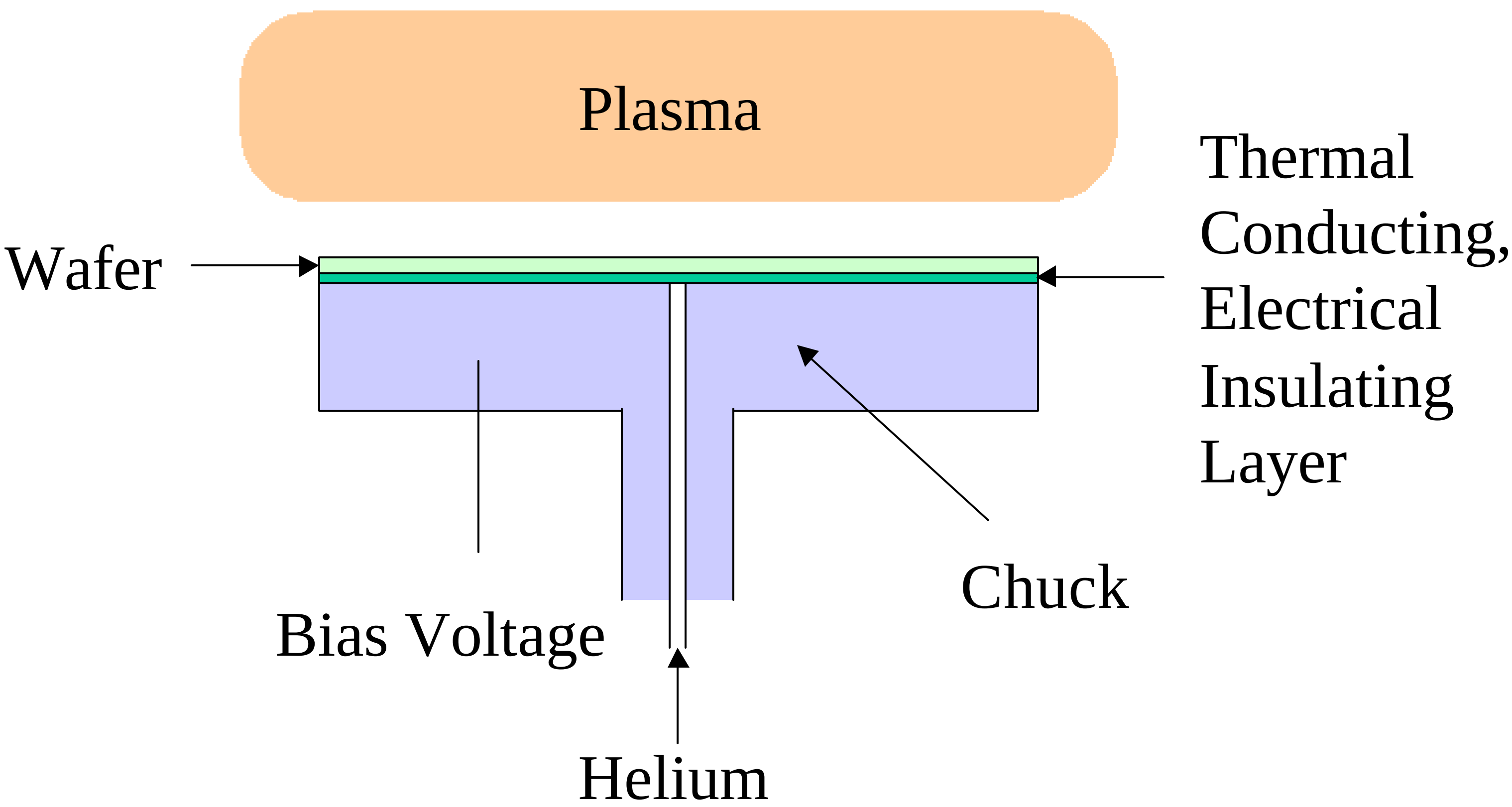


Clamp Ring
Wafer
Seal
O-ring
Water-cooled pedestal,
cathode, or chuck
Helium

Electrostatic Chuck (E-chuck)

- Helium needs to be pressurized
- Wafer has high pressure at backside because low chamber pressure
- Need mechanisms to hold wafer
- Either mechanical clamp or E-chuck
- Clamp ring causes particles and shadowing effect
- E-chuck is rapidly replacing clamp ring

Electrostatic Chuck



Facts of Helium

Name	Helium
Symbol	He
Atomic number	2
Atomic weight	4.002602
Discoverer	Sir William Ramsay and independently by N. A. Langley and P. T. Cleve
Discovered at	London, England and Uppsala, Sweden
Discovery date	1895
Origin of name	From the Greek word "helios" meaning "sun". Its line radiation (a yellow line at 587.49 nm) was first detected from the solar spectrum during in solar eclipse of 1868 in India by French astronomer,
Molar volume	21.0cm^3
Velocity of sound	970 m/sec
Refractive index	1.000035
Melting point	0.95 K or -272.05 C
Boiling point	4.22 K or -268.78 C
Thermal conductivity	0.1513 W m^{-1} K^{-1}
Applications	Cooling gas and carrier gas in CVD and etch processes

High Density Plasma (HDP) Sources

- Low pressure is desired for etch process
- Electrons are easily lost due to long MFP by collide with electrodes or chamber wall
- Hard to generate plasma
- Parallel plate system or capacitive coupled system can not generate high density plasma
- Different plasma systems are needed to generate HDP at low pressure

HDP Systems

- Inductively coupled plasma (ICP)
- Electron cyclotron resonance (ECR)
- Helicon

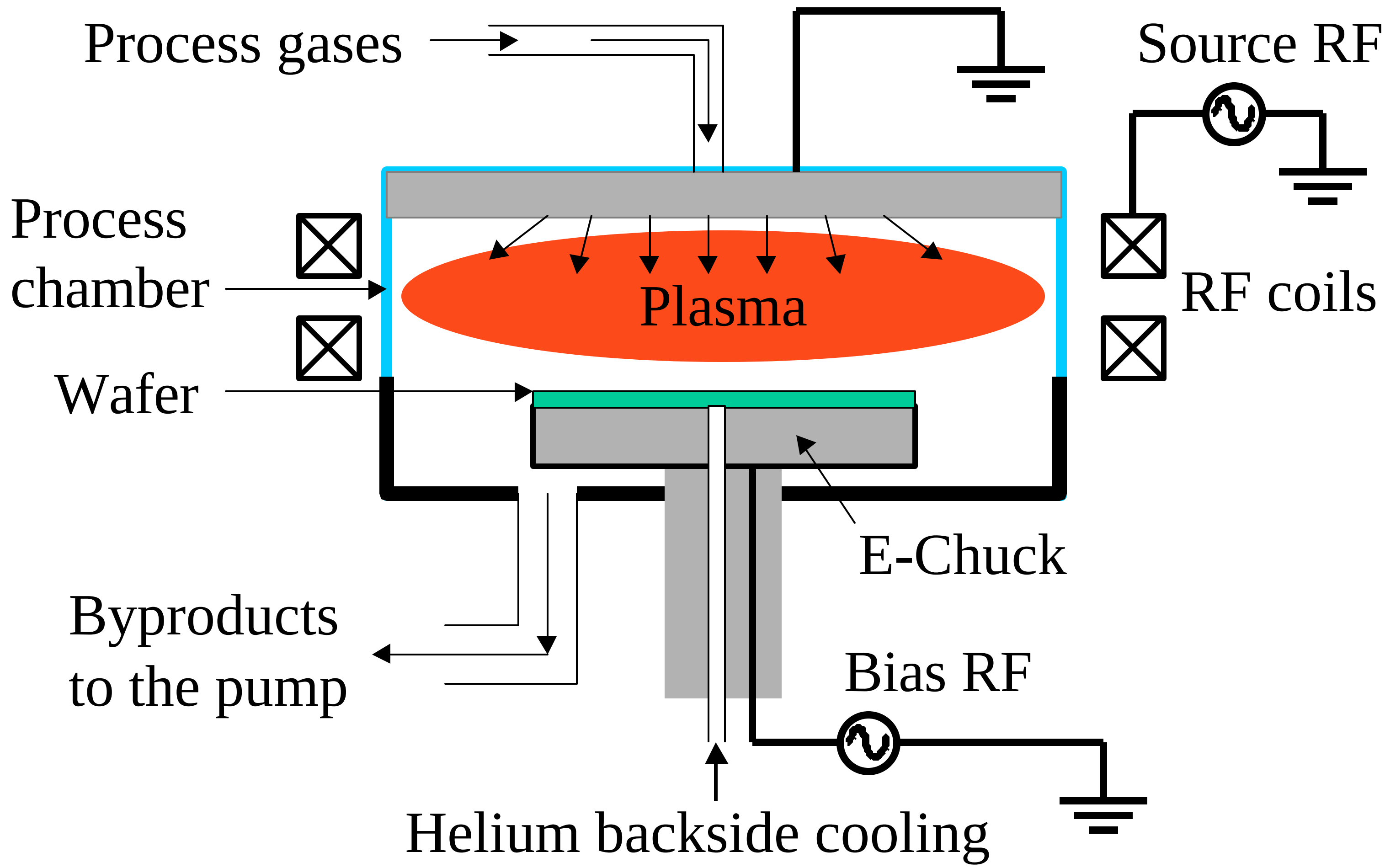
ICP

- Inductively couple RF power to plasma
- Like a transformer, also called TCP
- Changing magnetic field cause electric field
- Electrons are accelerated in angular direction
- Could achieve high plasma density at low pressure

ICP Chamber

- Upper part of chamber: ceramic or quartz
- Source RF inductively couple with plasma
- Source RF generates plasma and controls ion density
- Bias RF controls ion bombardment energy
- Ion energy and density independently controlled

Schematic of ICP Chamber



ECR

- In magnetic field, electron gyro-frequency

$$W_e \text{ (MHz)} = 2.80\ B \text{ (Gauss)}$$

- If incident microwave frequency equals to W_e

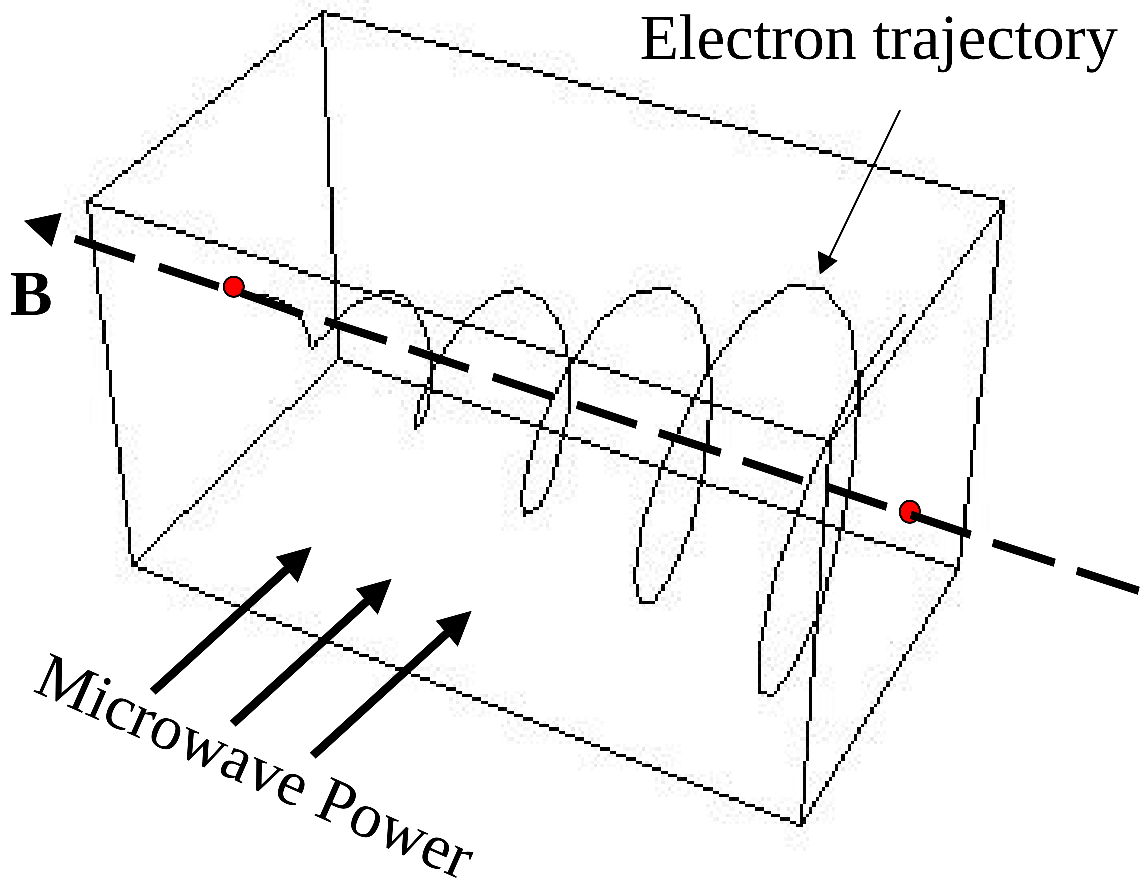
$$w_{MW} = W_e$$

- Resonance
- Electrons get energy from microwave

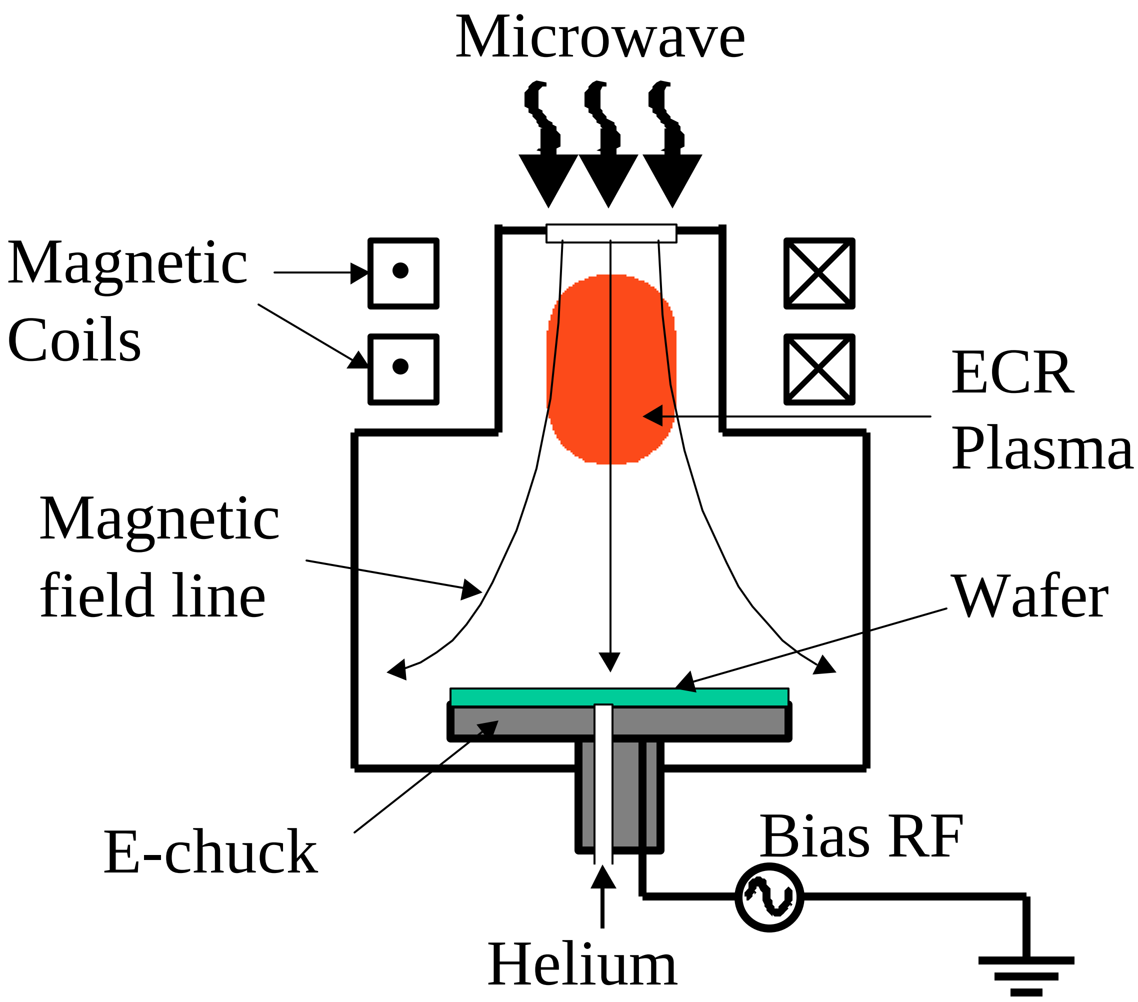
ECR

- Resonance condition won't change with fixed w_{MW} and B
- Electrons gyro-radius, r = v_t/W_e is very small
- Electron can be accelerated to high energy for ionization collision
- Generate high density plasma at low pressure

Illustration of ECR



Schematic of ECR Chamber



Endpoint

- Each atom has its own emission wavelength
- Color of plasma changes when etch different materials
- Optical sensors can be used to detect the change and indicate the endpoint for plasma etch processes

Etch Endpoint Wavelengths

Film	**Etchant**	**Wavelength (Å)**	**Emitter**
Al	Cl_2, BCl_3	2614	AlCl
		3962	Al
Poly Si	Cl_2	2882	Si
		6156	O
Si_3N_4	CF_4/O_2	3370	N_2
		3862	CN
		7037	F
		6740	N
SiO_2	CF_4 and CHF_3	7037	F
		4835	CO
		6156	O
PSG, BPSG	CF_4 and CHF_3	2535	P
W	SF_6	7037	F

Plasma Etch Processes

Advantage of the Plasma Etch

- High, controllable etch rate
- Good selectivity
- Anisotropic etch profile

- Disadvantage: expensive, complicated system
  - Vacuum, RF, robot, E-chuck and etc.

Etch Mechanisms and Requirements

- Oxide etch using damaging mechanism
- More physical than chemical
- Higher RF power and lower pressure
- Silicon and metal etches using blocking mechanism
- Chemical than physical
- Usually require less RF power

PLASMA ETCH

- Etch dielectric
- Etch single crystal silicon
- Etch polysilicon
- Etch metal
- Summary

Dielectric Etch

- Etch oxide
  - Doped and undoped silicate glass
  - Contact (PSG or BPSG)
  - Via (USG, FSG or low-κ dielectric)
- Etch nitride
  - STI
  - Bonding pad

Dielectric Etch

- Fluorine chemistry

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

- CF_4 is commonly used as fluorine source
- NF_3 and SF_6 have also been used

Some Facts About Fluorine

Name	Fluorine
Symbol	F
Atomic number	9
Atomic weight	18.9984032
Discoverer	Henri Moissan
Discovered at	France
Discovery date	1886
Origin of name	From the Latin word "fluere" meaning "to flow"
Molar volume	11.20 cm^3
Velocity of sound	No data
Refractive index	1.000195
Melting point	53.53 K or -219.47 C
Boiling point	85.03 K or -187.97 C
Thermal conductivity	0.0277 W m^{-1} K^{-1}
Applications	Free fluorine as the main etchant for silicon oxide and silicon nitride etching processes

Contact Etch

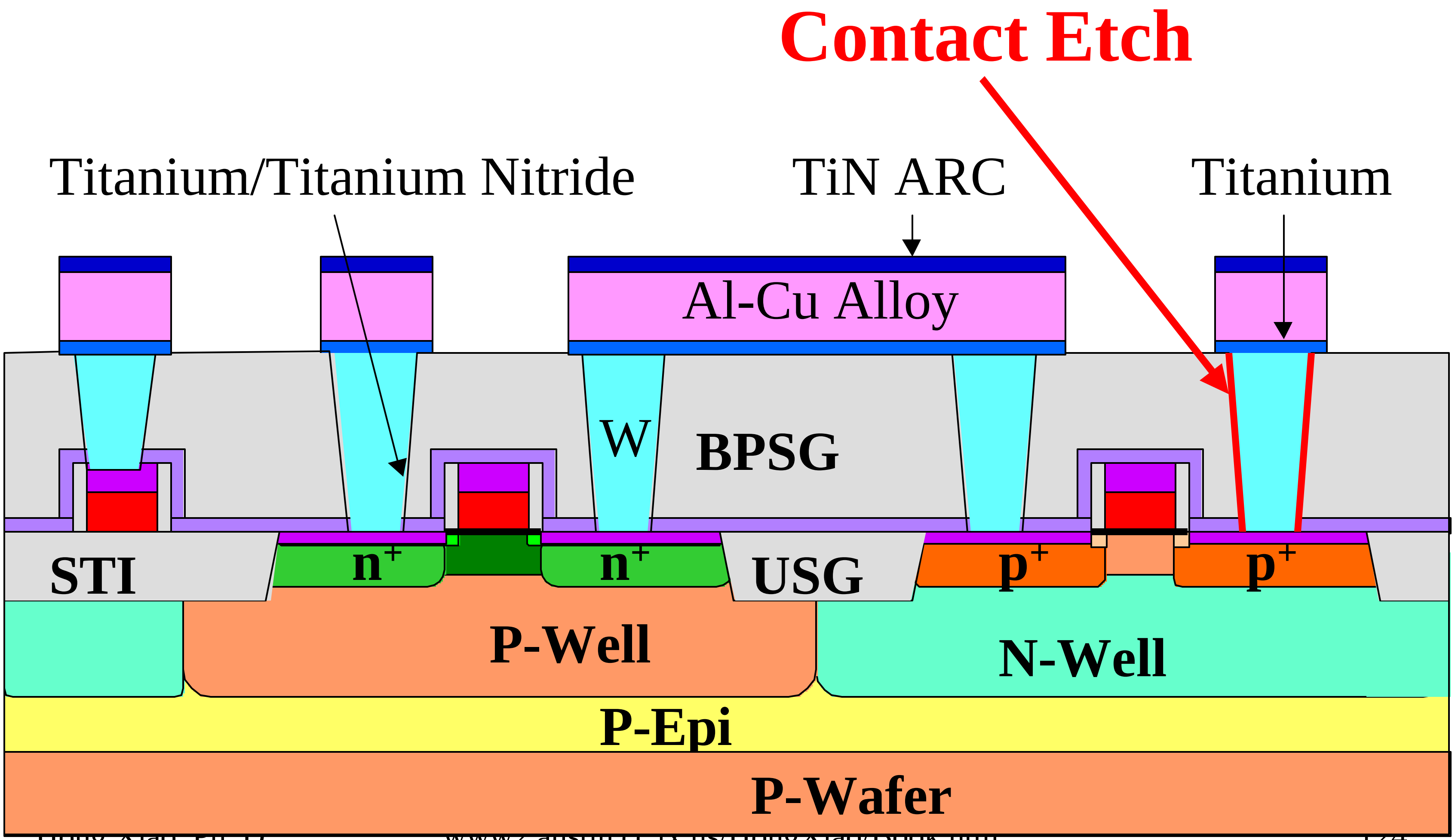
- Holes connect silicon to metal lines
- Doped silicate glass, PSG for BPSG
- Fluorine form CF_4 as the main etchant
- CHF_3 as polymer precursor to improve selectivity to silicon and silicide
- Ar to improve damaging effect
- Some people also use O_2 or H_2
- High selectivity to Si or silicide is required

Contact Etch

- Etch PSG or BPSG
- Open contact hole for silicon to metal interconnections
- Need high selectivity over silicide and photoresist
- Fluorine chemistry

$$\underset{\text{gas}}{F} + \underset{\text{solid}}{SiO_2} \longrightarrow \underset{\text{gas}}{SiF_4} + \underset{\text{gas}}{O}$$

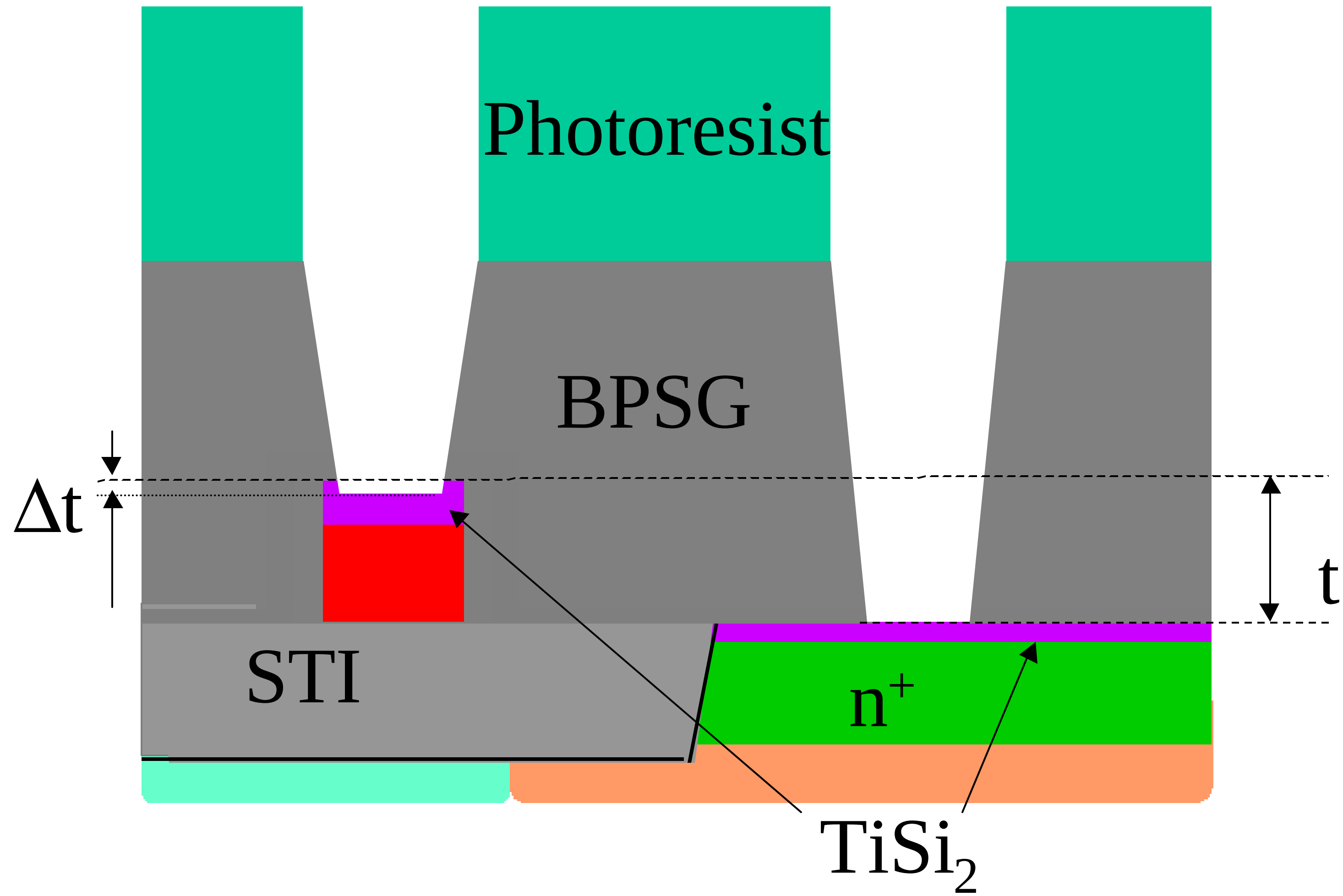
CMOS Cross-section



Challenge for Contact Etch

- Contact holes to polyside gate and local interconnection are about half of the depth of source/drain contact holes
- Require high (B)PSG to silicide selectivity

Contact Etch



Contact Etch

- F/C ratio F/C > 3, etch dominant

  F/C < 2, polymerization
- When etching oxide, oxygen byproduct can react with C to free more fluorine
- When etching silicon or silicide, no oxygen releasing, fluorine is consumed, F/C ratio drop below 2 and start polymer deposition
- Polymer blocks further etch process
- High BPSG-to-$TiSi_2$ selectivity

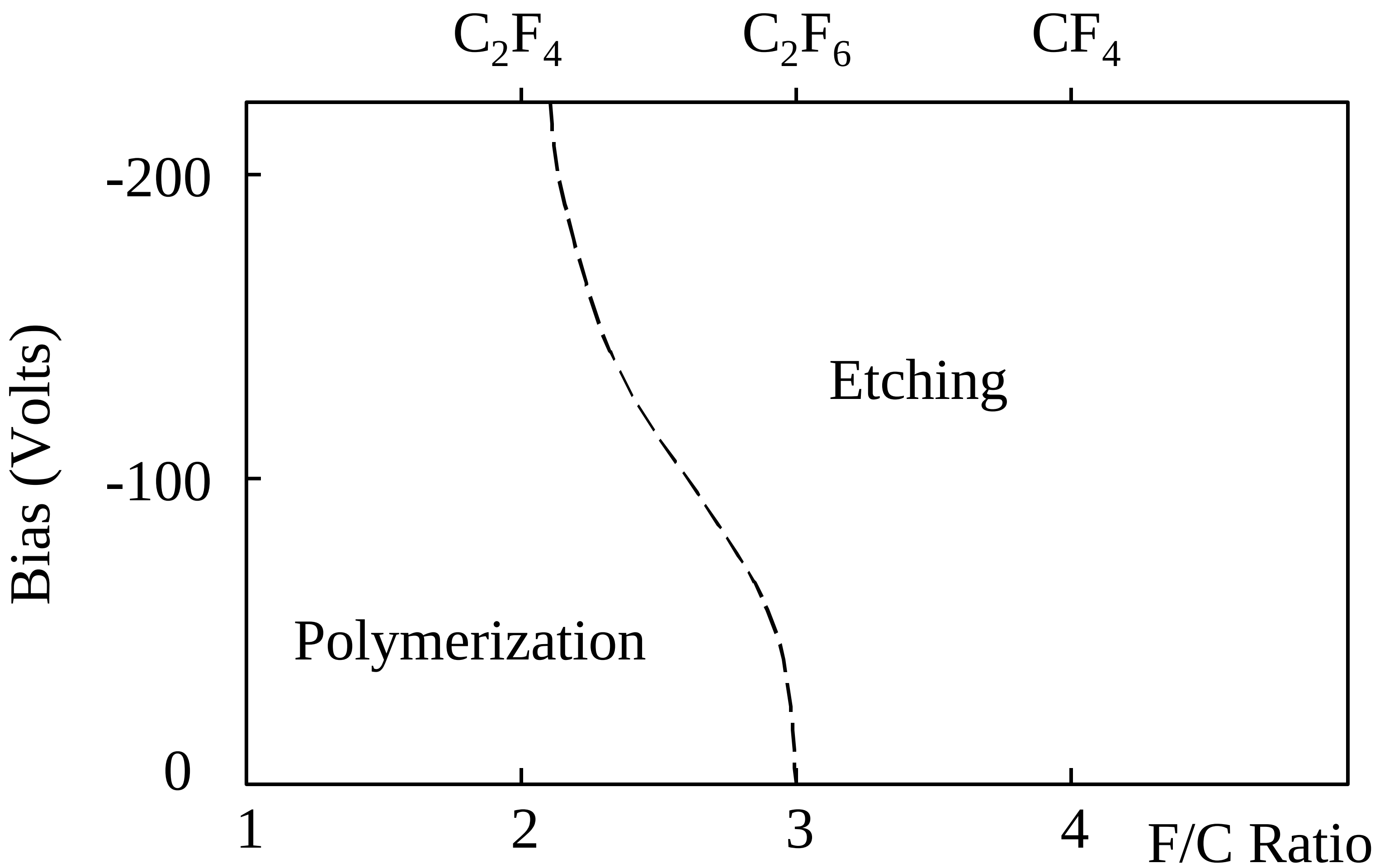
Dielectric Etch

$$CF_4 \xrightarrow{\text{plasma}} CF_3 + F$$

$$4F + SiO_2 \xrightarrow{\text{plasma}} SiF_4 + 2O$$

$$12F + TiSi_2 \xrightarrow{\text{plasma}} TiF_4 + 2SiF_4$$

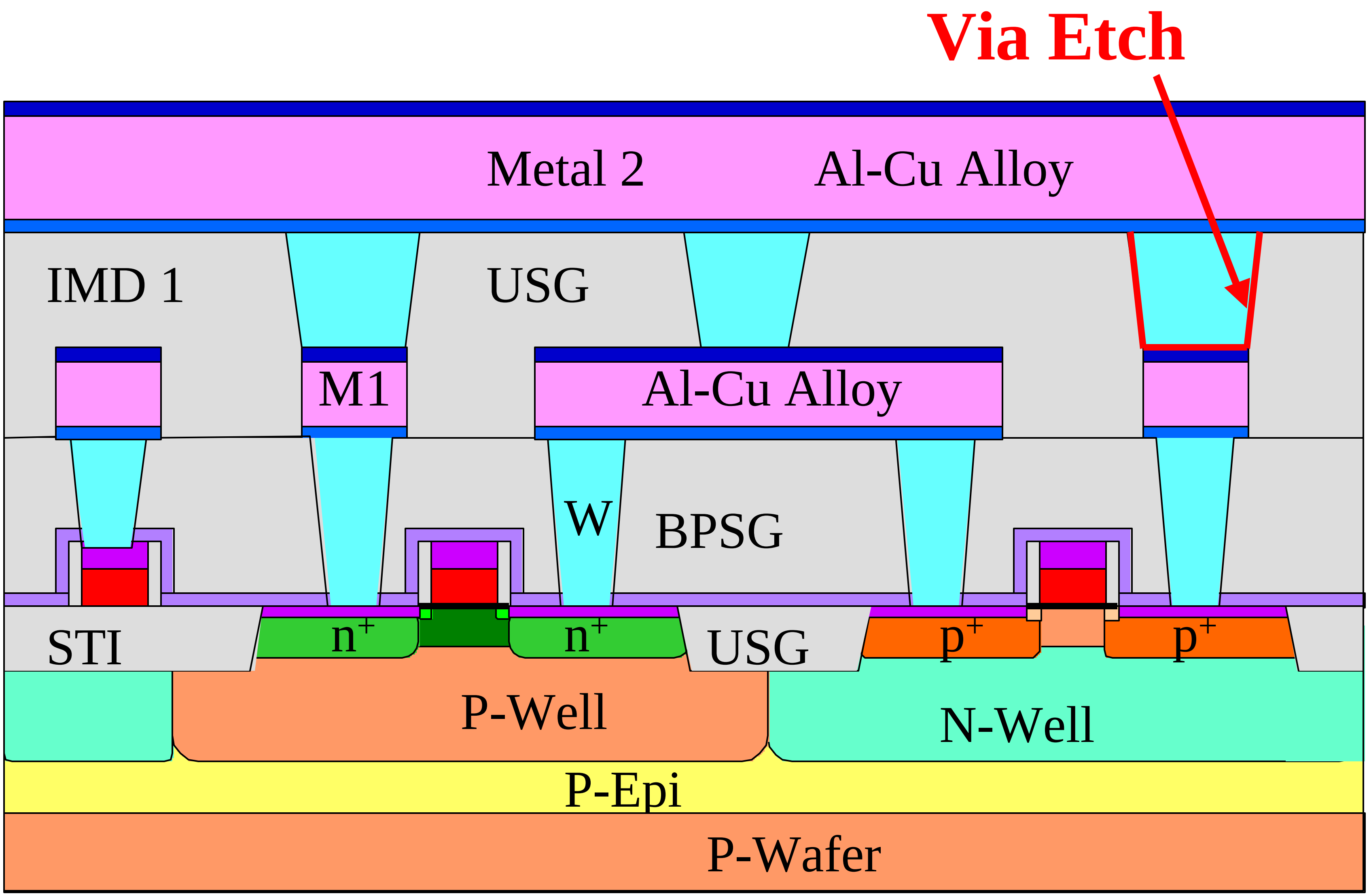
F/C Ratio, DC Bias and Polymerization



Via Etch

- Etch USG
- Open via hole for metal to metal interconnections
- Need high selectivity over metal and photoresist
- Fluorine chemistry

CMOS Cross-section



Etch Via

- PR mask
- Fluorine as the main etchant
- CF_4, CHF_3 and Ar are used for the etch process. O_2 or H_2 also can be used
- High selectivity over metal
- Avoiding metal sputtering
- Dual damascene etch

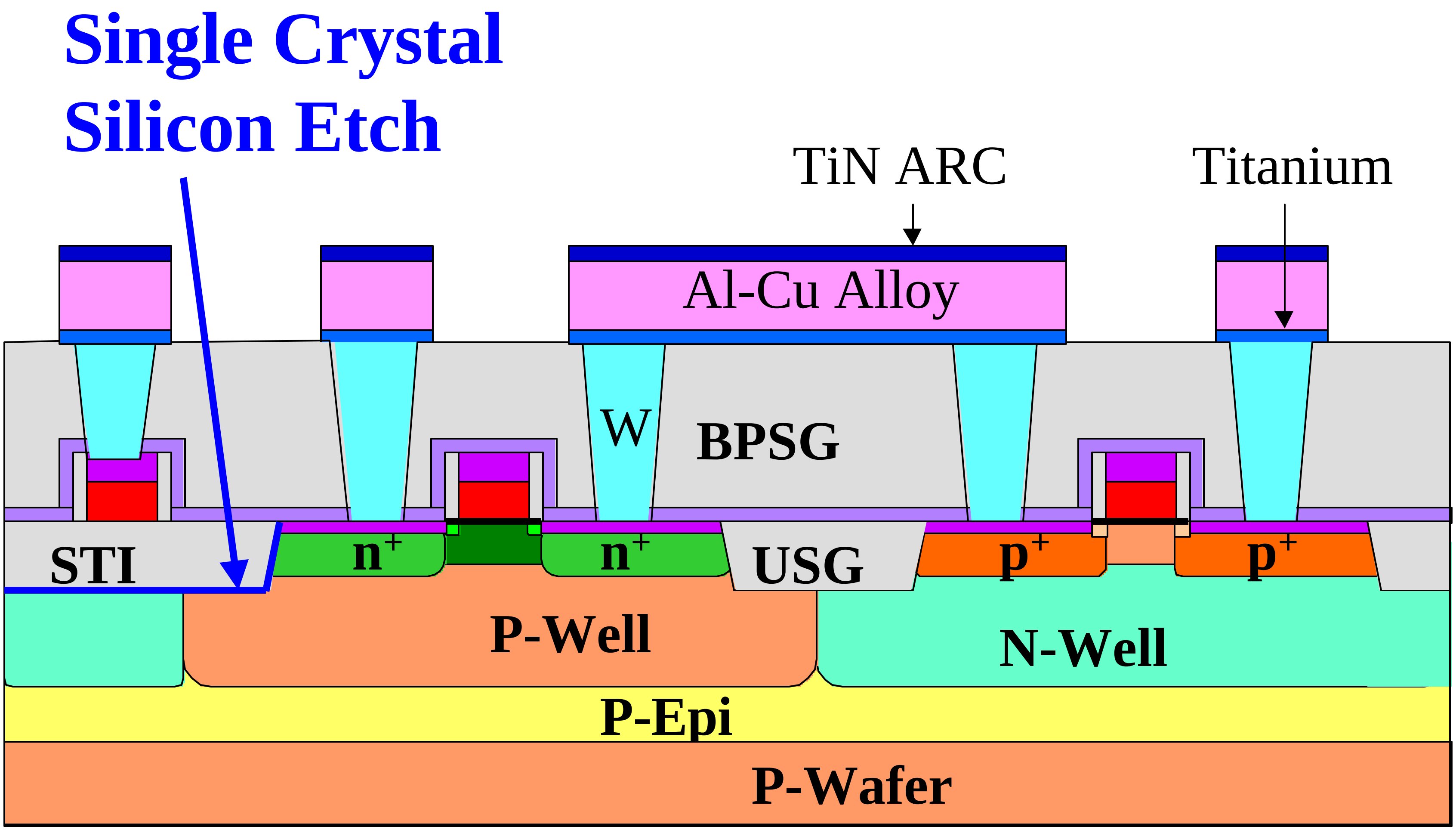
Summary of Dielectric Etch

Name of etch	Hard mask	Contact	Via	Bonding pad
Materials	Si_3N_4 or SiO_2	PSG or BPSG	USG or FSG	Nitride and oxide
Etchants	CF_4, CHF_3	CF_4, CHF_3, ...	CF_4, CHF_3, ...	CF_4, CHF_3, ...
Underneath layer	Si, Cu, Au,	Poly or silicide	Metal	Metal
Endpoints	CN, N or O	P, O, and F	O, Al and F	O, Al and F

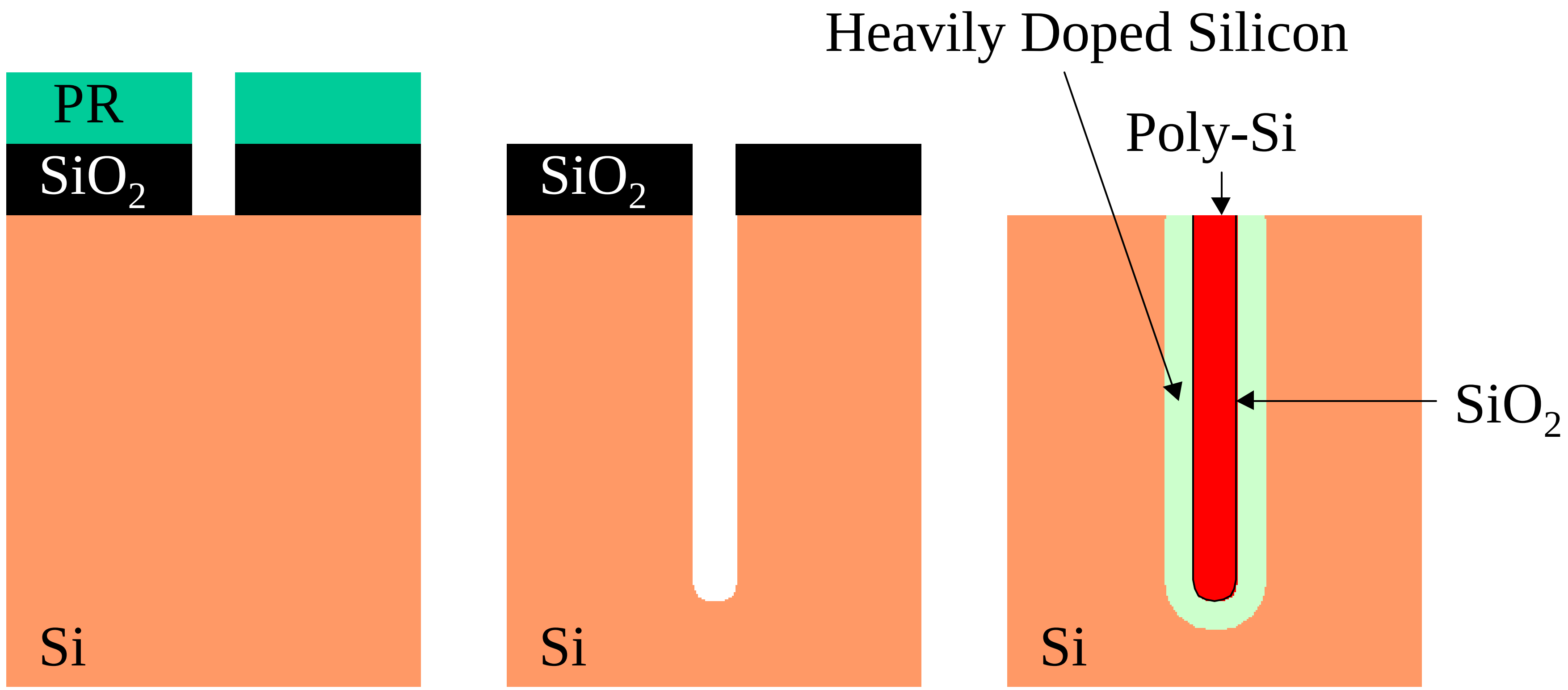
Single Crystal Silicon Etch

- Shallow trench isolation (STI)
- Deep trench for capacitor
- Hard mask, silicon nitride and oxide
- PR may cause substrate contamination
- Bromine chemistry
- HBr as the main etchant

CMOS Cross-Section



Deep Trench Capacitor



Etch hard mask

Etch silicon

Capacitor Formation

Some Facts About Bromine

Name	Bromine
Symbol	Br
Atomic number	35
Atomic weight	79.904
Discoverer	Antoine-J. Balard
Discovered at	France
Discovery date	1826
Origin of name	From the Greek word "bromos" meaning "stench"
Molar volume	19.78 cm^3
Velocity of sound	No data
Resistivity	> 10^{18} μΩ cm
Refractive index	1.001132
Melting point	-7.2 C
Boiling point	59 C
Thermal conductivity	0.12 W m^{-1} K^{-1}
Applications	Free bromine as the main etchant for single crystal silicon etching processes
Source	HBr

Single Crystal Silicon Etch Chemistry

$$HBr \xrightarrow{\text{plasma}} H + Br$$

$$Br + Si \rightarrow SiBr_4$$

- Small amount O_2 for sidewall passivation
- A little NF_3 for preventing black silicon
- Endpoint by time

Polysilicon Etch

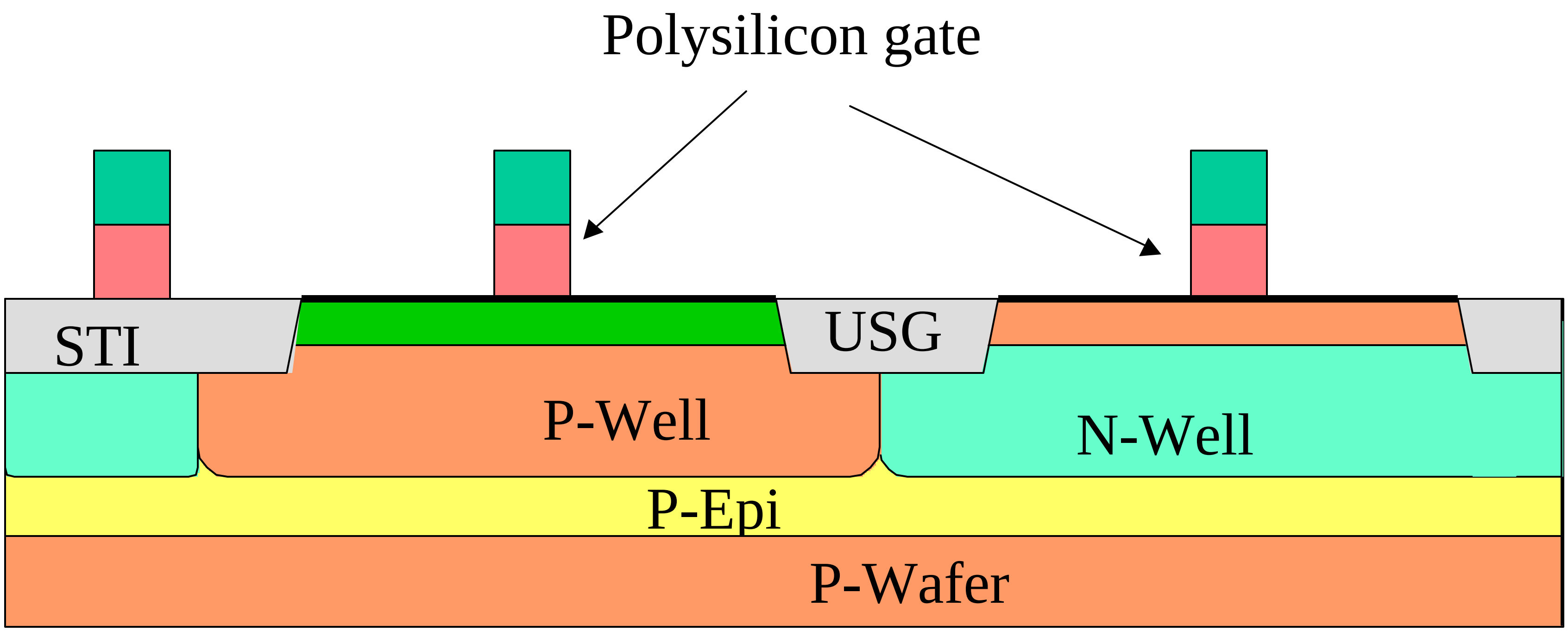
- Gates and local interconnections
  - Most critical etch process, smallest CD
- Capacitor electrodes for DRAM
- Require high selectivity over silicon dioxide
- Cl_2 chemistry

$$\underset{\text{gas}}{Cl} + \underset{\text{solid}}{Si} \longrightarrow \underset{\text{gas}}{SiCl_4}$$

Some Facts About Chlorine

Name	Chlorine
Symbol	Cl
Atomic number	17
Atomic weight	35.4527
Discoverer	Carl William Scheele
Discovered at	Sweden
Discovery date	1774
Origin of name	From the Greek word "chloros" meaning "pale green"
Molar volume	17.39 cm^3
Velocity of sound	206 m/sec
Resistivity	$> 10^{10}$ $\mu\Omega$ cm
Refractive index	1.000773
Melting point	-101.4 C or 171.6 K
Boiling point	-33.89 C or 239.11 K
Thermal conductivity	0.0089 W m^{-1} K^{-1}
Applications	Used as the main etchant for poly silicon and metal etching processes. Polysilicon, epitaxy silicon deposition chamber clean.
Sources	Cl_2, HCl

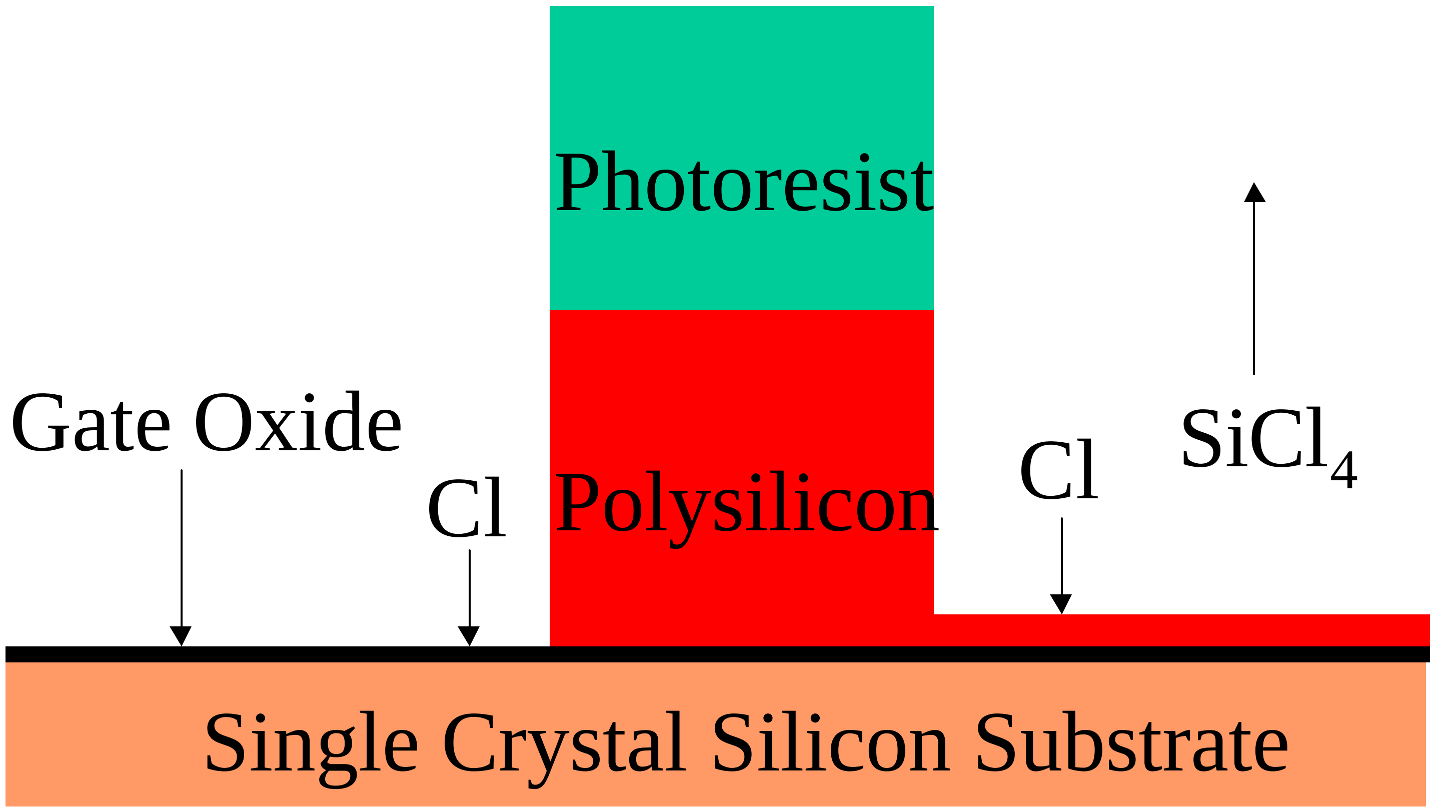
Gate etch



Polysilicon Etch

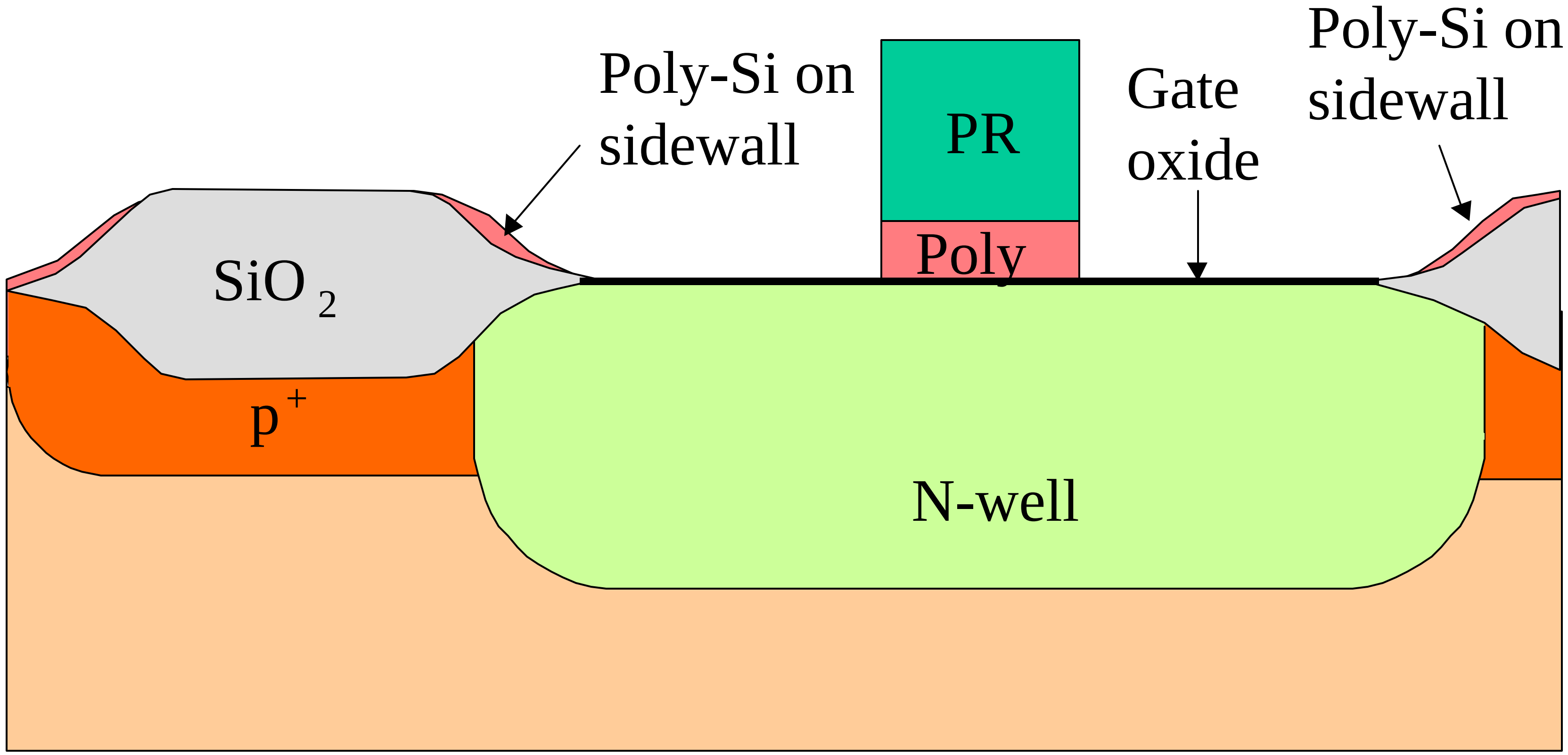
- Cl_2 as the main etchant
- HBr for sidewall passivation, blocking mechanism
- Add O_2 in over etch step to improve selectivity to SiO_2.
- High selectivity over SiO_2 is required

Polysilicon Etch



- High poly-to-oxide selectivity is required

Polysilicon Etch



Polysilicon Etch

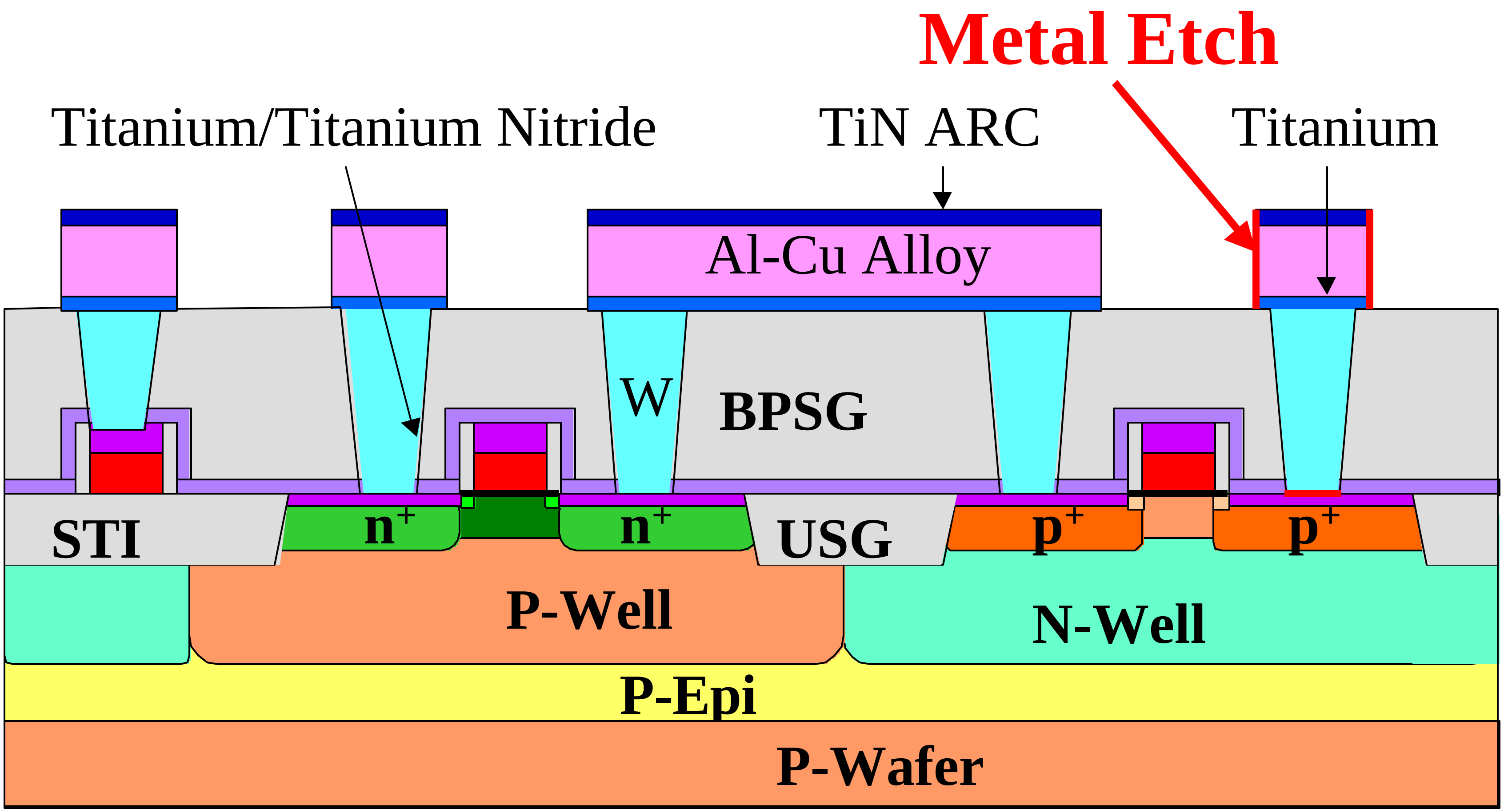
Process steps:

- Breakthrough
  - Removal of native oxide, energetic Ar^+ bombardment
- Main etch
  - High poly etch rate, Cl and HBr chemistry
  - Endpoint on O line
- Over etch
  - Reduce power, add O_2 for high selectivity over SiO_2

Metal Etch

- Etch TiN/Al·Cu/Ti metal stack to form metal interconnection
- Usually use Cl_2 + BCl_3 chemistry
- Need etch away Cu in Al either physically or chemically
- Need strip photoresist before wafer exposure to moisture in atmosphere

CMOS Cross-section



Etch Metal

- For metal interconnection
- Metal stack: TiN/Al•Cu/Ti
- Cl_2 as the main etchant
- BCl_3, N_2 are used for sidewall passivation
- O_2 is used to improve selectivity to oxide
- Main challenges: etch profile and avoiding etch residue
- Metal grain size can affect etch process

Metal Etch Chemistries

$$Cl_2 \xrightarrow{\text{plasma}} Cl + Cl$$

$$Cl + Al \xrightarrow{\text{plasma}} AlCl_3$$

$$Cl + TiN \xrightarrow{\text{plasma}} TiCl_4 + N$$

$$Cl + Ti \xrightarrow{\text{plasma}} TiCl_4$$

Photoresist Dry Strip

- Remote plasma source
  - Free radicals without ion bombardment
- High pressure, microwave plasma
- Very important to strip chlorine containing PR after metal etch to avoid metal corrosion
- In-situ with etch process in a cluster tool
- Improve throughput and yield

Photoresist Dry Strip

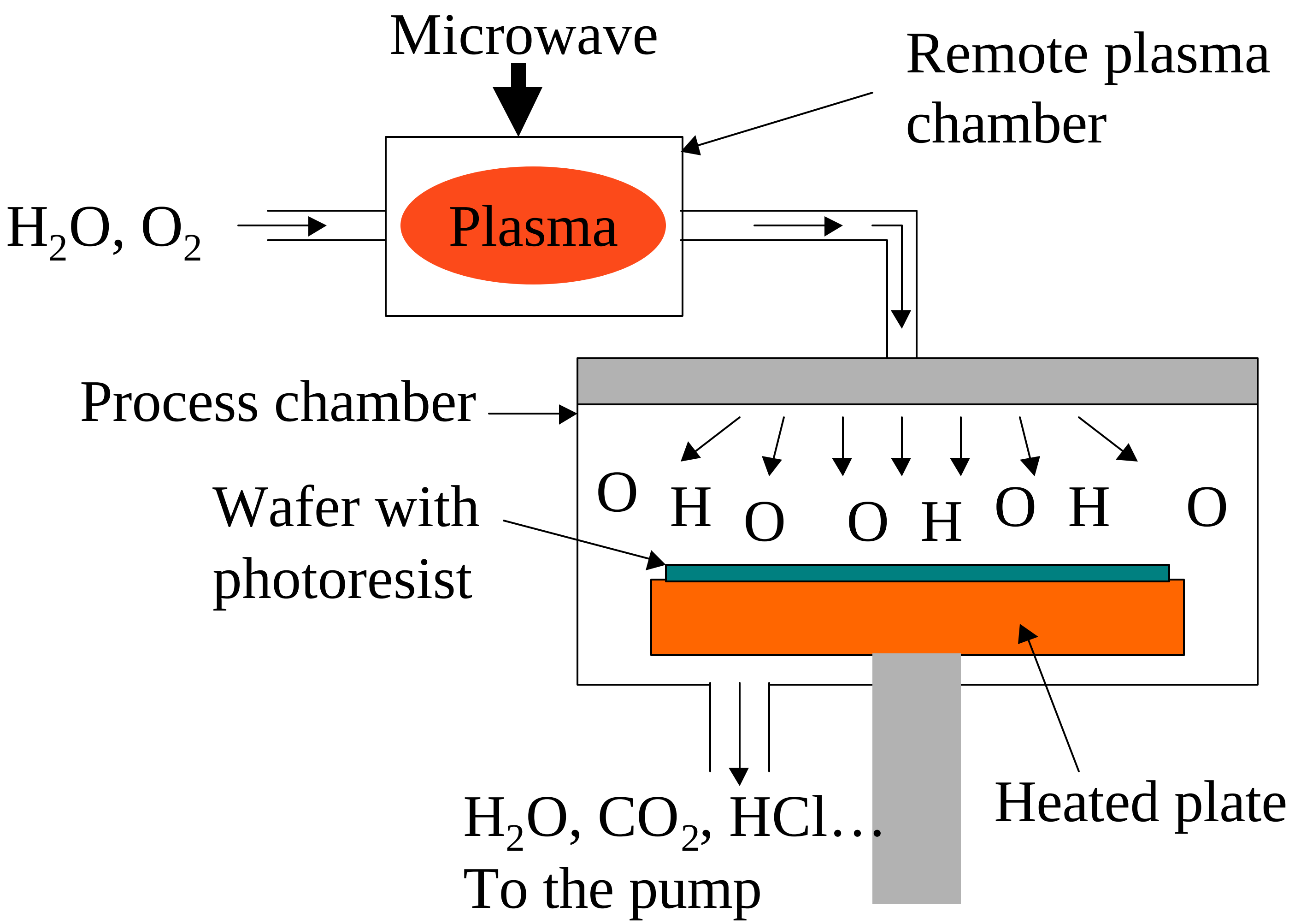
- O_2, H_2O chemistry

$$H_2O \xrightarrow{\text{plasma}} 2H + O$$

$$H + Cl \rightarrow HCl$$

$$O + PR \rightarrow H_2O + CO + CO_2 +$$

Photoresist Strip Process



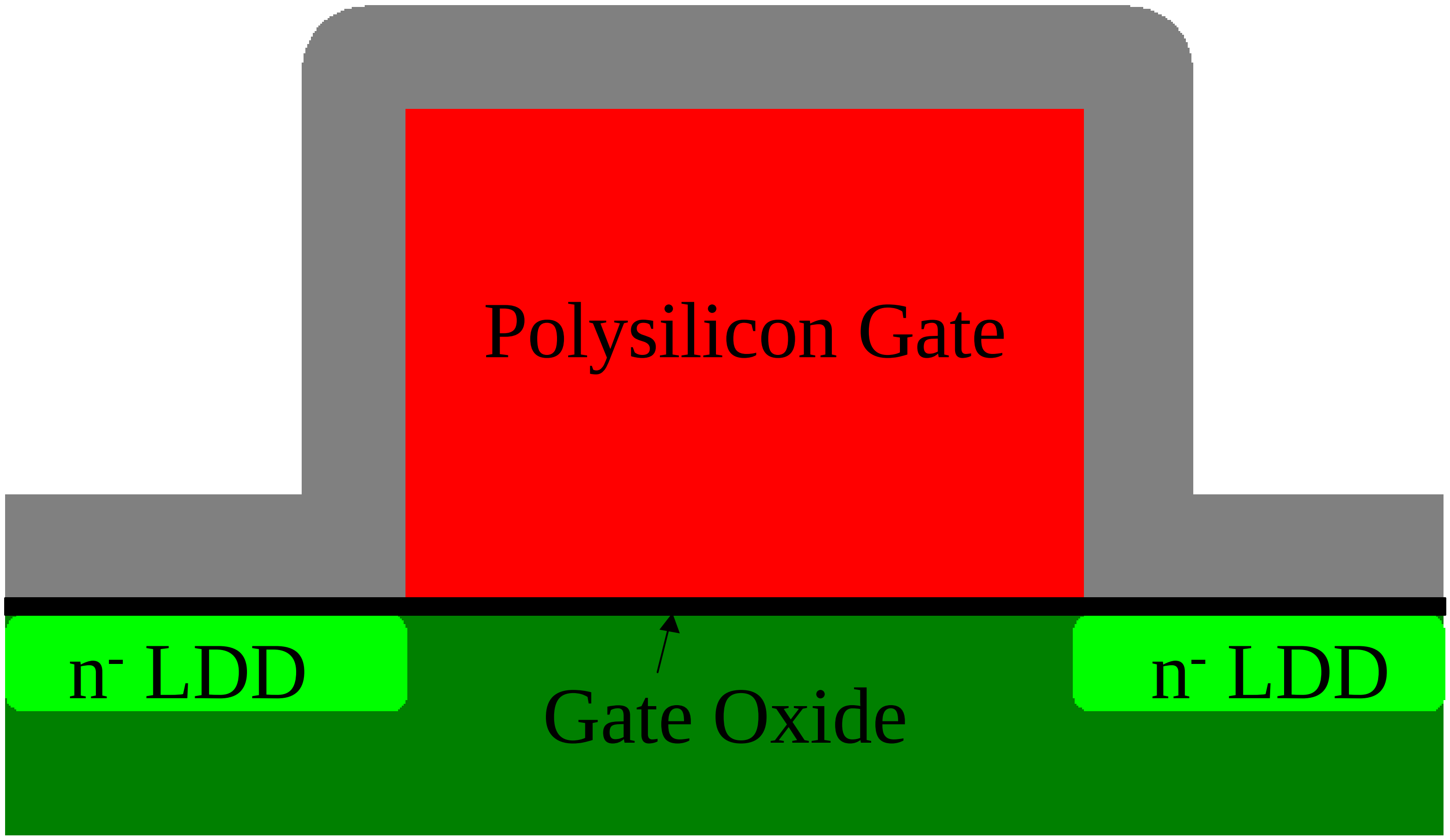
Dry Chemical Etch

- Unstable gases, such as XeF_2 and O_3
- Remote plasma source free radicals
- Free from ion bombardment
- Thin film strip and wineglass contact etch
- In-situ with RIE chambers on one frame
- Nitride strip in both LOCOS and STI
- Nitride and Poly-Si strip in PBL

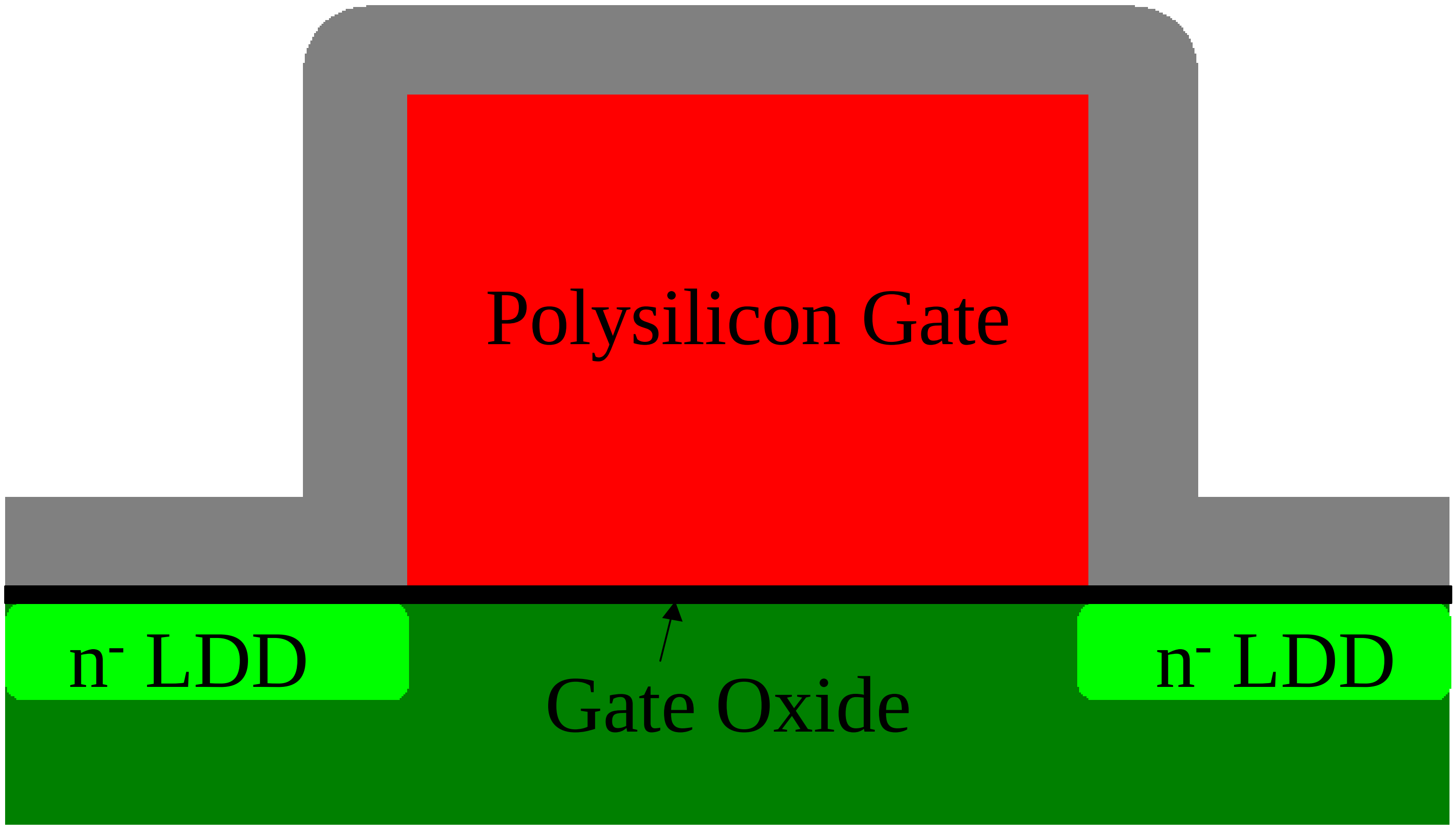
Blanket Dry Etch

- No photoresist. Etchback and film strip.
- Argon sputtering etch
  - Dielectric thin film applications
  - native oxide clean prior to metal deposition
- RIE etchback system
  - Can be used in-line with dielectric CVD tools
  - Sidewall spacer formation
  - PR or SOG planarization etchback

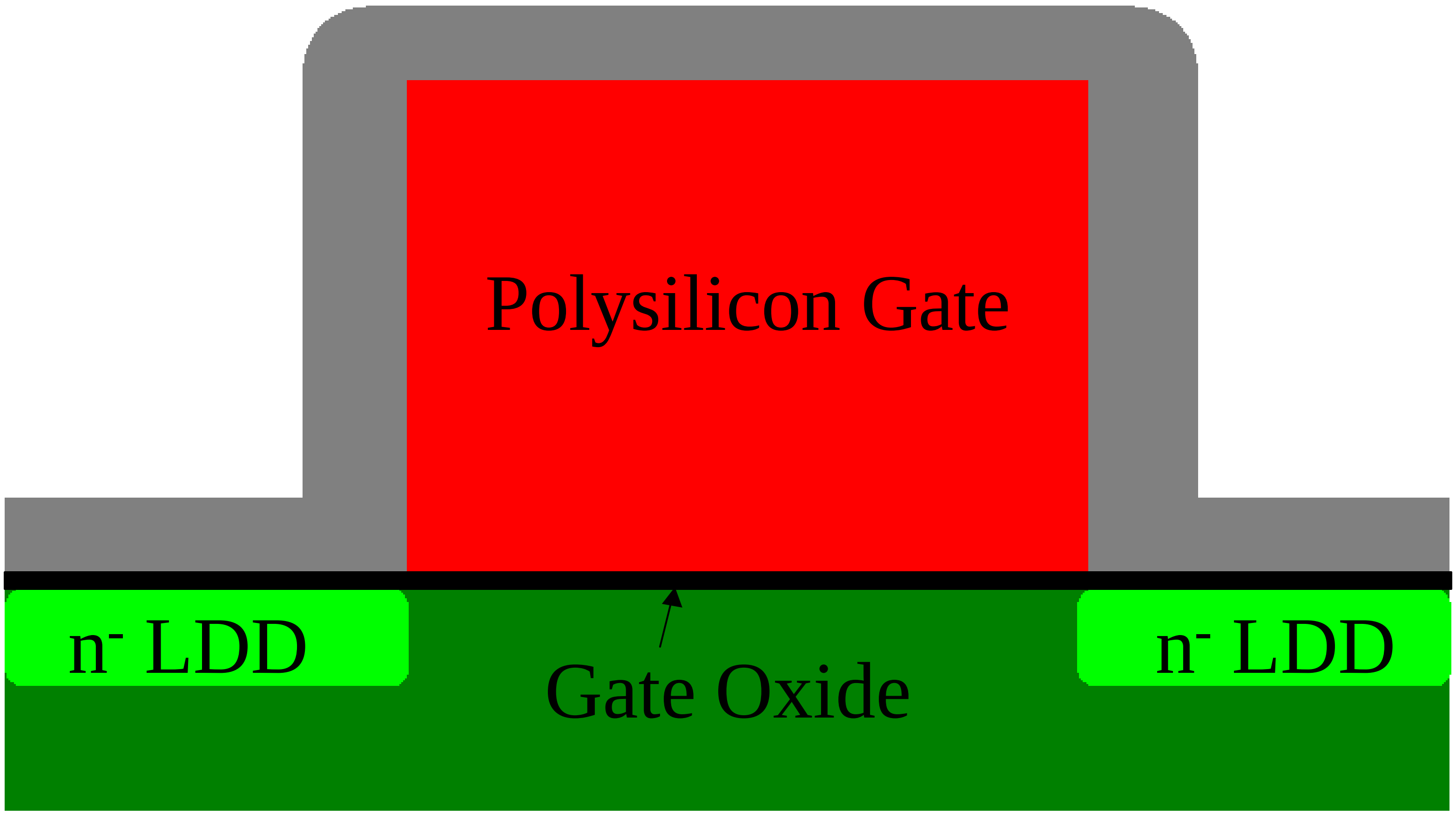
CVD O_3-TEOS USG



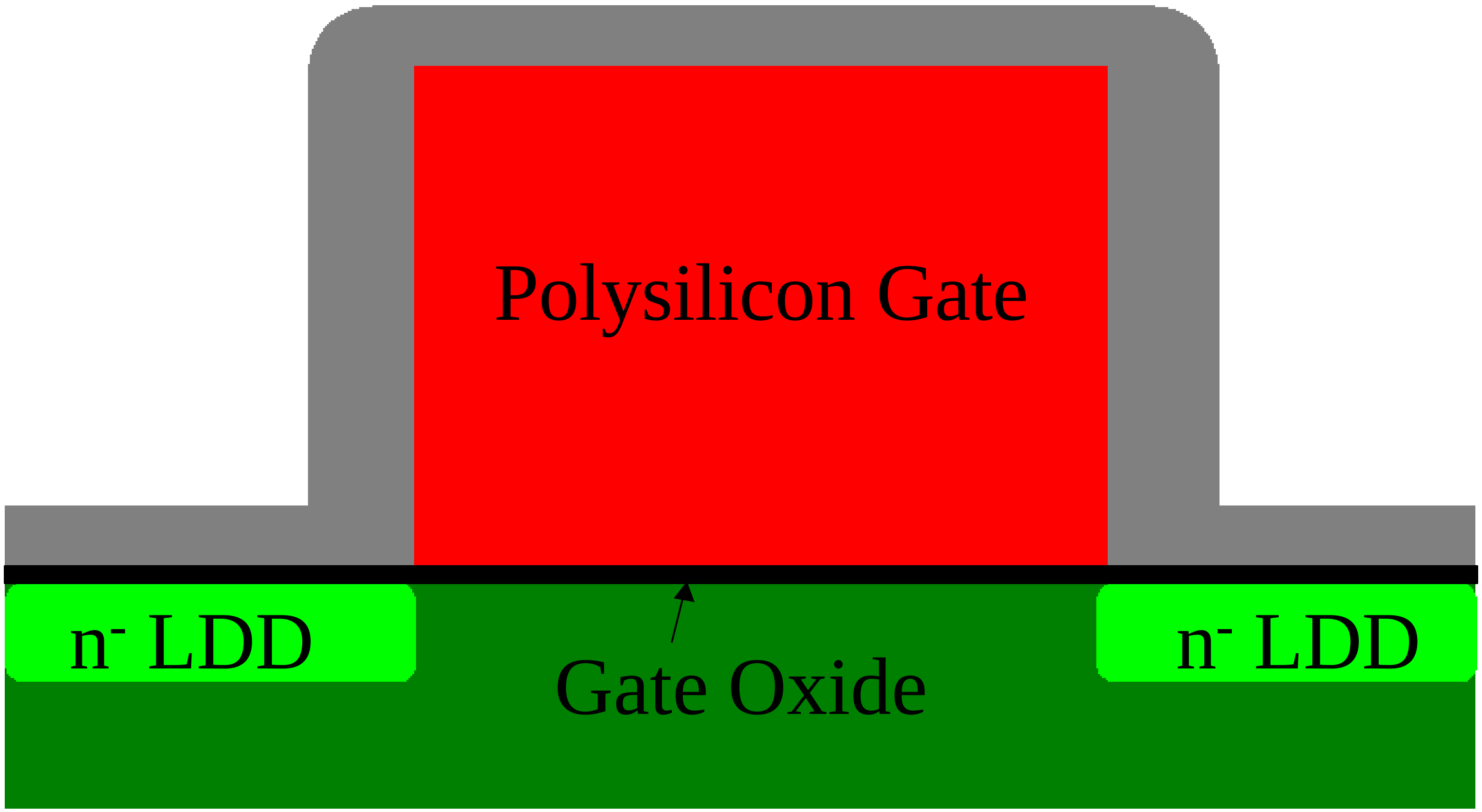
O_3-TEOS USG Etchback



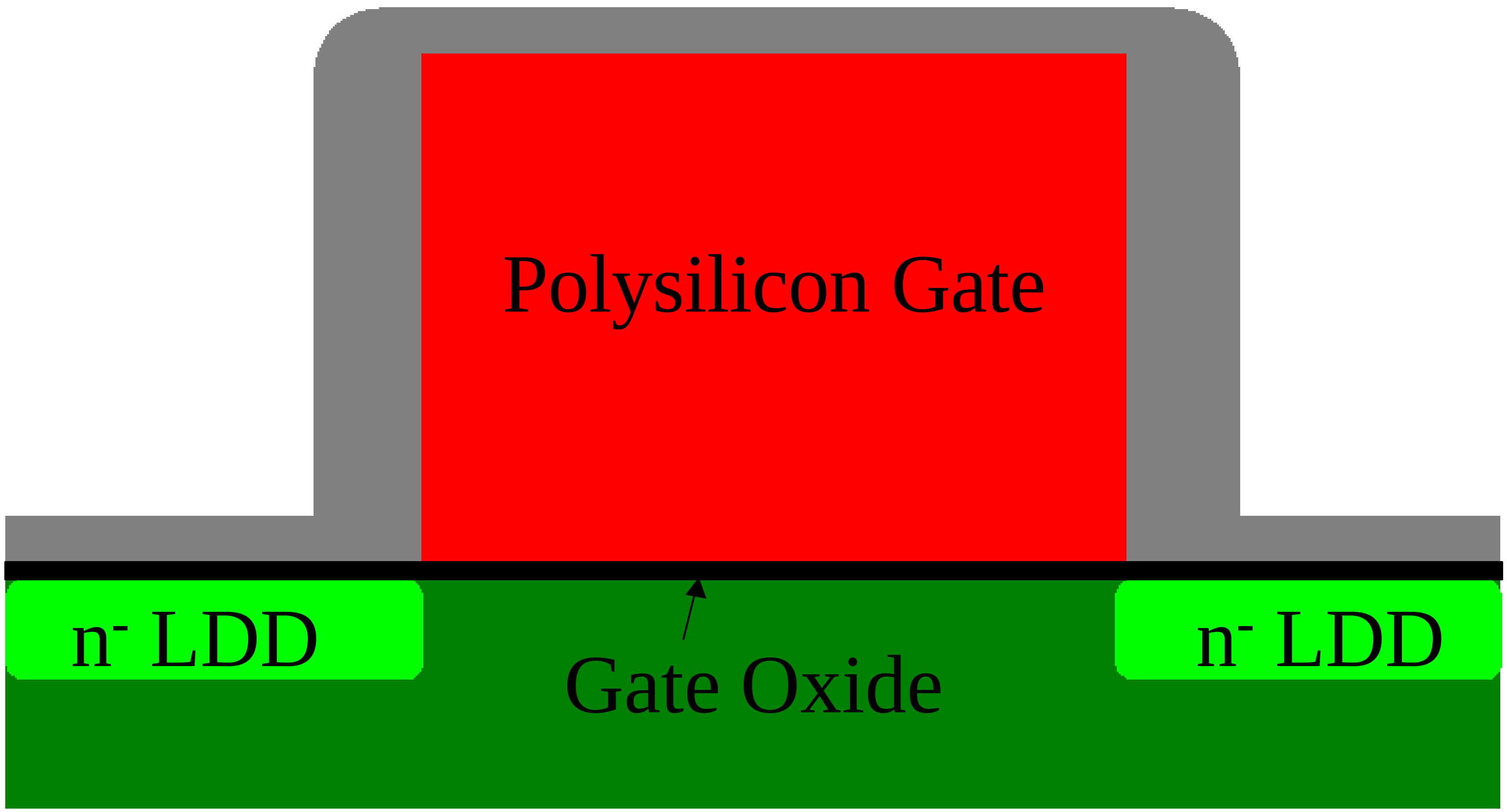
O_3-TEOS USG Etchback



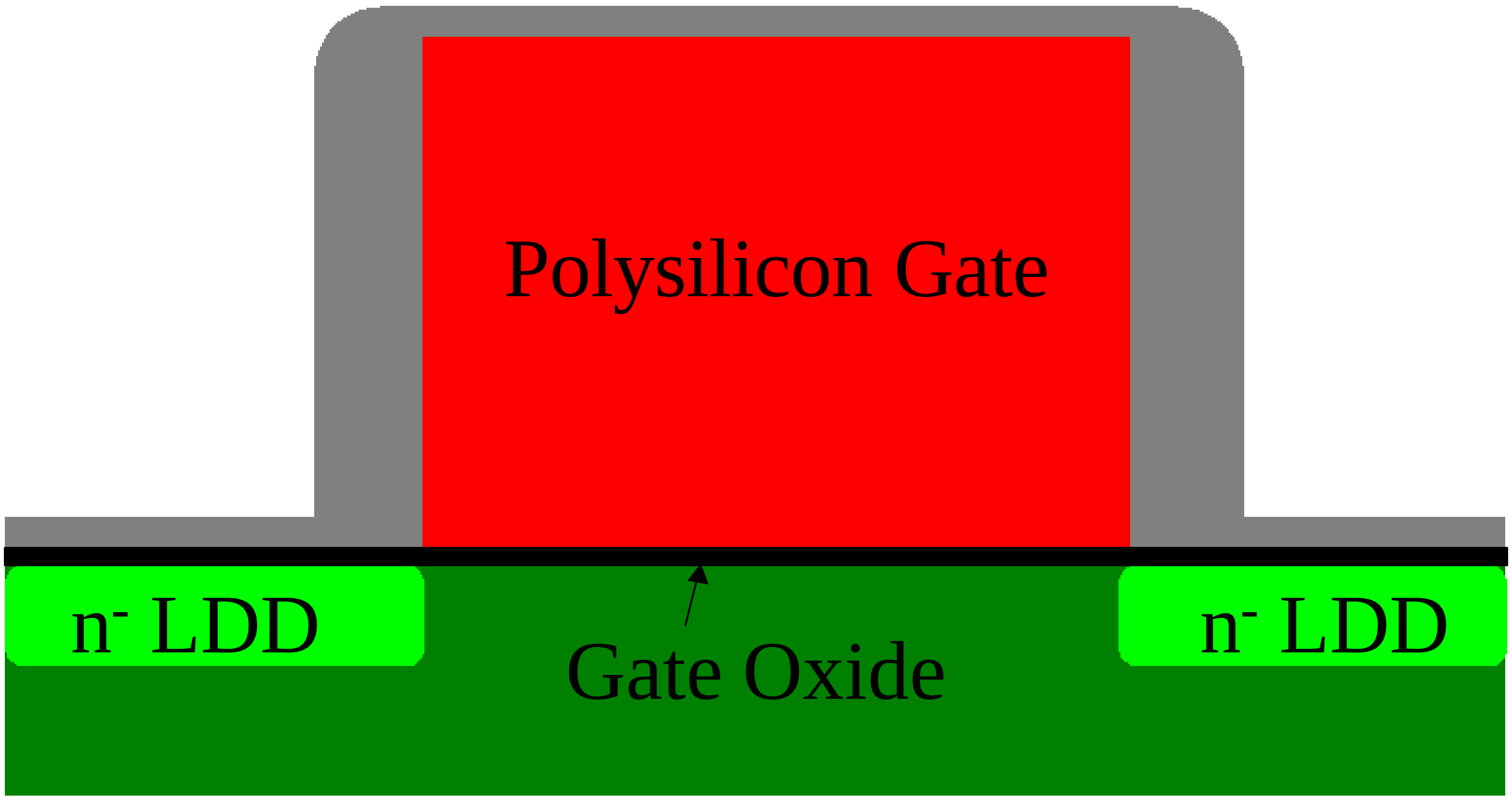
O_3-TEOS USG Etchback



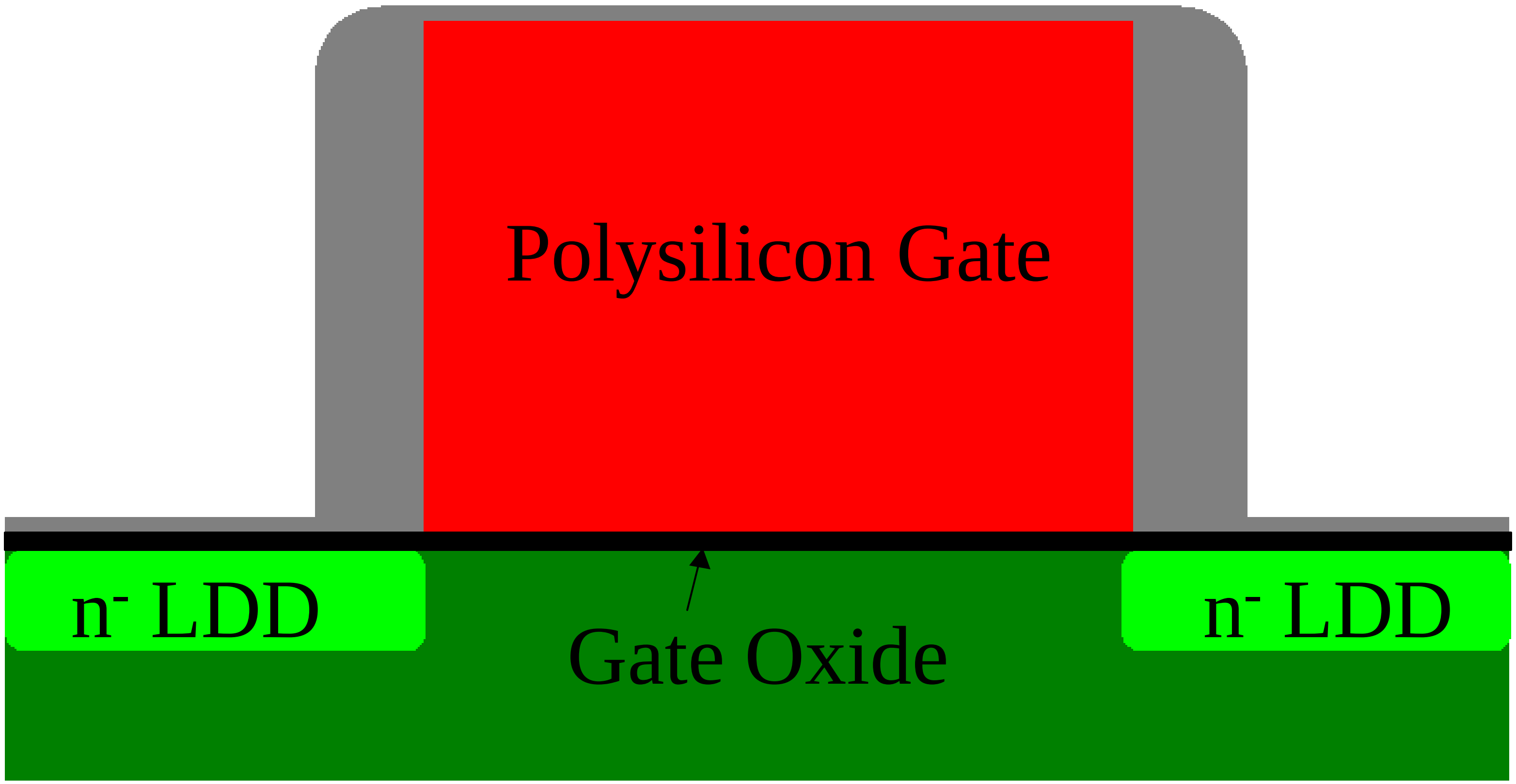
O_3-TEOS USG Etchback



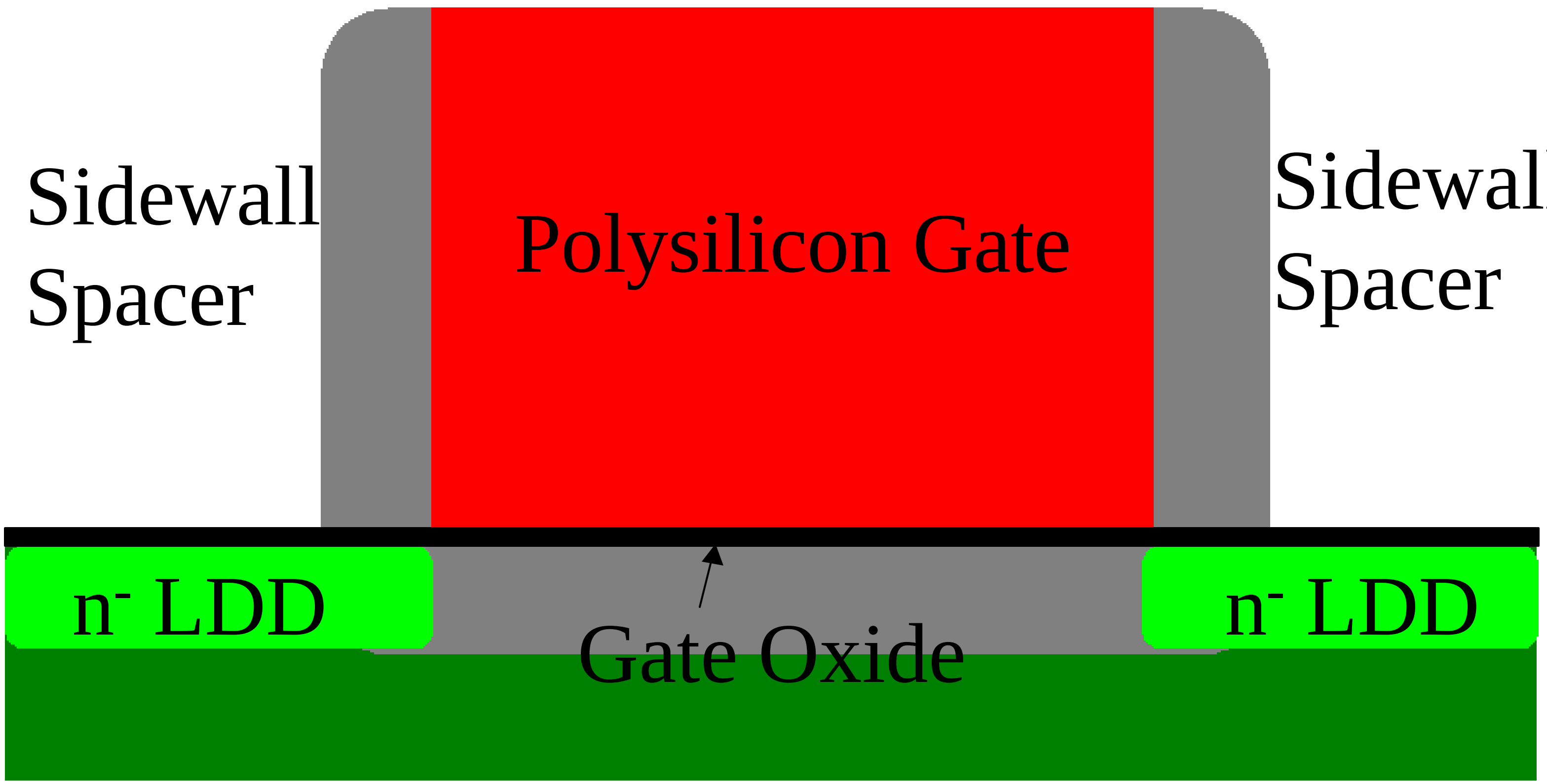
O_3-TEOS USG Etchback



O_3-TEOS USG Etchback



O_3-TEOS USG Etchback



Etch Safety

- Corrosive and toxic gases
  - Cl_2, BCl_3, SiF_4 and HBr
  - Could be fatal if inhalation at a high concentration (>1000 ppm)
- RF power can cause electric shock
- Can be lethal at high power

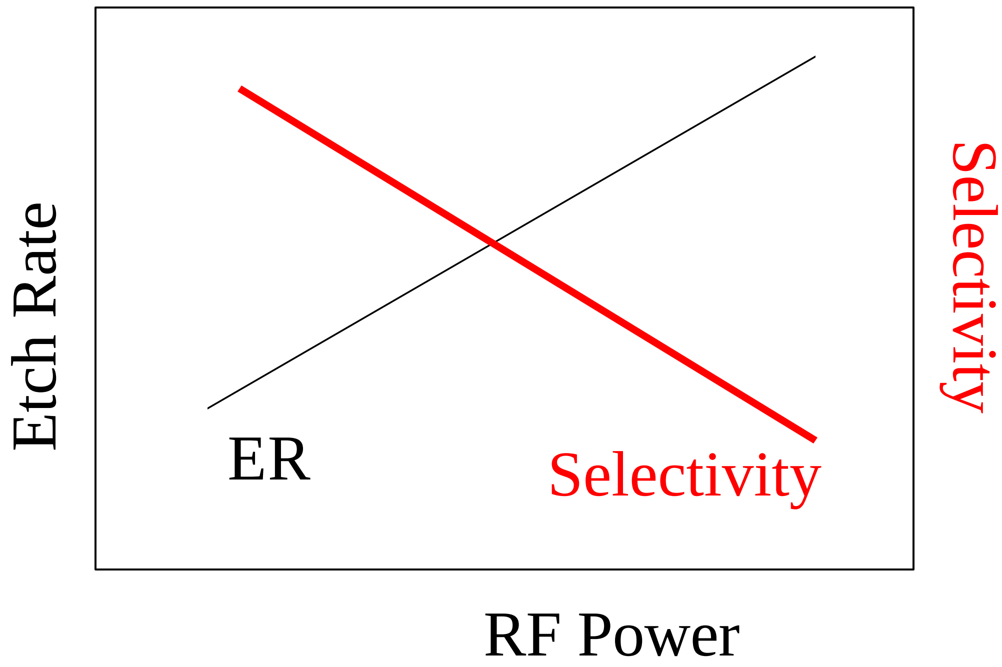
Etch Safety

- All moving parts, are mechanical hazards
- May cause injury if one does not stay clear
- Lock-out, tag-out

RF Power

- Increasing RF power increases ion density, ion bombardment energy, and number of free radicals
- Etch rate will increase significantly
- The most important “knob” that controls etch rate
- Check RF system first if etch rate is out of specifications

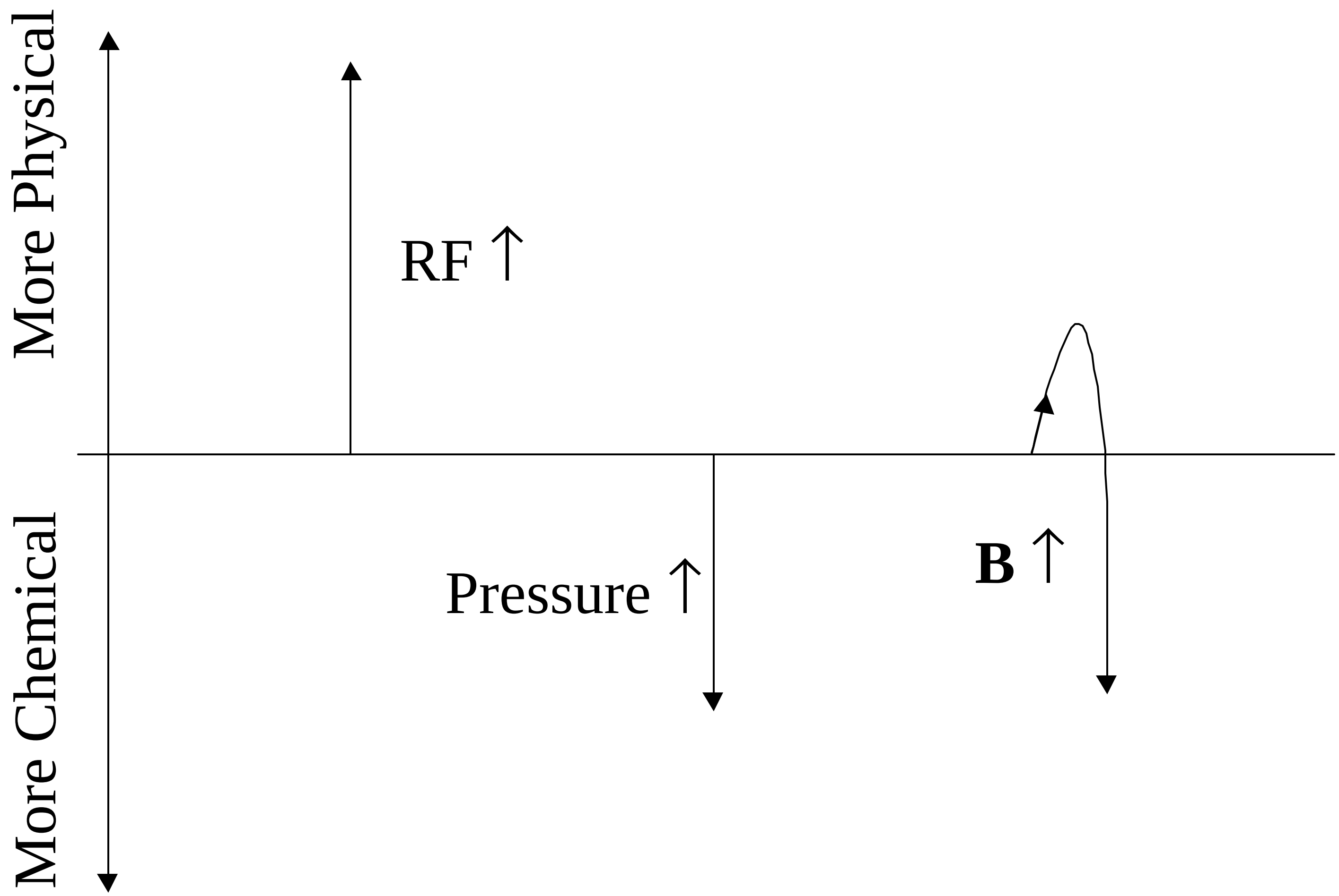
Plasma Etch Trends



Pressure

- Pressure affects plasma density and shape
- Has strong effects on etch uniformity

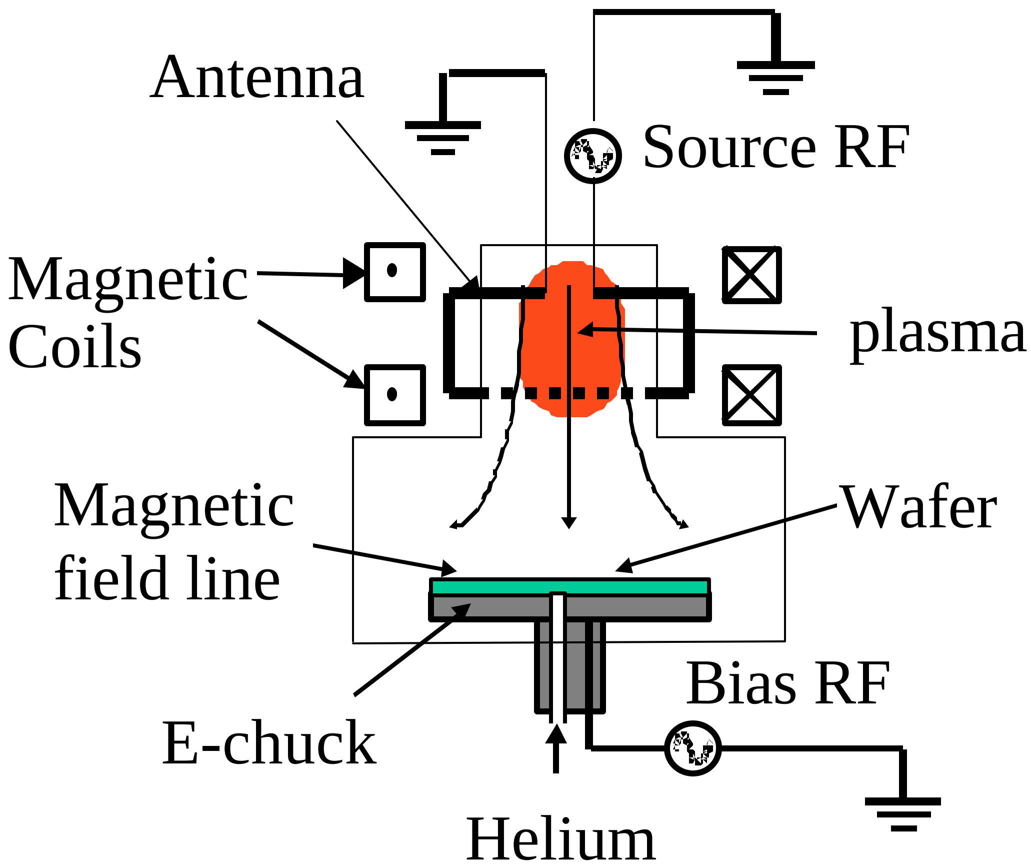
Etch Trends



Future Trends for Etch Processes

- High density plasma (HDP) at low pressure
  - Improve profile control
  - Increasing plasma density
  - Ion bombardment flux
- Independent ion flux and ion energy control
- HDP etchers in IC processing: ICP & ECR
- Helicon plasma source: ~100% ionization, candidate for future etch chamber design

Helicon Plasma Source



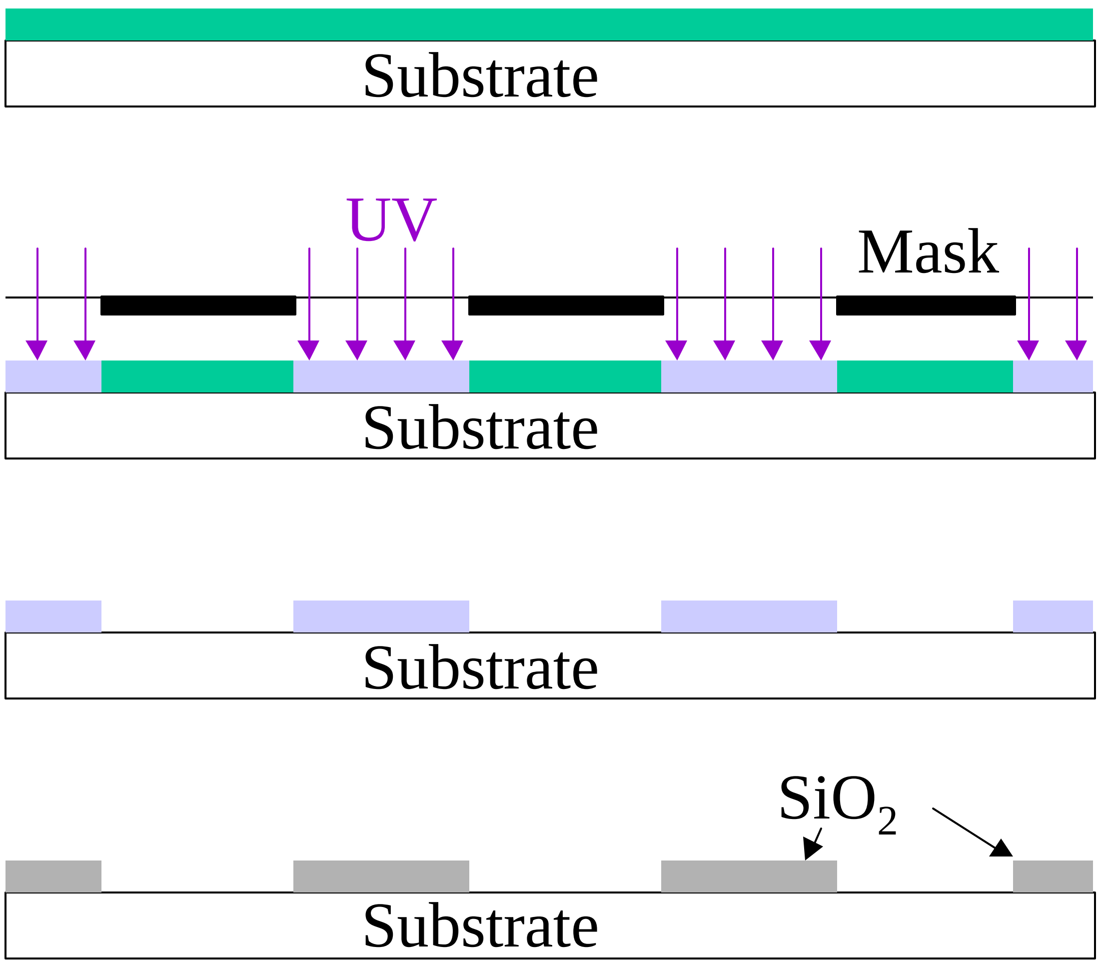
Future Trends for Etch Processes

- 300 mm system
- Plasma uniformity control
- Plasma position control

Copper Etch?

- Cl_2 chemistry
- Low pressure (< 5 mTorr)
- High temperature (>250 °C)
  - Cannot use photoresist
  - Need CVD oxide hard mask
- Competition with dual damascene process
- Very unlike can be used in IC production

Direct Hard Masking Photolithography



PECVD Si-PR

Exposure, partially oxidation of Si-PR

Cl_2 plasma removes unexposed Si-PR

Down Stream O_2 fully oxidation of Si-PR

Future Trends

- Challenges ahead:
- Etch high-κ materials of gate dielectric and capacitor dielectric
- Etch low-κ materials of inter-metal dielectric

Summary

- Plasma etch is widely used for patterned etch process to transfer image on photoresist to surface materials.
- Epi, poly, oxide and metal
- Fluorine for oxide etch
- HBr for single crystal silicon etch
- Chlorine for polysilicon and metal etch

Summary

- Certain vacuum and constant RF power are need to strike and maintain a stable plasma
- RF power is main knob to control etch rate
- Pressure affects uniformity and etch profile
- High plasma density at low pressure are desired for etch deep sub-micron features.
- Dry chemical etch can be achieved with remote plasma source