Status: 02.06.2020

2.7 Dry Etching

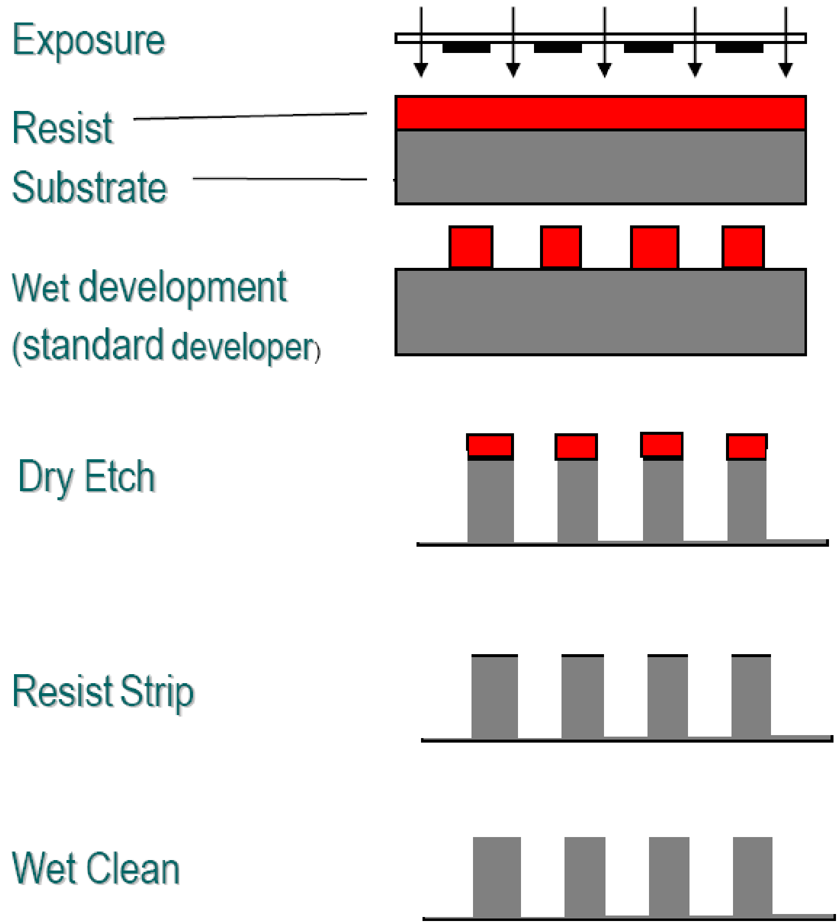
2.7.1 Introduction

Dry etching techniques are those that use plasmas to drive chemical reactions and/or employ energetic ion beams to remove material.

Goal: *Pattern transfer from mask to layer*

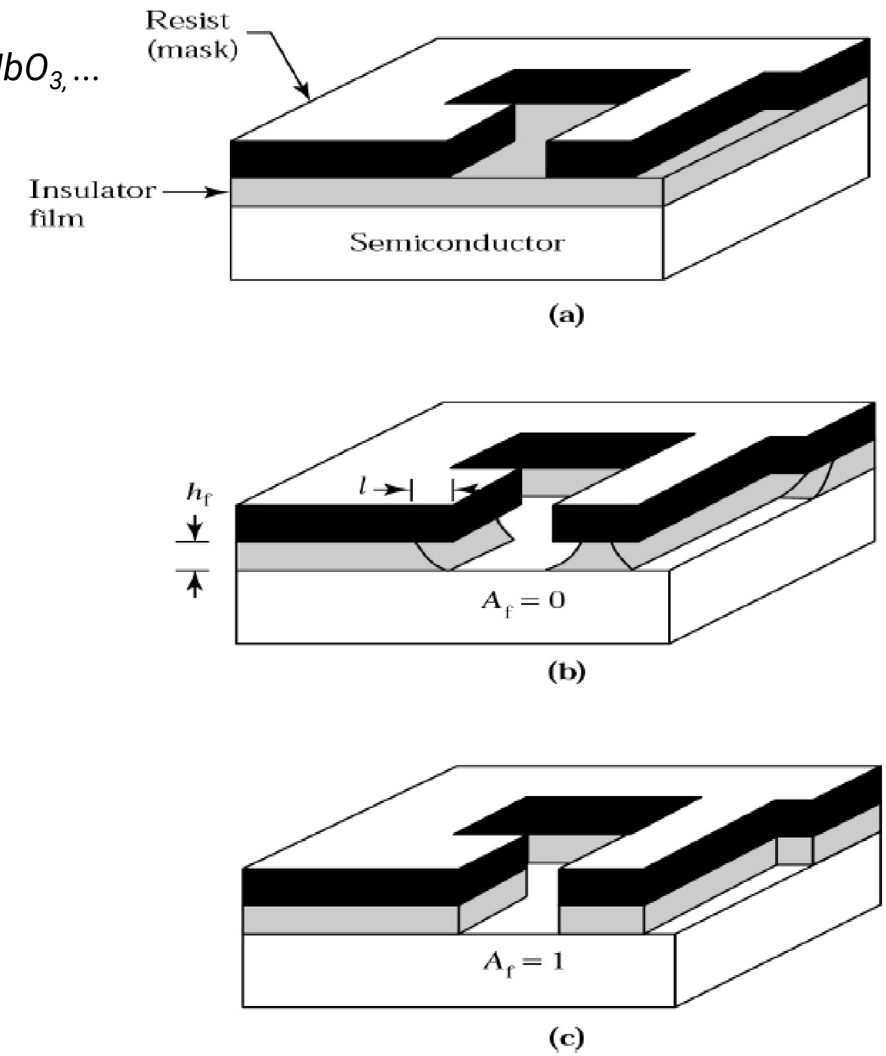
Dry etching methods:

- **Glow discharge methods**
  - *Dry physical etching (Sputter etching, ion etching)*
  - *Plasma assisted etching*
    - *- Dry chemical etching (Plasma etching)*
    - *- Reactive ion etching (RIE)*
- **Ion beam methods**
  - *Ion milling*
  - *Reactive ion beam etching*
  - *Chemical assisted ion milling*



Common materials to dry etch: **Si, SiO_2, Si_3N_4, Al, W, Ti, TiN, $TiSi_2$, Photoresist**

Difficult materials to dry etch: **Cu, Al_2O_3,** *Fe, Ni, Co, $LiNbO_3$, ...*



Degree of Anisotropy:

$$A_f \equiv 1 - \frac{l}{h_f} = 1 - \frac{R_l t}{R_v t} = 1 - \frac{R_l}{R_v}$$

For isotropic etching: ***$R_l = R_v$ and $A_f = 0$***

For completely anisotropic etching: ***$R_l = 0$ and $A_f = 1$***

Comparison of dry etching methods

Technique	*Mechanism*	*Etching particles*	*Pressure [Pa]*	*Directional behavior*
Barrel Etching	*chemical*	*reactive radicals*	*100*	*isotropic*
Plasma Etching (PE)	*phys. & chem.*	*reactive radicals, weakly ion assisted*	*10 - 100*	*isotropic with anisotropic component*
Reactive Ion Etching (RIE)	*phys. & chem.*	*reactive radicals, strongly ion assisted*	*1 - 10*	*anisotropic with isotropic component*
Reactive Ion Beam Etching (RIBE)	*phys. & chem.*	*reactive ions*	*≤ 0.01*	*anisotropic with isotropic component*
Sputter Etching	*physical*	*inert ions*	*1 - 10*	*anisotropic*
Ion Beam Etching (IBE)	*physical*	*inert ions*	*≤ 0.01*	*anisotropic*

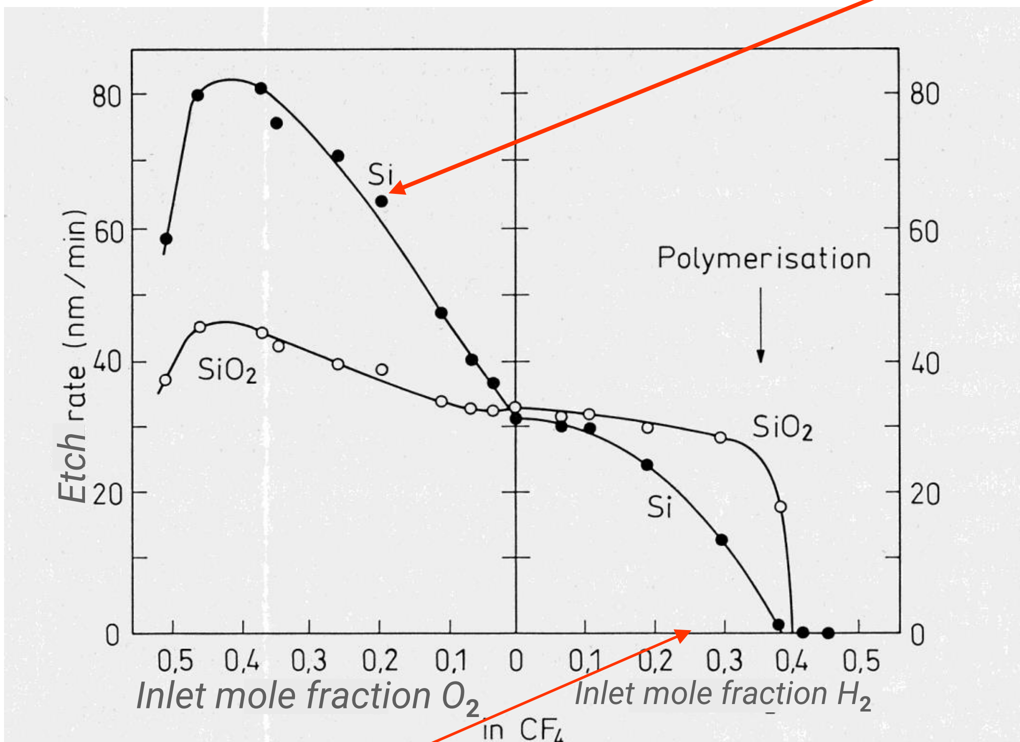
2.7.2 Chemistry

2.7.2.1 Overview

Typical or representative plasma etch gases for films used in IC fabrication		
Material	**Etchant**	**Comments**
Polysilicon	SF_6, CF_4 CF_4/H_2, CHF_3 CF_4/O_2 HBr, Cl_2, Cl_4/HBr/O_2	Isotropic or near isotropic (significant undercutting); poor or no selectivity over SiO_2. Very anisotropic; nonselective over SiO_2. Isotropic; more selective over SiO_2 . Very anisotropic; most selective over SiO_2.
Single-crystal Si	same etchants as Polysilicon	
SiO_2 PSG BPSG	SF_6, NF_3, CF_4/O_2, CF_4 CF_4/H_2, CHF_3/O_2, C_2F_6, C_3F_8 CHF_3/C_4F_8/CO	Can be near isotropic (significant undercutting); anisotiopy can be improved with higher ion energy and lawer pressure; poor or no selectivity over Si. Very anisotropic; selective over Si. Anisotropic;selective over Si_3N_4.
Si_3N_4	CF_4/O_2 CF_4/H_2 CHF_3/O_2, CH_2F_2	Isotropic; selective over SiO_2 but not over Si. Very anisotropic; selective over Si but not over SiO_2. Very anisotropic; selective over Si and SiO_2.
Al	Cl_2 $Cl_2/CHCl_3$, Cl_2/N_2	Near isotropic (significant undercutting). Very anisotropic; BCl_3 often added to scavenge oxygen.
Tungsten (W)	CF_4, SF_6 Cl_2	High etch rate; nonselective:over SiO_2. Selective over SiO_2.
Ti	Cl_2, $Cl_2/CHCl_3$, CF_4	
TiN	Cl_2, $Cl_2/CHCl_3$, CF_4	
$TiSi_2$	Cl_2, $Cl_2/CHCl_3$, CF_4/O_2	
Photoresist	O_2	Very selective over other films.

2.7.2.2 Control of Selectivity

Dependence of etch rates of Si and SiO_2 in CF_4 plasmas on the content of O_2 and H_2



Schumicki, Abb. 5.6

Adding H_2 drastically lowers Si etch rate by formation of stable HF

$H^+ + F + e^- \rightarrow HF$

However, etch rate of SiO_2 remains longer constant

Allows SiO_2/Si etch selectivity to be increased tremendously

Addition of O_2:

Even with plasma the etch rate is slow (insufficient F concentration)

Adding O_2 to the plasma can increase F concentration

$O + CF_3 \rightarrow COF_2 + F$ then

$O + COF_2 \rightarrow CO_2 + 2F$

and consumes CF_x

--> ***Etch rate of Si*** increases faster than of SiO_2

Concentration of F increases further because recombination of CF_x and F becomes increasingly unlikely.

Also: Less adsorption of C on Si because CF_x is not sufficiently available

Etch rate decreases at higher O_2 concentrations: Dilution of F conc. with overly abundant O_2

Similar trend is for SiO_2

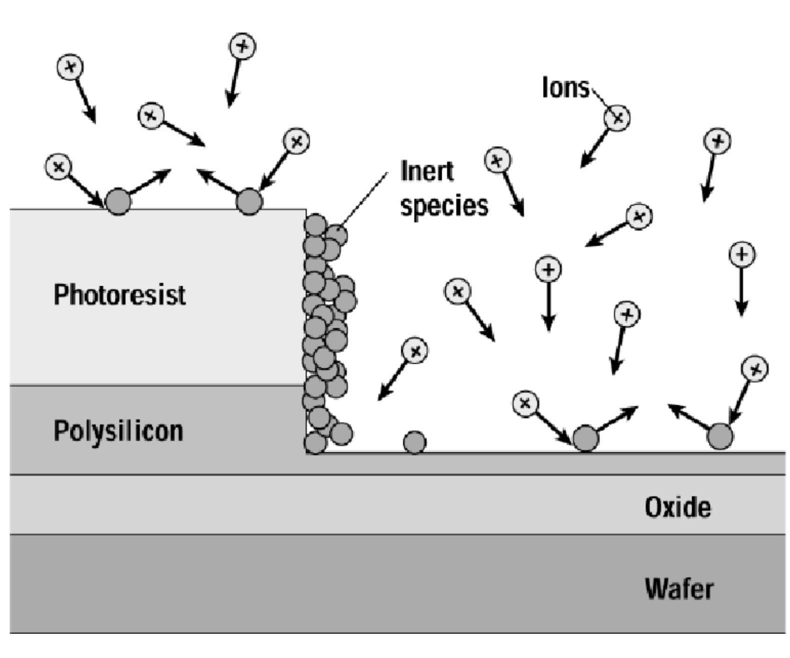
Etch rate is higher for Si

Si/SiO_2 selectivity is good

Isotropic etching

2.7.2.3 Control of Anisotropy

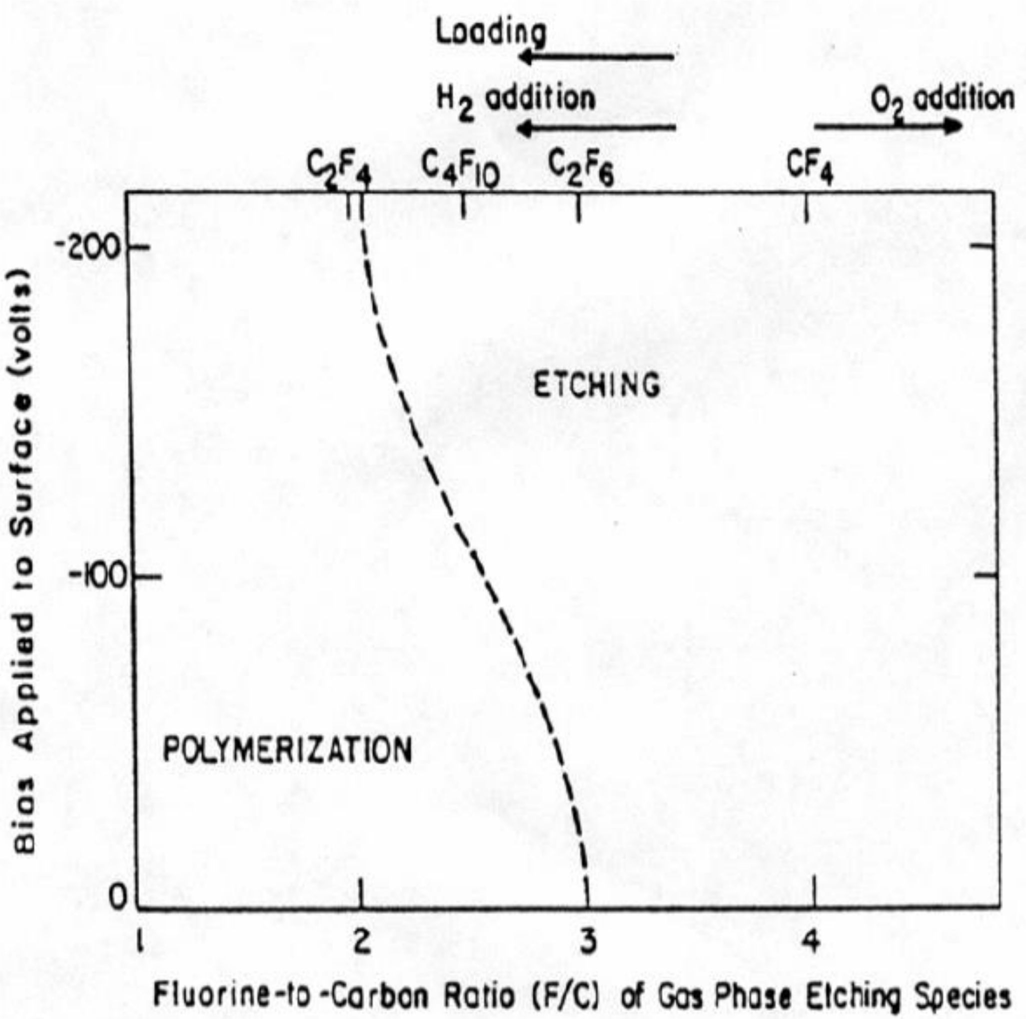
Formation of Sidewall Passivating Films



Source: Lecture Advanced Topics in Fabrication and Microengineering, John Hopkins University, Baltimore

- Formation of nonvolatile fluorocarbons that deposit on the surfaces **(Polymerization)**
- The deposit can only be removed by physical collisions with incident ions
- Fluorocarbon films deposits on all surfaces, but the ion velocity is nearly vertical. As a result, as the etching proceeds there is little ion bombardment of the sidewalls and the fluorocarbon film accumulates
- Adding hydrogen encourages the formation of the fluorocarbon films because hydrogen scavenge fluorine, creating a carbon-rich plasma (same thing happened when C_2F_6 is used instead of CF_4)
- Less accumulation is observed on SiO_2 than Si surfaces
- Tradeoff between ***Si/SiO2 selectivity*** and ***Anisotropy***

Controlling Polymerization



J.W.Coburn, H.F.Winters, J. Vac. Sci. Technol. 16 (1979) 391.

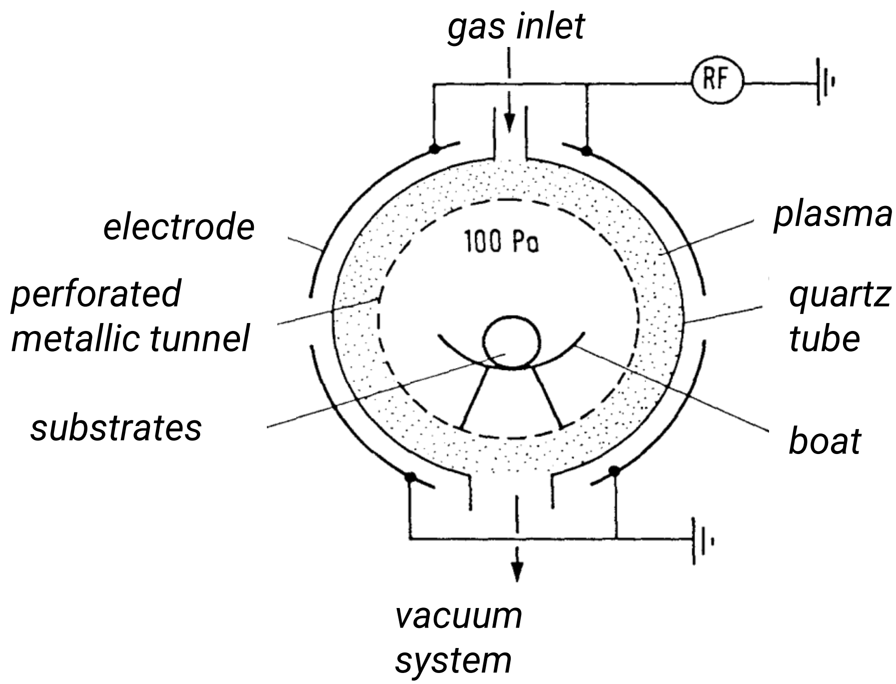
- *Higher F/C-ratio leads to more etching*
- *Lower F/C-ratio leads to more polymerization*
- *Can be determined by the gas used*
- *Adding H_2 consumes F*
  – *leads to polymerization*
- *Adding O_2 consumes C*
  – *leads to etching*

2.7.3 Processes and Equipment

2.7.3.1 "Pure" Chemical Etching

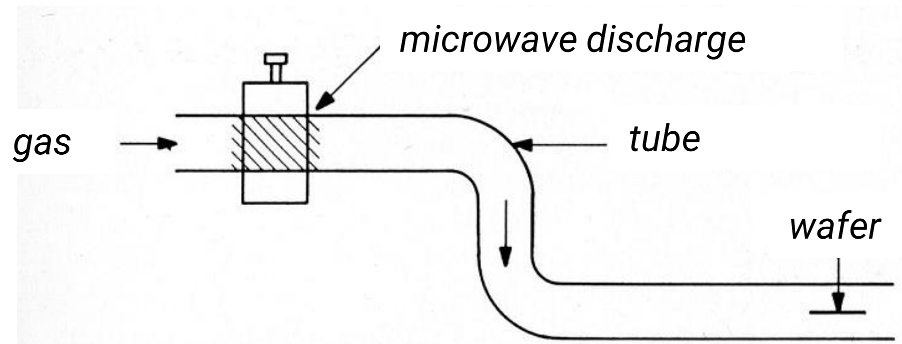
Barrel Reactor

- *Plasma and substrate separated*
- *Chemical etch by reactive radicals (only neutrals reach the wafers)*
- *Very selective*
- *Isotropic*
- *Many wafers in a batch*
- *Application: Stripping resist in oxygen plasma*



Downstream Reactor

- *Generation of long-living reactive molecules/atoms in RF (13.56 MHz) or MW (2.45 GHz) plasma separated from the wafer*
- *Kink suppresses radiation, no damage*
- *Soft process*



/Schumicki, S.115/

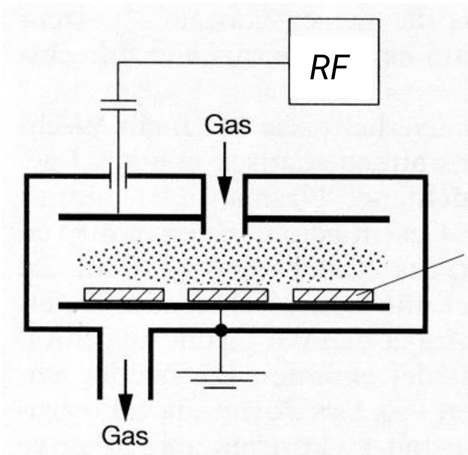
2.7.3.2 Plasma Etching

Parallel Plate (Planar) Reactor

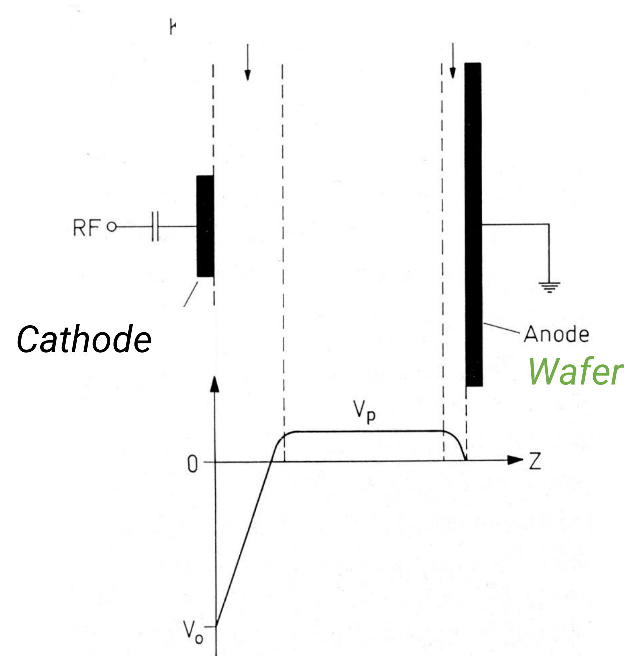
- *Substrate in the plasma*
- *Low throughput*
- **PE mode:** *- Wafer, anode & reactor grounded (large electrode)*
  - Cathode HF driven (small electrode)

- *Prevalent chemical etching by neutral radicals*
- *Low-energy ion bombardment at wafer (plasma potential V_p ~ 10 eV)*

10 -100 Pa



Wafer

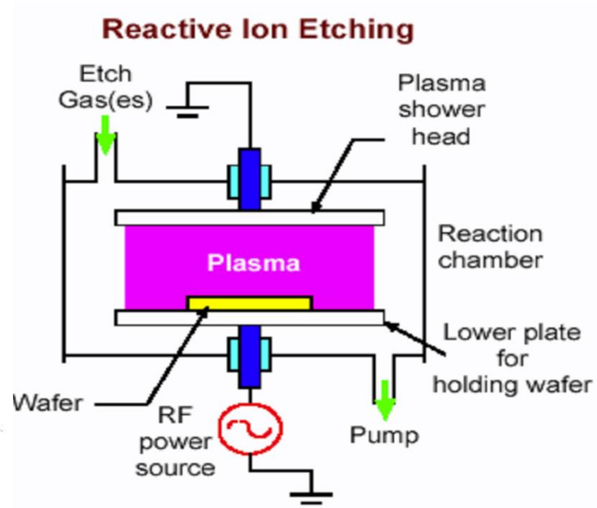


2.7.3.3 Reactive Ion Etching

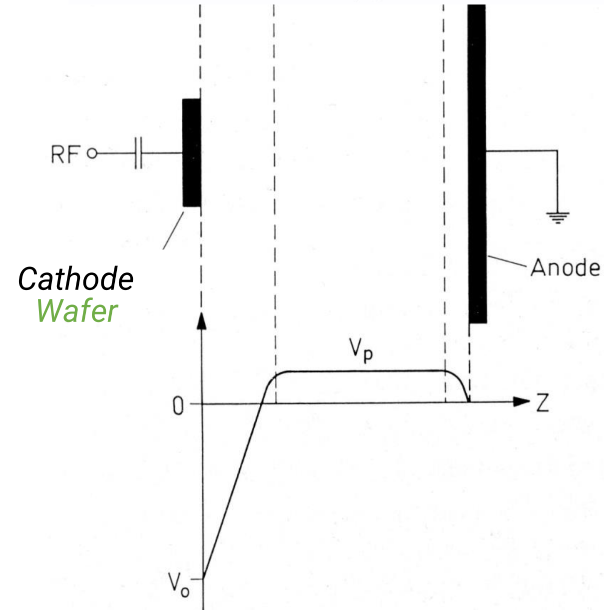
Parallel Plate (Planar) Reactor

- *Substrate in the plasma*
- *Low throughput*
- **RIE mode:** *- Wafer HF driven (cathode, small electrode)*
  - Reactor & anode grounded (large electrode)

p < 10 Pa



- *Ion bombardment at wafer, physical component can be tuned from low to high by voltage (Cathode voltage V_0 depends on RF power and external DC bias, 0.1 - 1 keV)*
- *RIE combines the benefits of chemical etching along with that of directional ion milling*
- *The combined etch results in a selectivity ratio between SiO_2 and Si of 35 compared with 10 in plasma only etching*
- *"RIE has become the choice for all advanced processes" (AMAT)*



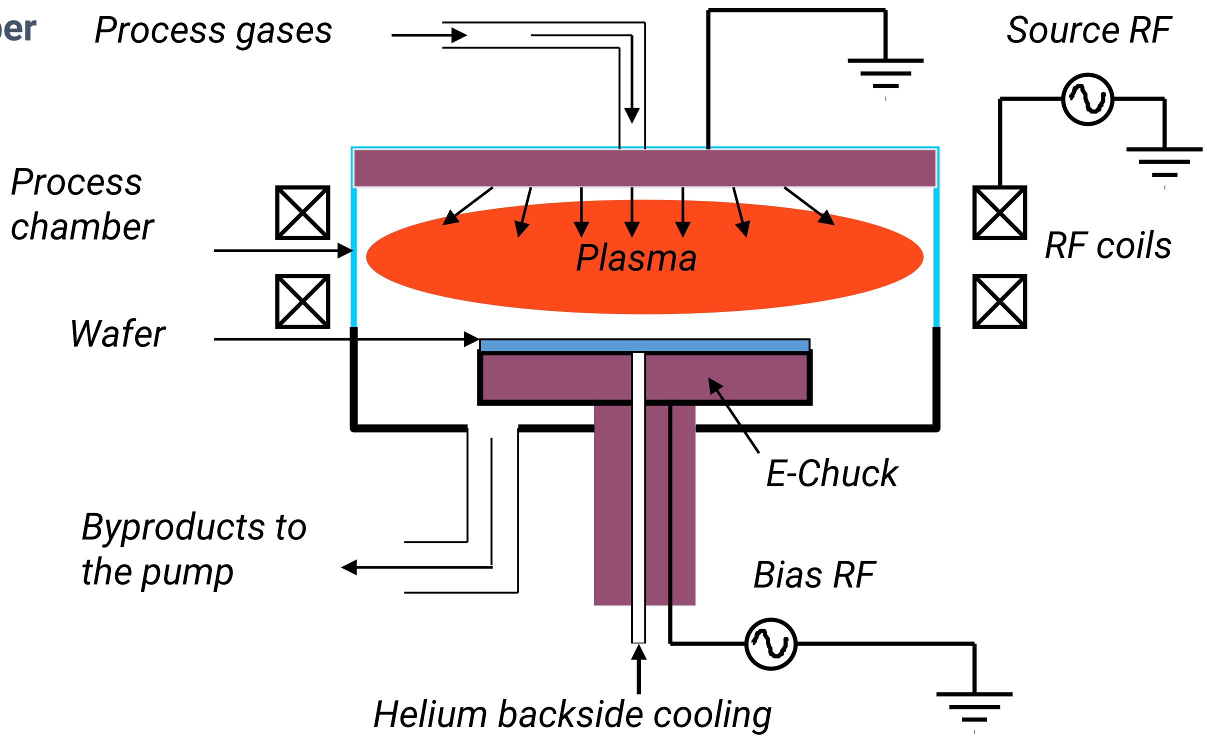
High Density Plasma (HDP) Reactors

- *High Density Plasma:* **ICP**, *TCP, DPS, MERIE, μW, MORIE,* **ECR**
  Highly efficient transfer of electromagnetic energy into the plasma
  --> high density of reactive particles

Inductively Coupled Plasma (ICP) reactor

Goals: *High plasma density*
Separate control of physical and chemical etching

Schematic of ICP Chamber



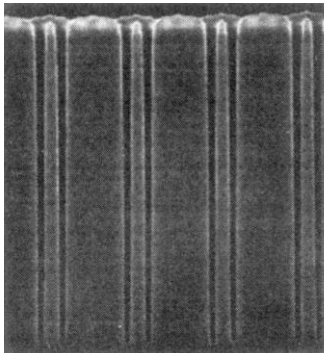
2.7.4 Process examples

2.7.4.1 Overview

A) Trench (Si): $Cl_2/Ar/N_2$ or Cl_2/HBr

$Si + 4Cl \rightarrow SiCl_4$ (at $T > -40$ °C) or

$Si + 4Br \rightarrow SiBr_4$ (at $T > +25$ °C)



Source: *"MNE 94" IBM, Siemens*

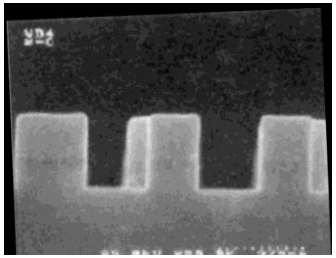
B) Gate (Poly Si, Silicide): Cl_2/Ar, Cl_2/SF_6 or Cl_2/O_2

$Si + 4Cl \rightarrow SiCl_4$ (at $T > -40$ °C)

e.g. Tungsten silicide WSi_x:

$W + 6F \rightarrow WF_6$ (at $T > -50$ °C)

$W + 6Cl \rightarrow WCl_6$ (at $T > +90$ °C) !

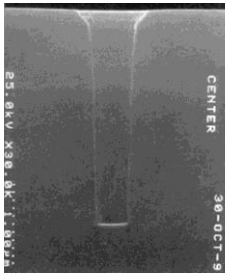


Source: *SI 3/98 Lam Research*

C) Via (oxidic films): $C_4F_8/H_2\,(O_2)$ or $CHF_3/C_2F_6/Ar$

$SiO_2 + 4F \rightarrow SiF_4 + O_2$ (at $T > -130$ °C or

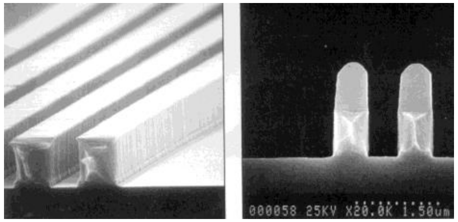
$SiO_2 + 4F + 2C \rightarrow SiF_4 + 2CO$ at $T > -130$ °C)



Source: *Etch Tech 4/96 Applied Materials*

D) Interconnects (Al alloys): $BCl_3/Cl_2/N_2$

$Al + 3Cl \rightarrow AlCl_3$ (at $T > +60$ °C)



Source: *Etch Tech 7/96 Applied Materials*

2.7.4.2 Dry Etching of Metals

Al (Si, Cu) Alloy

$AlCl_3$ is volatile above ~50 °C !
Al films are initially covered by native Al_2O_3, removal by ion bombardment
CuCl is volatile only above 250 °C, desorption needs additional energy at surface

Process control:

1. Phase: Prevailing ion bombardment for oxide removal

2. Phase: Prevailing chemical etching by Cl or Br radicals (from HCl, HBr)
- Anisotropy has to be achieved by side-wall passivation
→ Polymerization is supported by addition of CH_4, $CHCl_3$, CHF_3
- Soft ion bombardment to enable desorption of CuCl
Problem: Selectivity to resist → Use DUV hardened resist or hard masks

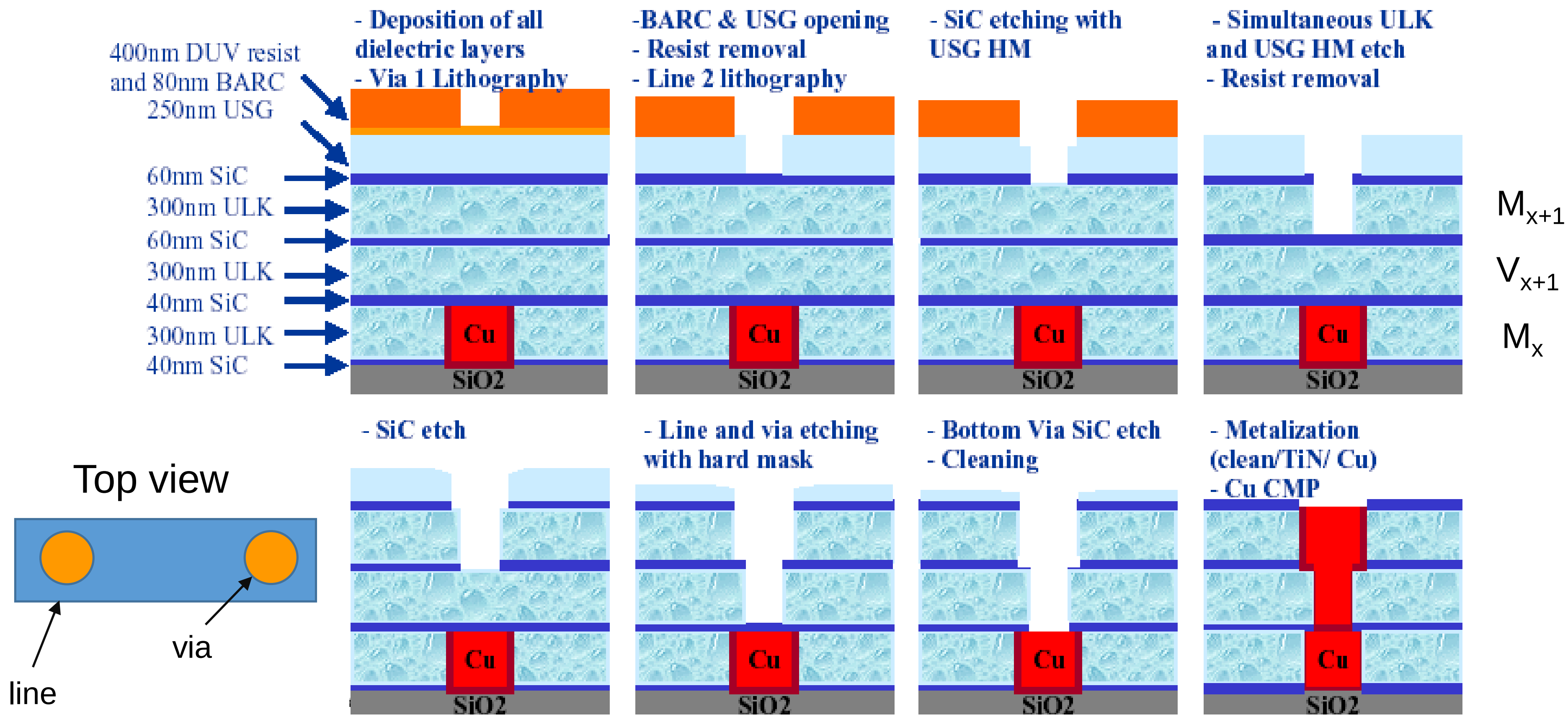
3. Post-treatment: Immediate removal of Cl containing masks and polymers by fluorine treatment and intensive rinsing in water to prevent subsequent corrosion

TiW:	CF_4/O_2 (isotropic) or CF_4
Mo:	$CF_4/CBrF_3$
W:	CF_4/O_2; SF_6/Ar

2.7.4.3 ILD Etching: Porous ULK Dual Damascene patterning

Patterning Scheme for JSR LKD5109 140 nm wire/280 nm pitch

❑ Dual Hard-mask, Partial Via First Approach in LKD 5109



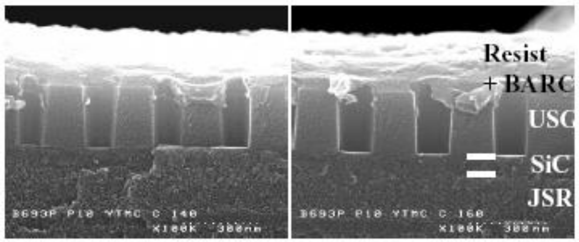
- *To reduce topography and*
- *To enable single layer resist*

Source: LETI (ULISSE project)

Dual damascene LKD5109 140 nm wire/280 nm pitch

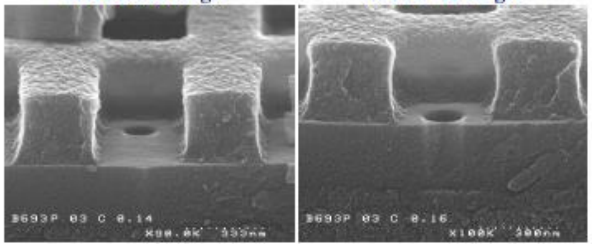
BARC and USG hard-mask opening

0.14µm via — 0.16µm via



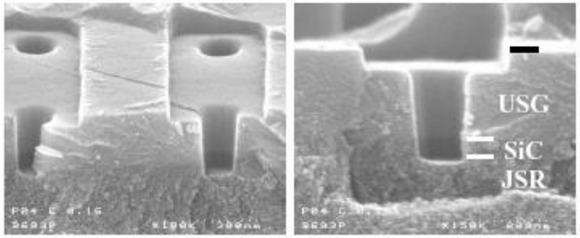
Line 2 lithography on via topology

0.34µm/0.14µm trench/via target — 0.36µm/0.16µm trench/via target



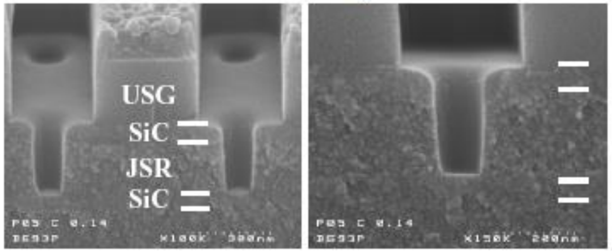
SiC (bottom hard-mask) etching

0.36µm/0.16µm trench/via target



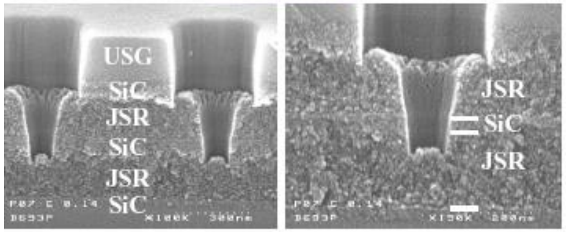
USG hard-mask and ULK etching

0.34µm/0.14µm trench/via target

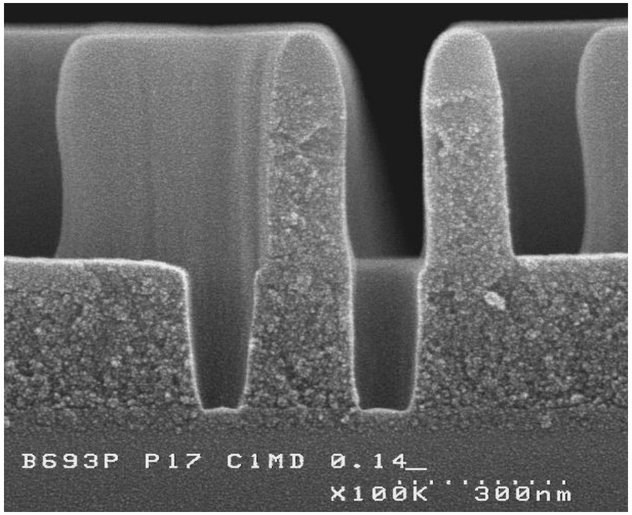


SiC etching (top and embedded hard-masks)

0.34µm/0.14µm trench/via target



ULK (line + via) etching



Source: LETI (ULISSE project)