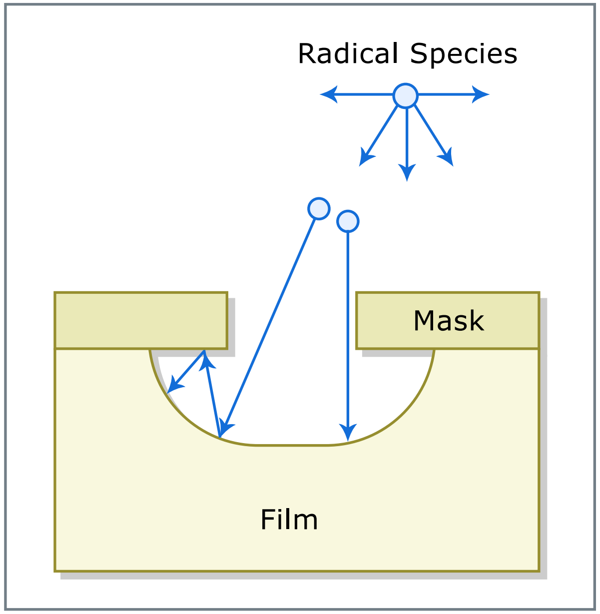
Dry Etching



We covered **wet etching**
which is essentially *chemical* and *isotropic*
(because it is chemical, it is highly *selective*)

Figure by MIT OCW.

Now we consider **dry etching** (which has largely replaced wet)
based on highly *anisotropic sputtering process* ↓↓↓↓↓↓↓↓
and may include reactive ions,
so can also be *chemical and selective.*

Brief history of two types of etch processes…

Dry Etching supplants *wet*

Wet etching was used exclusively till 1970's

Etch bias: bad for small scale features

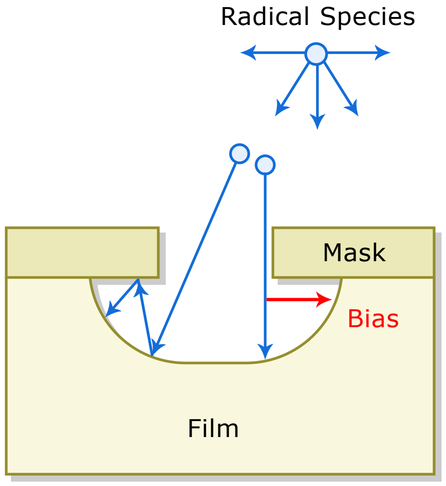


Figure by MIT OCW.

1. Need better definition of small features
   therefore **dry etching,**
   accelerated ions
   from *plasma*

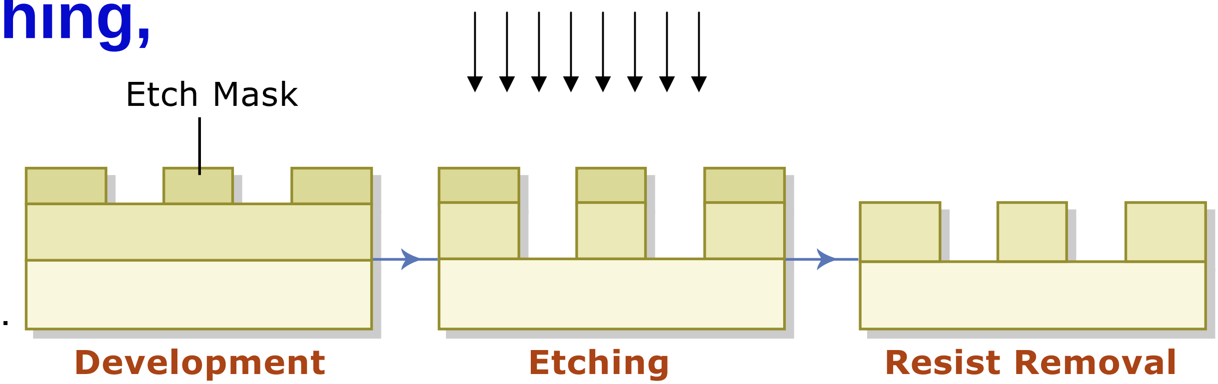


Figure by MIT OCW.

2. Widely used SiN passivation layer found difficult to **wet** etch
   (HF used but it attacks SiO_2),

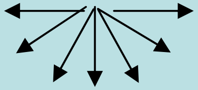
Reactive species in *plasma* found to accelerate **dry etching:**

$CF_4 + O_2$ in plasma much better, and does not attack PR

Etching

Wet etch (***Chemical***: *wet, vapor or in plasma*)

isotropic (*usually*), highly selective



Used less for VLSI (poor feature size control)

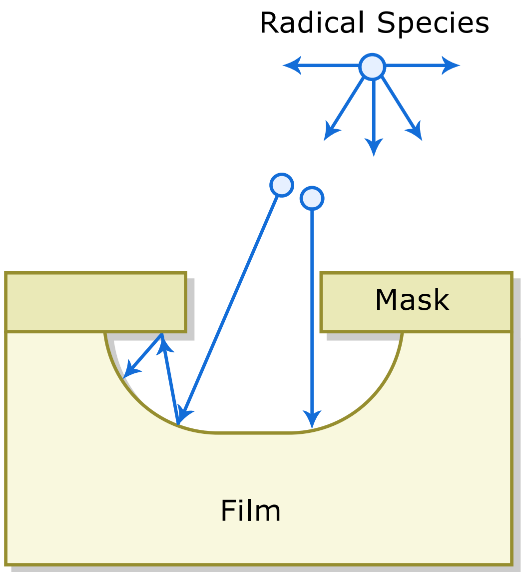
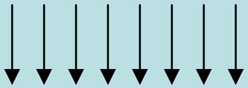


Figure by MIT OCW.

Dry etch (***Physical***: *ions, momentum transfer*)

anisotropic, not selective

Sputter etching



More widely used for small features

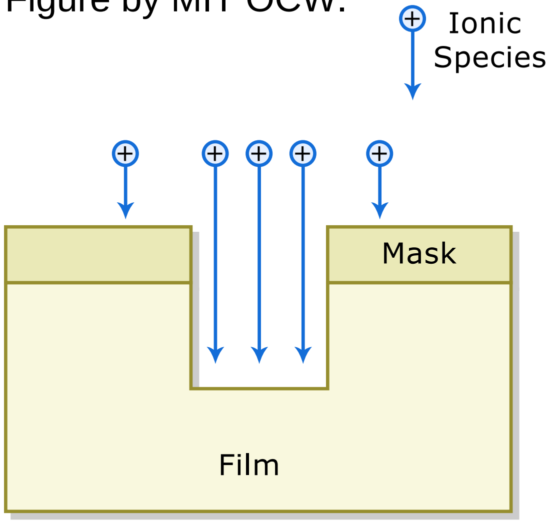
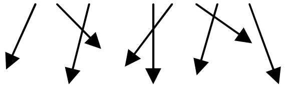


Figure by MIT OCW.

Combination (*Physical & Chemical*)

Ion-enhanced or

Reactive Ion Etching (RIE)



combines best of *directionality* and *selectivity*

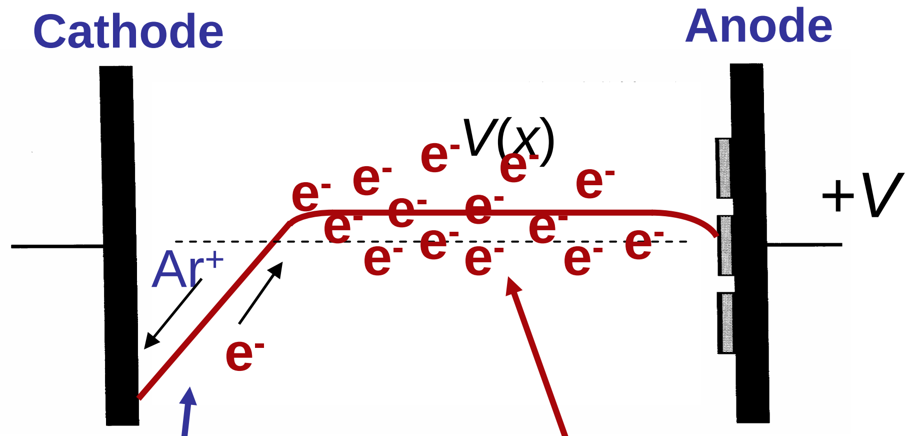
Review plasmas

$1 \text{ mT} < p < 100 \text{ mT}$

DC plasma

$v_{Ar+} \approx 4 \times 10^5$ m/s,
mean free path ≈ 3 cm

$v_{e-} \approx 2 \times 10^7$ m/s
λ much longer



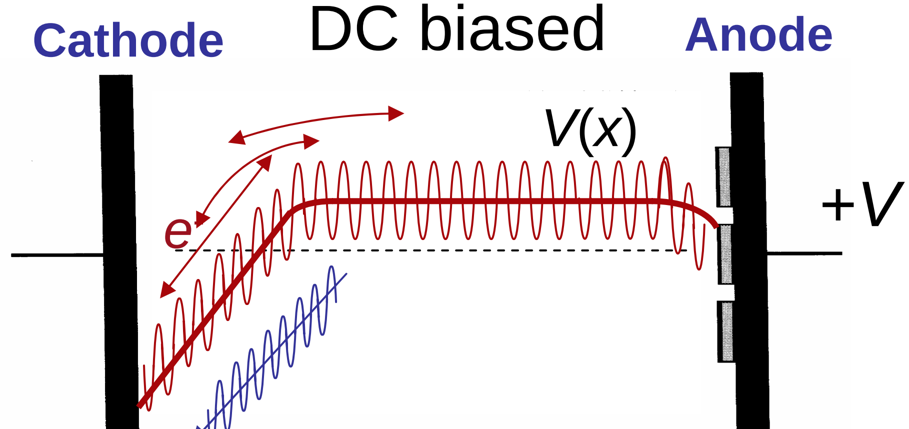
Fewer e^-s found in high-field, dark spaces

Electrons largely confined to positive potential, high conductivity, $V \approx 0$

RF plasma

$f = 13.6$ MHz , $\tau \approx 12$ ns

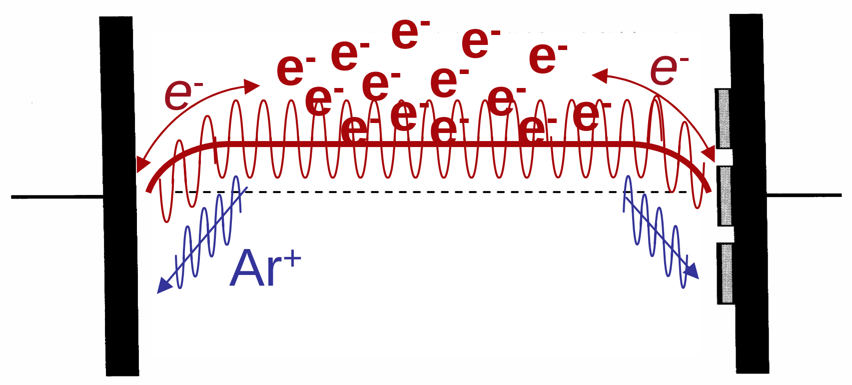
e^- transit time over 10 cm:
$t \approx 10$ ns.
e^- follows RF field



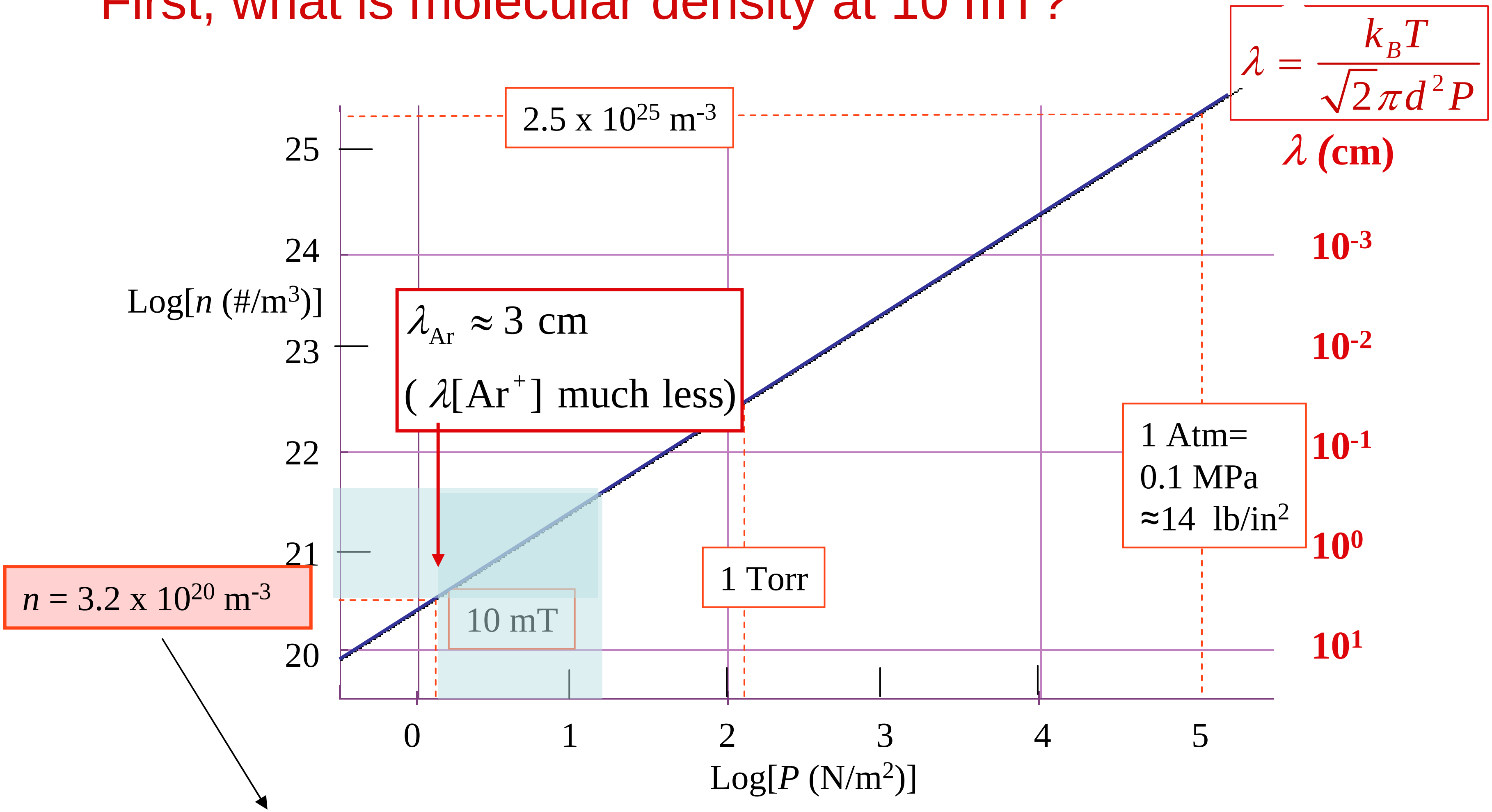
Ar$^+$ transit time over 10 cm
$t \approx 2$ µs

Ar$^+$ drifts with DC field

But wait a minute!
If the plasma is
a good conductor,
does the RF field
penetrate it?



***Exercise**: does RF field penetrate plasma?*
First, what is molecular density at 10 mT?



$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 P}$$

2.5 x 10^{25} m^{-3}

$\lambda_{Ar} \approx 3$ cm

($\lambda[Ar^+]$ much less)

$n = 3.2$ x 10^{20} m^{-3}

10 mT

1 Torr

1 Atm=
0.1 MPa
≈14 lb/in^2

If $n_{e-} < 1\%\ n$, take $n \approx 10^{18}$□m^{-3}

$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

We estimated $\tau \approx 0.01\ \mu s$, so at 10 mT, $\sigma \approx 300\ s^{-1}$

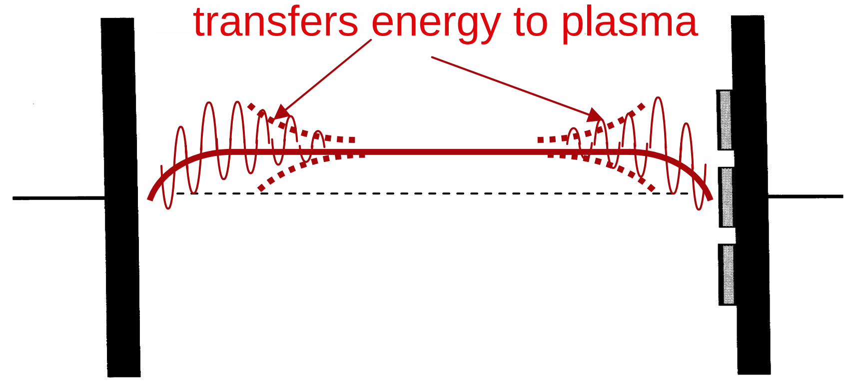
Is this a good metal? **No!**

Metals: $\rho_e < 100\ \mu\Omega\text{-cm} = 1\ \mu\Omega\text{-m}$, $\sigma > 10^6\ s^{-1}$

What then is the RF field penetration depth, skin depth?

$$\boxed{\delta = \frac{1}{\sqrt{\mu\sigma\omega}} \approx 5\ \text{mm}}$$

Energy pumped in from edges of plasma



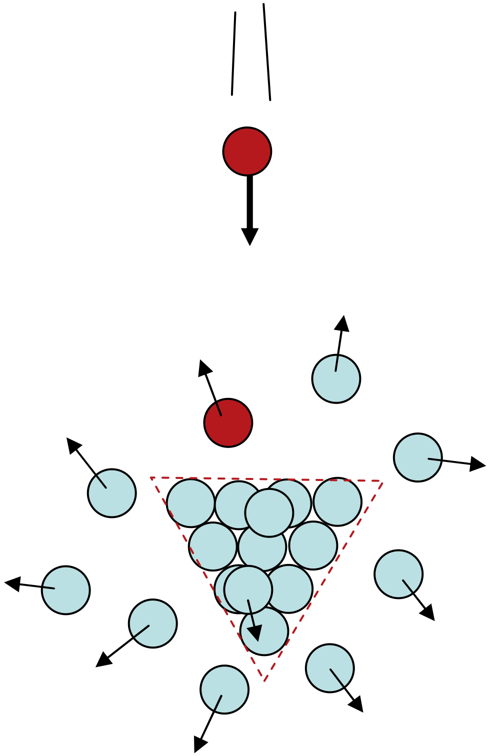
This is where RF field transfers energy to plasma

Is this consistent with our argument that plasma is quenched

at low p by too few collisions, long λ; small n, σ, larger skin depth; $\delta >> l$: quench

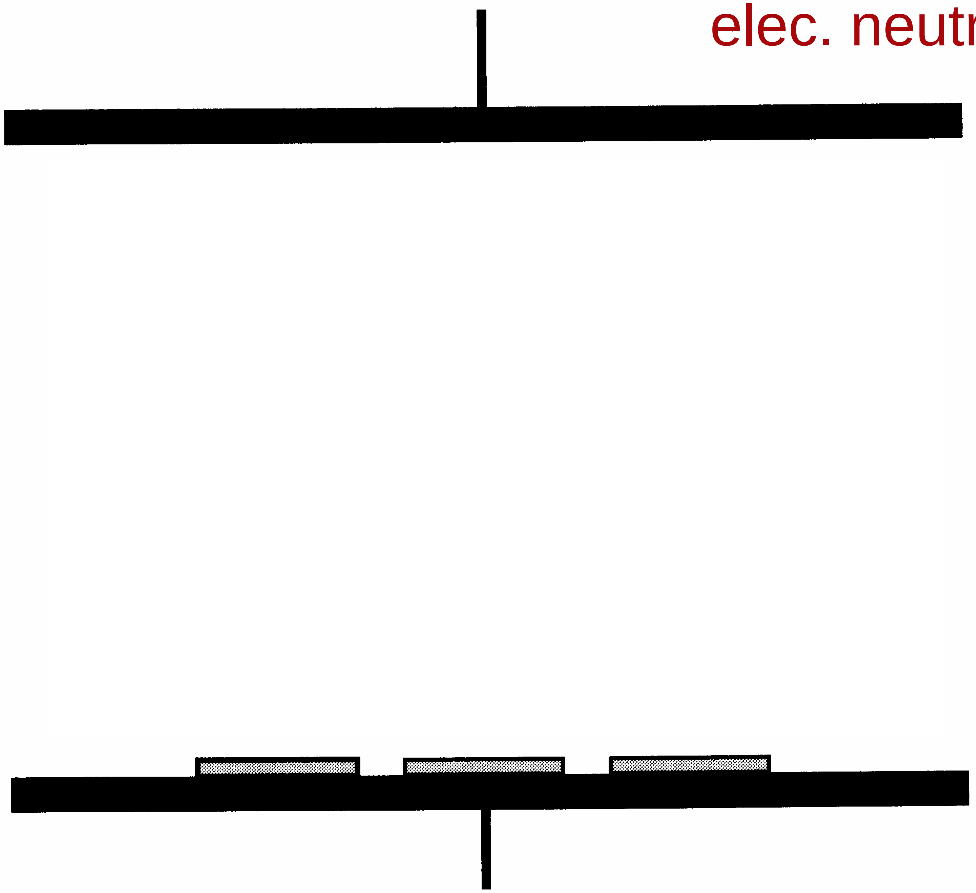
at high p by too little acceleration? large n, σ, small skin depth; $\delta << l$: quench

Dry etch combines



physical etch

nobles: Ar^+

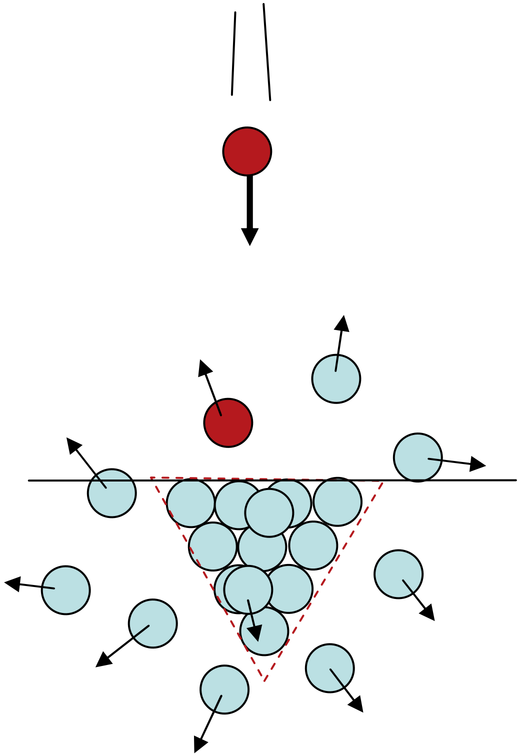


+ reactive ions

free radicals, i.e. elec. neutral and incomplete bonding: CF_3, F, Cl

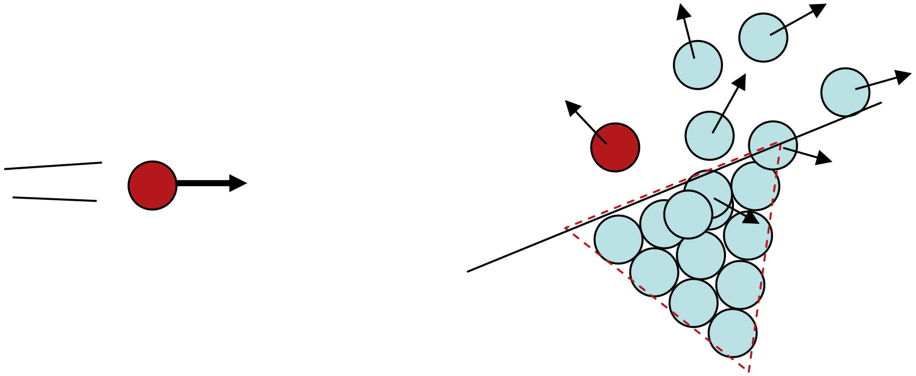
So $CF_4(g)$ gives $F(g)$

Physical etching
involves *directional momentum transfer by Ar+, Cl+ etc.*

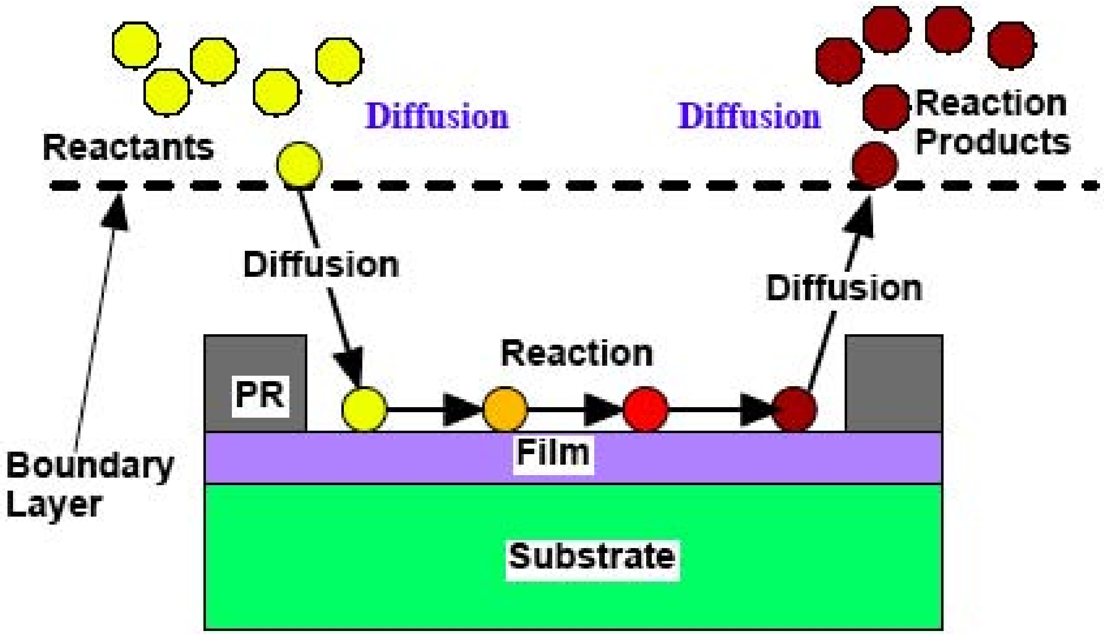


Because momentum is transferred
with every collision,
sticking is essentially unity, *S* ≈ 1.
This enhances anisotropic character

Sputter yield depends on angle of incidence,
helping planaraization



Chemical etching involves *transport* and *reaction*



Reactive species ***diffuse*** through boundary layer and along surface of wafer

Thermally activated ***reaction*** at surface gives soluble species

Products ***diffuse*** through boundary layer, transported away

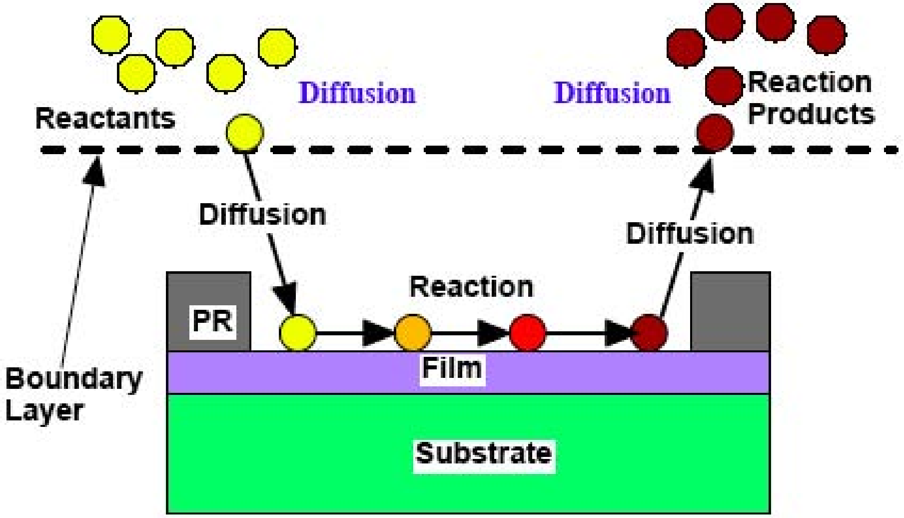
Advantages: high *selectivity* due to chemical reactions

Disadvantages: *Isotropic (except for Si)*, poor *process control*

(can be transport or reaction limited, just like CVD),

strong *T*-dependence

Chemical etching
involves *transport* and *reaction*

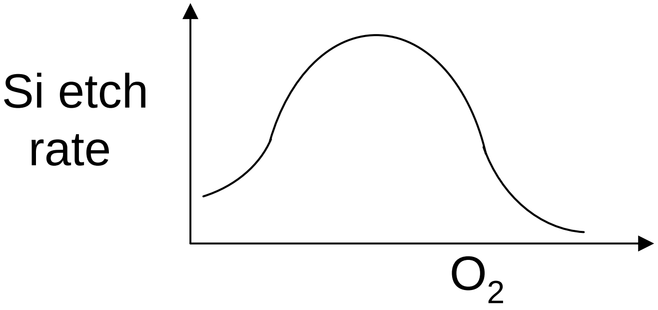


We saw: $CF_4(g)$ gives F(g)

$$4F\,(g) + Si \longrightarrow SiF_4\,(g)$$

So $CF_4(g)$ can etch Si

Adding O_2 enhances Si etch:
O_2 combines with CF_3, CF_2 reducing their recombination with F.
But too much O_2 oxidizes Si.



Chemical etching

Even though free radicals are highly reactive,
multiple steps required result in low effective sticking coefficients, $S \approx 0.01$.

This increases isotropic character of etch.

Benefit remains *selectivity*

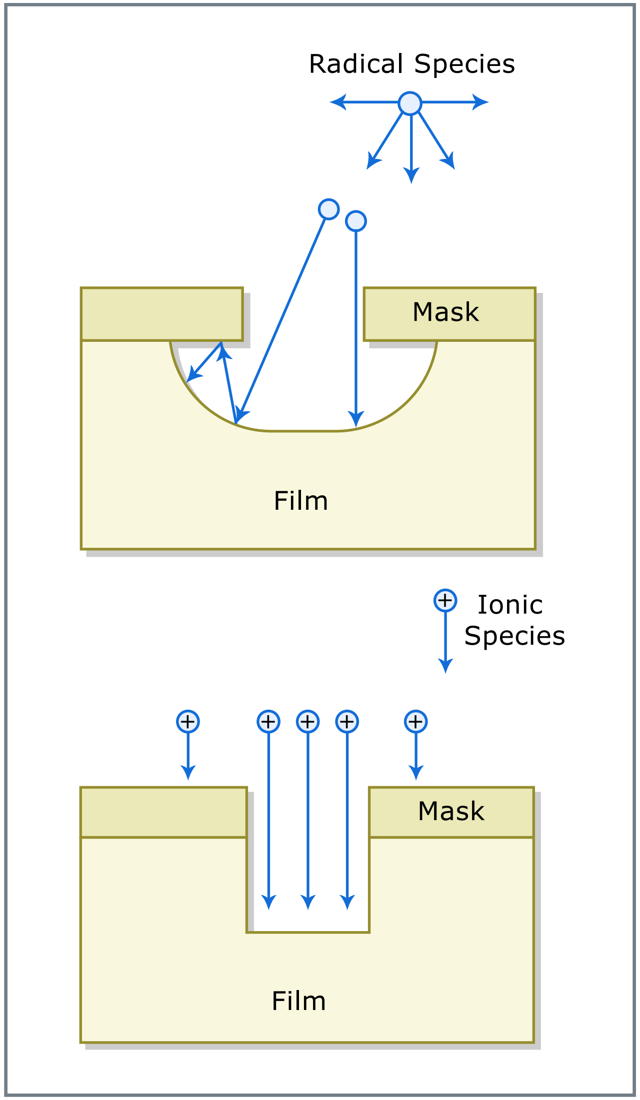
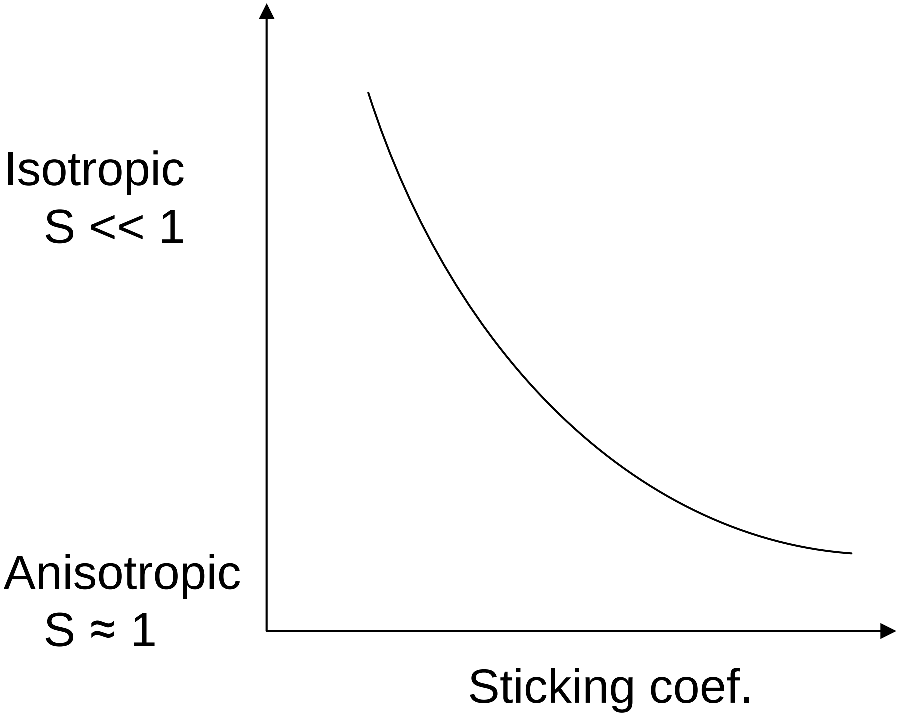


Figure by MIT OCW.



Ion-enhanced chemical etching

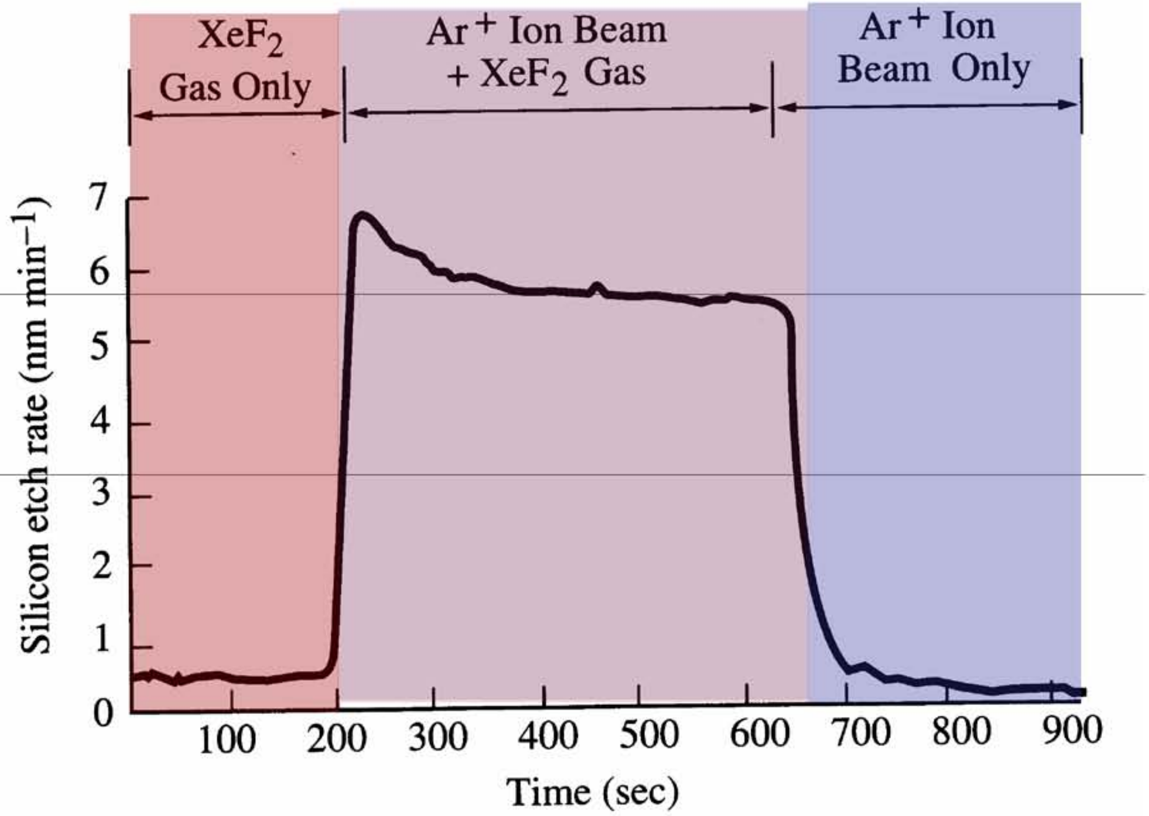
Physical and chemical processes not just independent of each other.

Ion beam can enhance chemical etching:

XeF_2 etching of Si

No plasma

No XeF_2



Further, the profile is not linear combo, but highly anisotropic

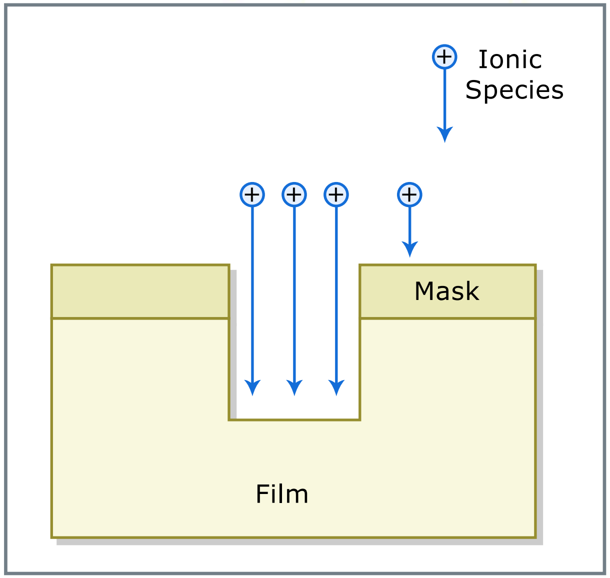


Figure by MIT OCW.

Wow!

The best of both

Aniso. + selctive

Ion-enhanced chemical etching

Why does rate of one process
depend on the other being present?

Tailor mix of gas as well as
ion energy & rate
to select desired wall profile.

Possible mechanisms:

1. Ions break bonds, render XeF_2 more reactive
2. Ions increase formation of of volatile byproducts
3. Ion beam may sputter away byproducts

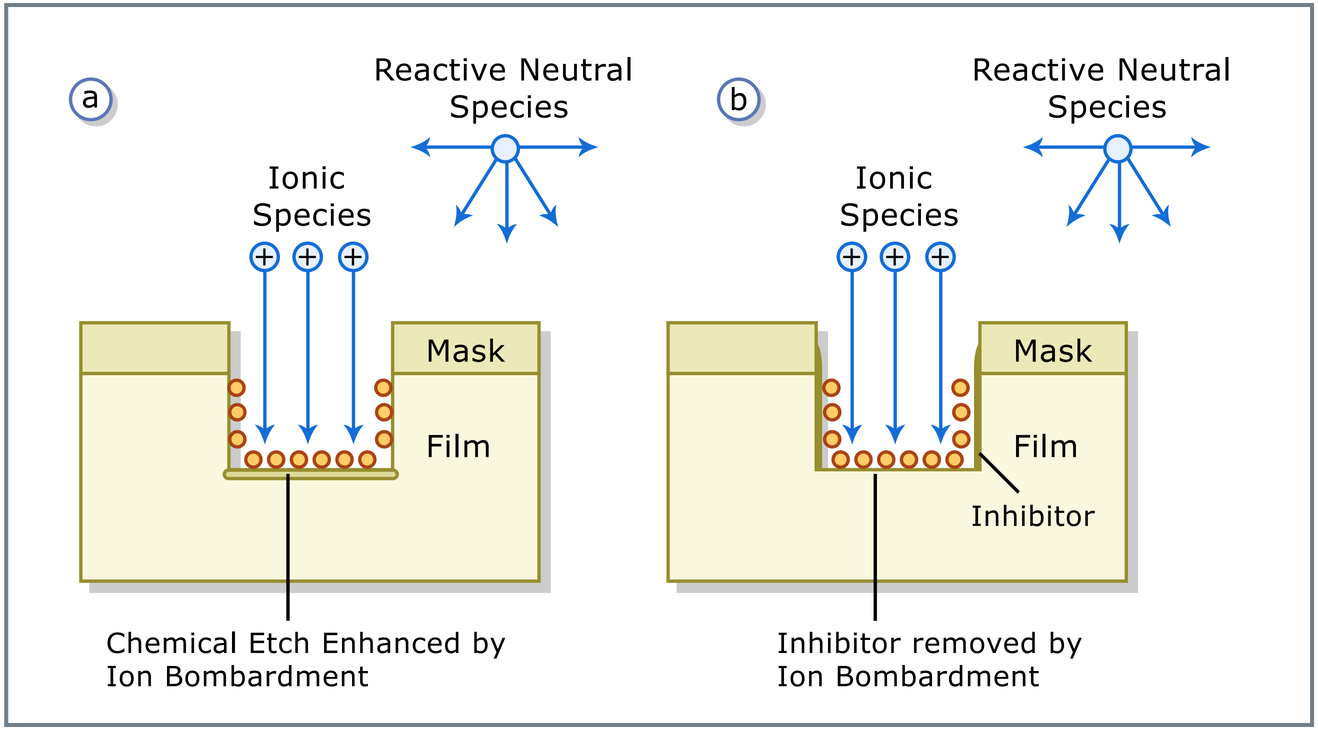


Figure by MIT OCW.

All that remains: consider, classify various combinations, configurations of physical and chemical etch

Barrel etcher: chemical etching only; shield keeps ion bombardment from wafers. Isotropic and selective

like pure *wet* etch,
but in gas phase.

Little damage;
Poor uniformity
edge to center;

Figure removed for copyright reasons.

Please see: Figure 10-15 in Plummer, J., M. Deal, and P. Griffin. *Silicon VLSI Technology: Fundamentals, Practice, and Modeling*. Upper Saddle River, NJ: Prentice Hall, 2000. ISBN: 0130850373.

Used most for
PR removal
by O_2:
Barrel “asher”

Polymer + $O_2 \Rightarrow CO_2 + H_2O$

Parallel plate; *plasma mode* etching: similar to PECVD EXCEPT that *etch gas is used instead of noble gas*.

Larger wafer electrode
(which defines *plasma mode*)
gives weaker
ion bombardment
of wafers
(more uniform etch
than barrel)

Figure removed for copyright reasons.

Please see: Figure 10-9 in Plummer et al, 2000.

Both *physical &*
chemical etch occur.

More *uniform* etch
than barrel etcher.

At higher *p,*
physical etch
contributes less.

Gentle

Parallel plate; *reactive ion etching* (RIE) mode:

More appropriately called “*reactive and ion*“ etching;

smaller etch electrode, greater voltage drop above wafers; incoming ions are more energetic.

Greater voltage drop gives greater etch anisotropy and greater physical etch, less selectivity.

Figure removed for copyright reasons.

Please see: Figure 10-9 in Plummer et al, 2000.

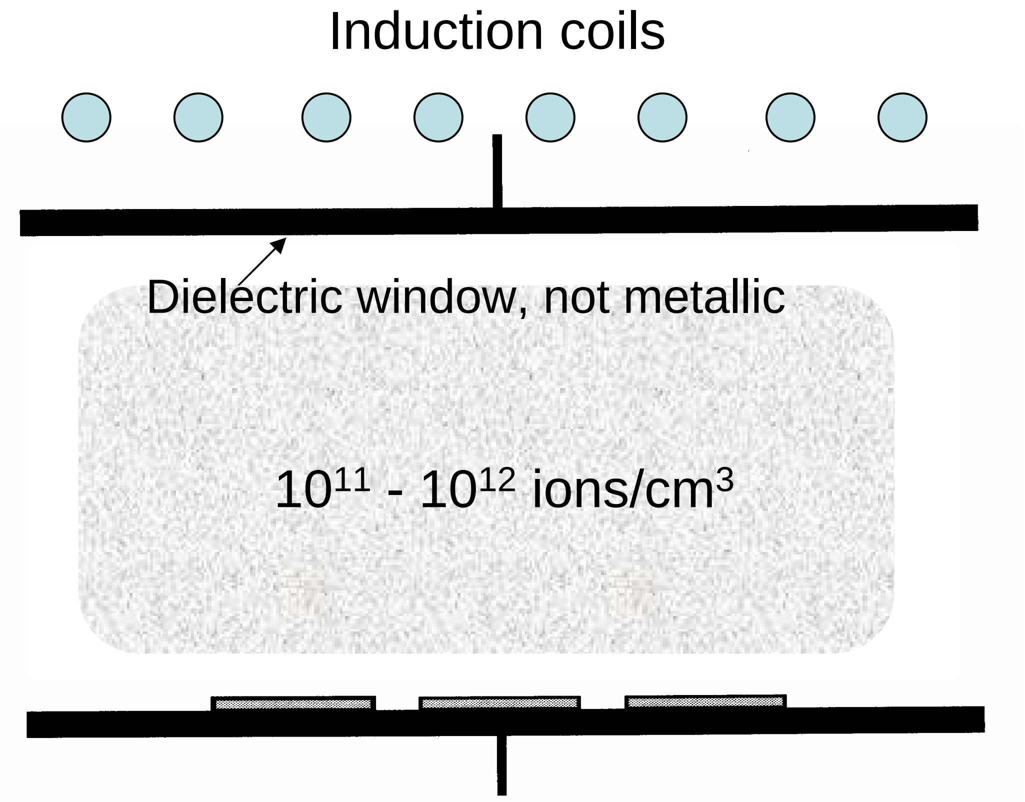
Lower gas pressure
(10 - 100 mT)
increases mean-free path,
increases anisotropy.

Triode sputtering system:
separate power supply
to separate ion generation
from wafer bias voltage.

Aggressive

High-density plasma systems

secondary excitation source that is not capacitively coupled;
instead inductively coupled plasma (ICP); growing popularity

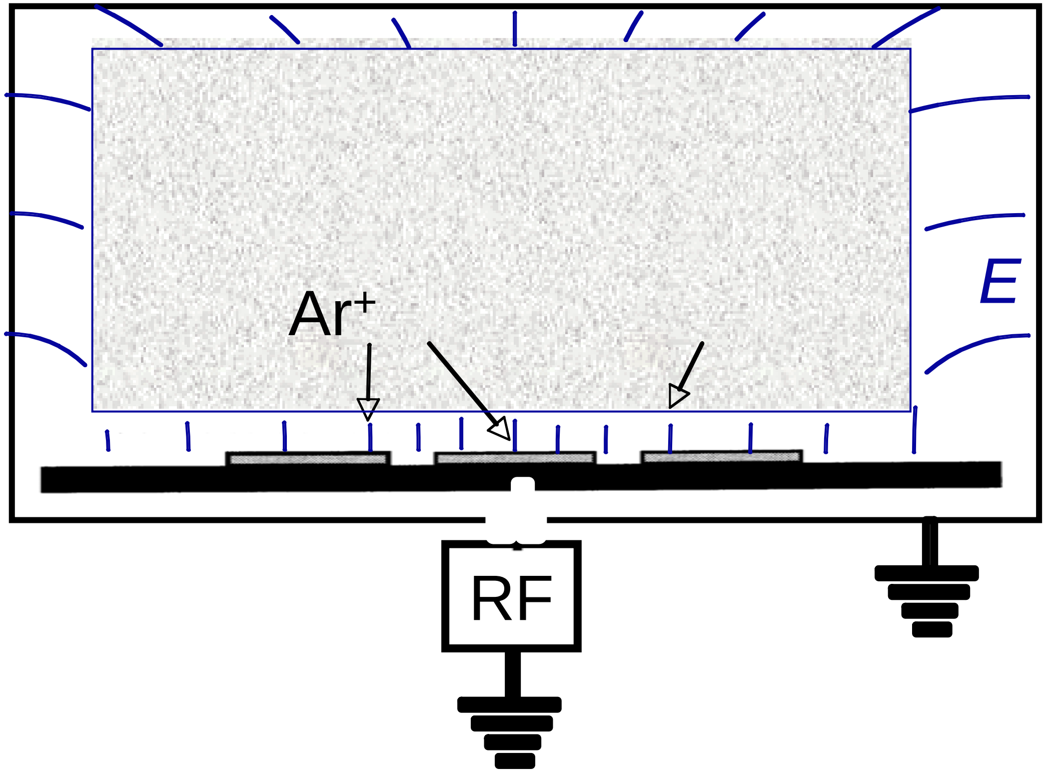


Plasma density no longer depends on pressure. High plasma density can be achieved at lower pressures (1 -10 mT).

Lower gas pressure means more anisotropy…
but also more
substrate damage

Sputter etching & ion milling

nearly *completely physical* (not chemical) etching; no reactive gas



Wafers here
in position of target
in sputter deposition

Anisotropic etch
with low selectivity

Problems with ion milling:

trenching, redeposition charging gives ion path change

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Can add a reactive species to chamber:
“reactive ion-beam etching”

FIB: Focused ion beams (usually Ga) no used to prepare TEM specimens, 3-D structures, shape recording heads

Problems with ion milling:

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Please see: Figure 10-20 in Plummer et al, 2000.

Problems with etching

Uniformity:

1. "*bull's eye*": wafer etches faster at outside, less inside
   (barrel etcher)

2. "*Macro-loading*": too many wafers rob others of etchant
   (long-range gas transport problem)

3. "*Micro-loading*": unmasked large areas hoard etchant
   (short-range gas transport problem)

Review of etching process

		Pressure	Etch rate	Energy (eV)	Selectiv'y	Anisot'y
Physical	Sputter etch Ion milling	1mT-1 T	enhanced		low	high
	HDPE 0.1-3 W/cm^2	1- 10 mT	enhanced	10-500	high	high
	RIE	10-100 mT	enhanced		high	high
	Plasma etch	10-100 mT	low	low	moderate	moderate
	Barrel etcher	10-100 mT	moderate	10 - 700 eV	high	low
Chemical	Wet etch	*irrelevant*	enhanced		high	low

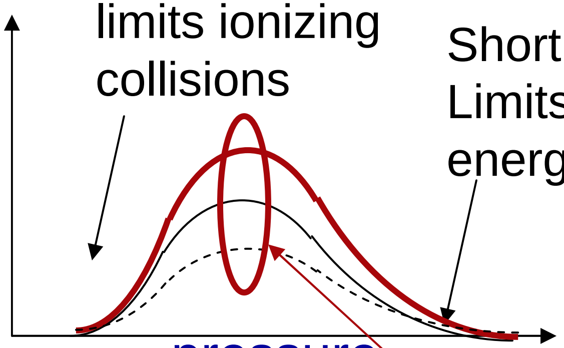
Etching miscellany

Etch rate $\propto$ to active species flux (neutrals & ions) $J = cv$

$\propto$ plasma density & pressure

RF power

Plasma density



Long λ limits ionizing collisions

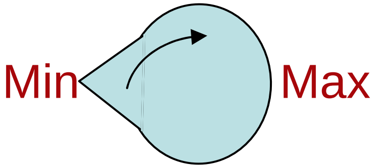
Short λ Limits ion energy

pressure

RF power + inductively coupled power

Dial-up the parameters you want:

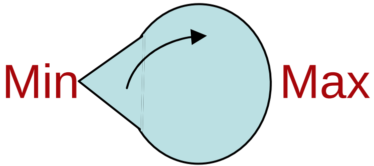
Higher anisotropy



Lower anisotropy

Pressure

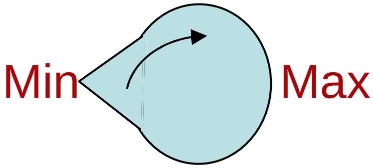
Noble; physical



Reactive; chemical

Gas composition

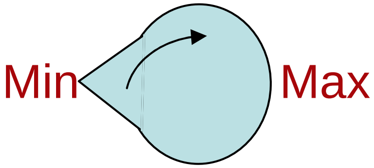
Lower anisotropy



Higher anisotropy

Substrate bias
(Cathode size)

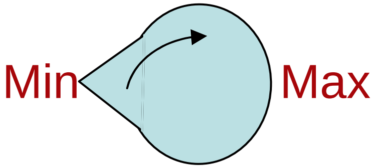
Small => anisotropic



Large => isotropic

Wafer electrode area

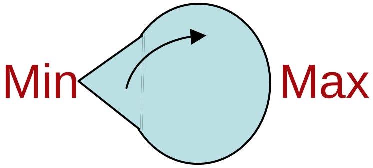
Low damage, better selectivity



Greater plasma den, sheath *V*, physical damage

RF power

More physical etch, anisotropy



More chemical etch, selectivity

Gas flow rate

Etch byproducts should have low boiling point

BOILING POINTS OF TYPICAL ETCH PRODUCTS

ELEMENT	CHLORIDES	BOILING POINT (°C)	FLUORIDES	BOILING POINT (°C)
Al	$AlCl_3$	177.8 (subl.)	AlF_3	1291 (subl.)
CU	CuCl	1490	CuF	1100 (subl.)
Si	$SiCl_4$	57.6	SiF_4	-86
Ti	$TiCl_3$	136.4	TiF_4	284 (subl.)
W	WCl_6	347	WF_6	17.5
	WCl_5	276	WOF_4	187.5
	$WOCl_4$	227.5		

Figure by MIT OCW.

Figure removed for copyright reasons.

Please see: Table 10-3 in Plummer et al, 2000.

Figure removed for copyright reasons.

Please see: Figure 10-25 in Plummer et al, 2000.

Etching SiO_2

$4F + SiO_2 \Rightarrow SiF_4 + O_2$

Too isotropic and poor selectivity /Si

Solution: reduce F production and increase C