Nanometer Scale Patterning and Processing

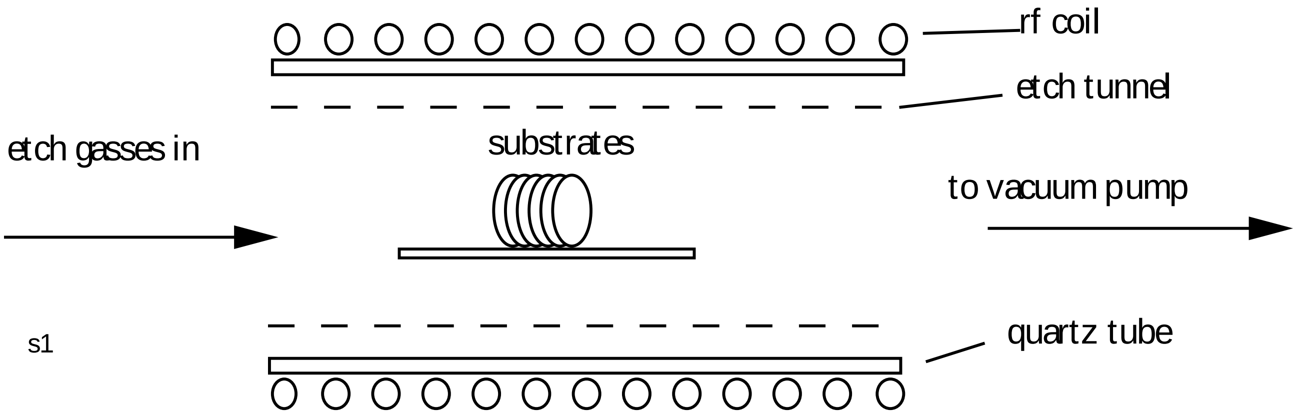
Spring 2016

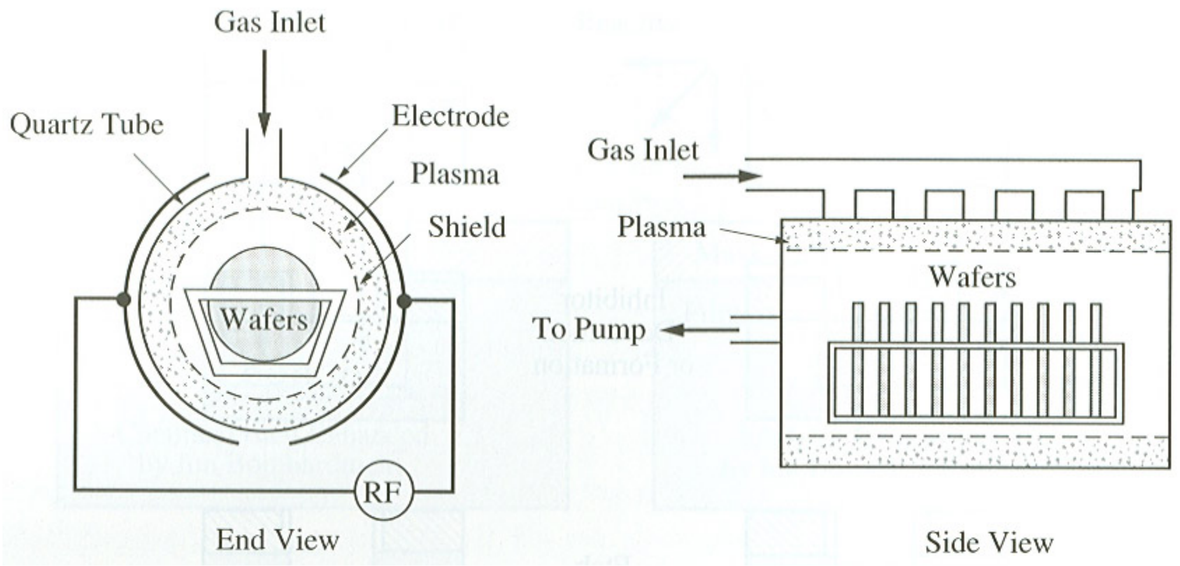
Lecture 45

Dry Etching, Part 1

DRY ETCHING

Pure Chemical Etch in Plasmas





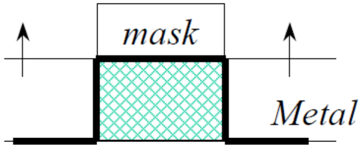
- Isotropic
- Like wet etch, but in gas phase
- Little damage, poor uniformity (e.g. wafer edge to center)
- Suitable for resist striping
  - Polymer + $O_2 \rightarrow CO_2 + H_2O$

Volatility of Etching Product

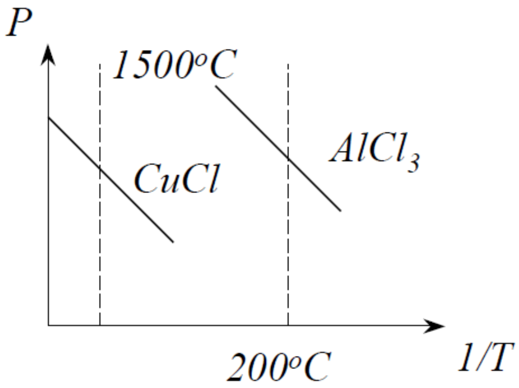
* Higher vapor pressure ⇒ higher volatility

$e.g.\ Si + 4F^* \rightarrow SiF_4 \uparrow$ (high vapor pressure)

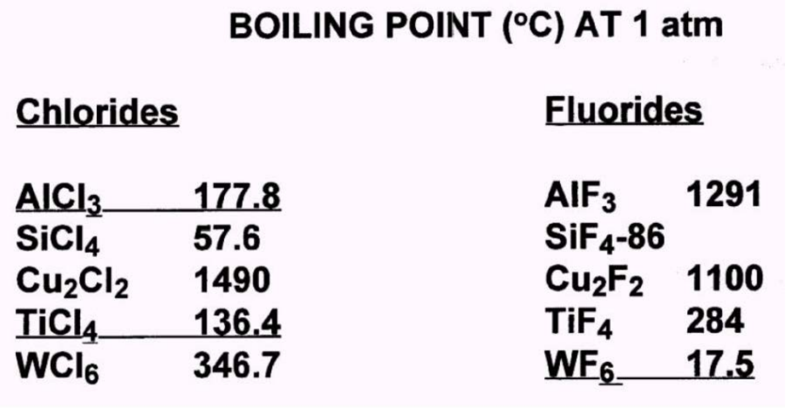
$e.g.\ Cu + Cl \rightarrow CuCl\,(low\ vapor\ pressure)$



$$P = P_0 e^{-\Delta H_v / kT}$$

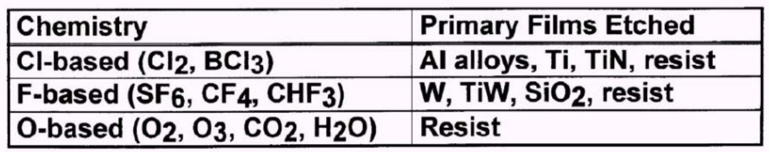


Cl_2 as etching gas.



BOILING POINT (°C) AT 1 atm

Chlorides		**Fluorides**	
$AlCl_3$	177.8	AlF_3	1291
$SiCl_4$	57.6	SiF_4	-86
Cu_2Cl_2	1490	Cu_2F_2	1100
$TiCl_4$	136.4	TiF_4	284
WCl_6	346.7	WF_6	17.5



Chemistry	Primary Films Etched
Cl-based (Cl_2, BCl_3)	Al alloys, Ti, TiN, resist
F-based (SF_6, CF_4, CHF_3)	W, TiW, SiO_2, resist
O-based (O_2, O_3, CO_2, H_2O)	Resist

Example

Difficult to RIE Al-Cu alloy with high Cu content

1~2% typical

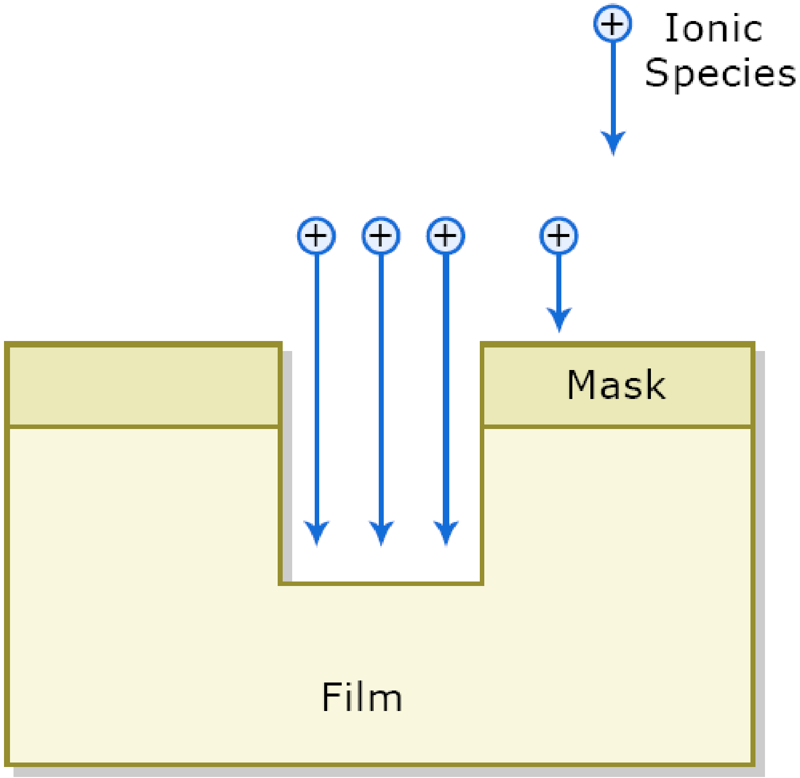
[Al-Cu alloy]

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		

Physical Etching

- Wafer exposed to inert gas and/or plasma
- Etch is from momentum transfer from accelerated ions
  - Acting anisotropically
  - Good etch definition
  - Low selectivity
  - Rate is mass transport dependent
- Parallel version of Focused Ion beam etching



Combination of Chemical and Physical etching

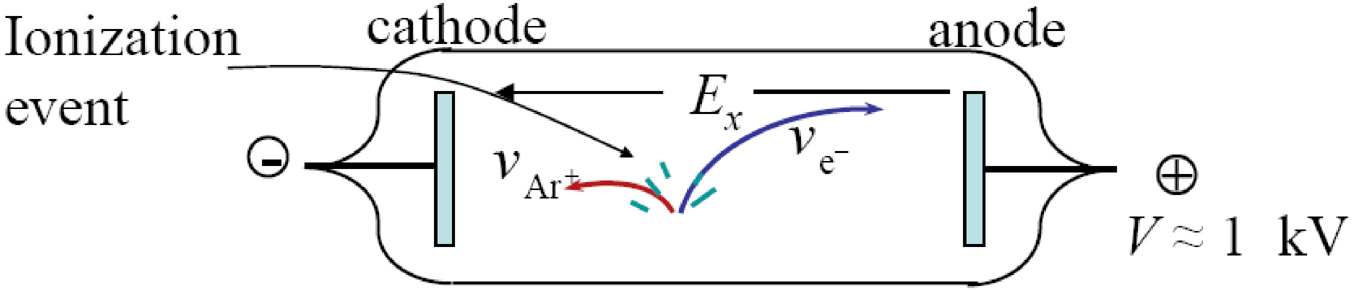
Ion-enhanced or Reactive Ion Etching (RIE)

Blends best of directionality and selectivity

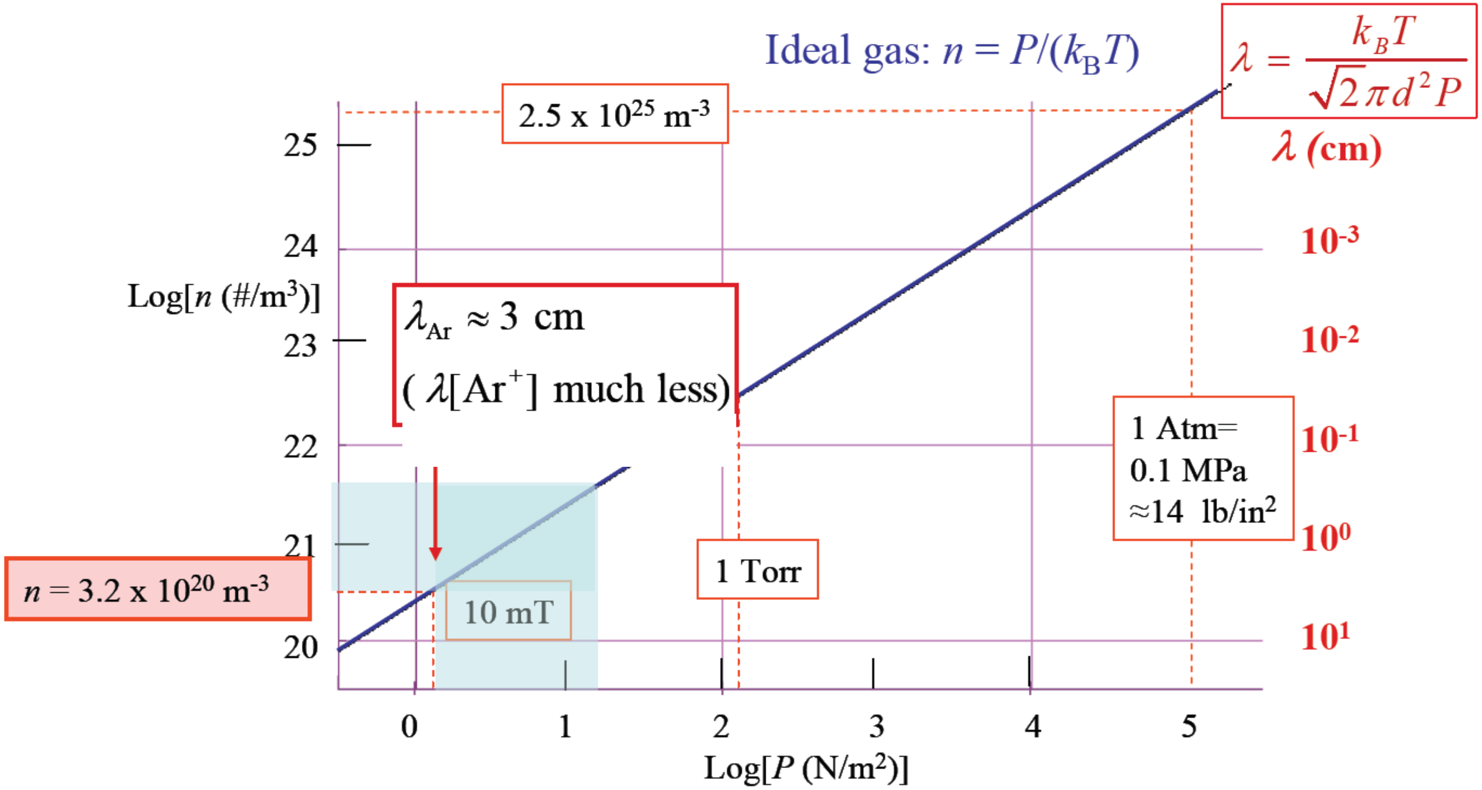
Plasma: A gas of ionized particles

Ar gas discharge

Ionization potential of Ar ≈ 16 eV



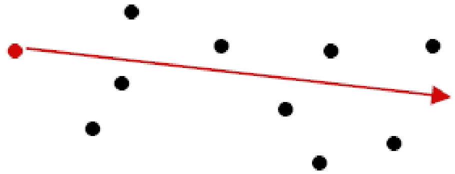
Plasma self-sustaining only for pressures 10 mT < P < 100 mT



At 10 mT, molecular spacing≈ $n^{-1/3}$= 0.15 microns

Particle Energy in Plasma

Spacing between molecules $\approx n^{-1/3} = 0.15$ microns.



Thermal velocity of Ar, $v \approx \sqrt{\dfrac{3k_BT}{m_{\text{Ar}}}} \approx 10^3$ m/s

Velocity of
ions at x = λ:

$$\boxed{v_f^2 = v_0^2 + 2ax \approx 2\frac{Eq}{m}\lambda}$$

E field accelerates Ar$^+$, e^- between collisions.

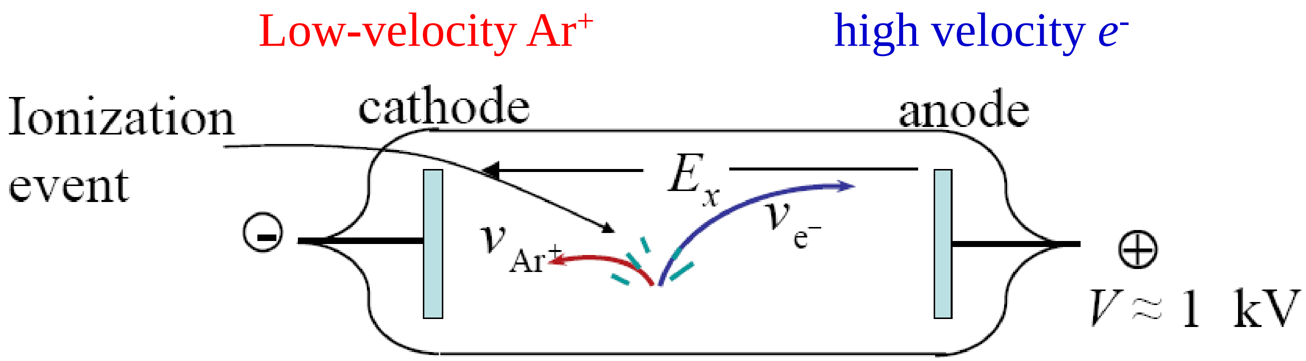
$v_{\text{Ar}} \approx 4 \times 10^5$ m/s

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

(only 0.1% to 1% of n_{Ar} are ions):

New Picture of Plasma

$$v_{kT} \approx 10^3 \ \text{m/s}$$
$$v_{Ar+} \approx 4 \times 10^5 \ \text{m/s}$$
$$v_{e-} \approx 2 \times 10^7 \ \text{m/s}$$



The plasma is highly conducting due to electrons:

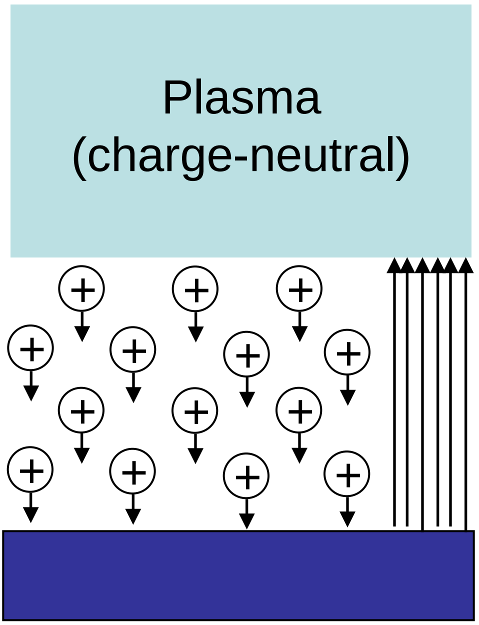
$$\boxed{J = nq\bar{v}_x}$$

Thus $J_{e-} >> J_{Ar+}$

$$J_{e-} = \sigma E = nq\bar{v}_x \approx nq\frac{at}{2} \approx nq\frac{Eq}{2m}\frac{\lambda}{v}$$

$$\sigma_{e-} \approx \frac{nq^2}{2m}\frac{\lambda}{v} = \frac{ne^2\tau}{2m}$$

Origin of the Sheath Voltage



Reservoir and generator of Ar^+ and electrons

Plasma
(charge-neutral)

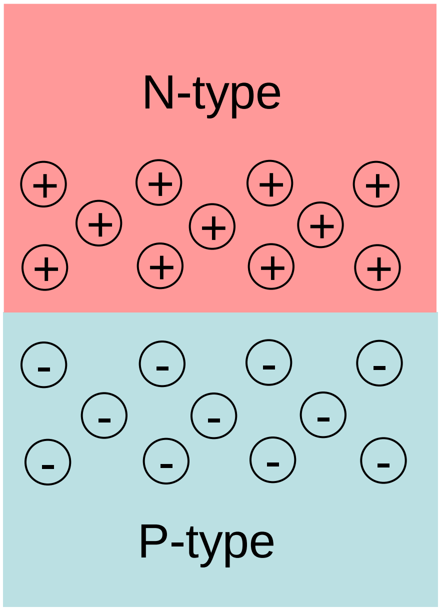
Long-lived Ar^+

Short-lived Electrons

Sink of Ar^+ and supplier of electrons

Cathode

Built-in potentials



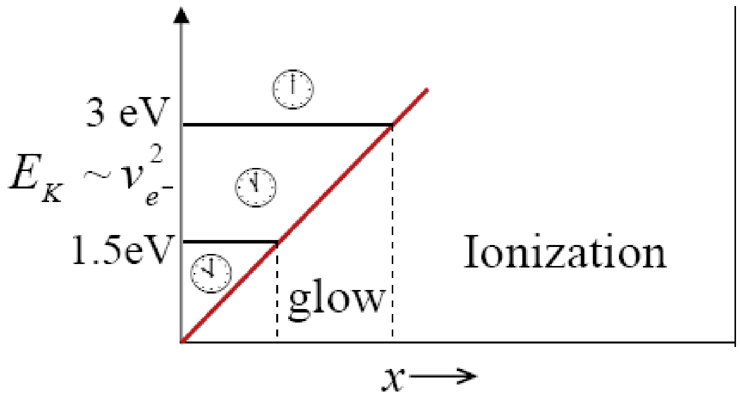
N-type

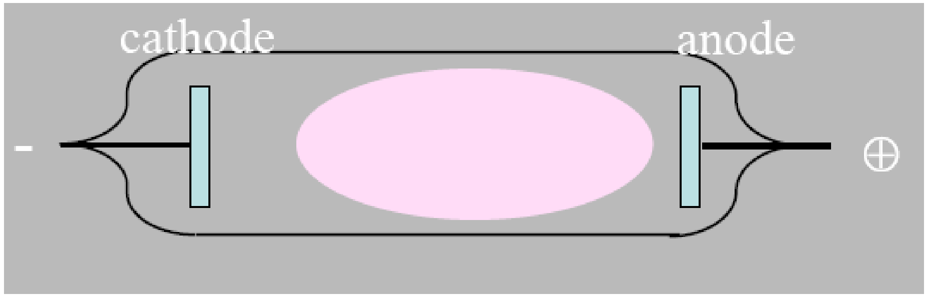
P-type

Space charged region of Semiconductors (P-N junction)

Inside a plasma

(D.C. or "cathode sputtering")



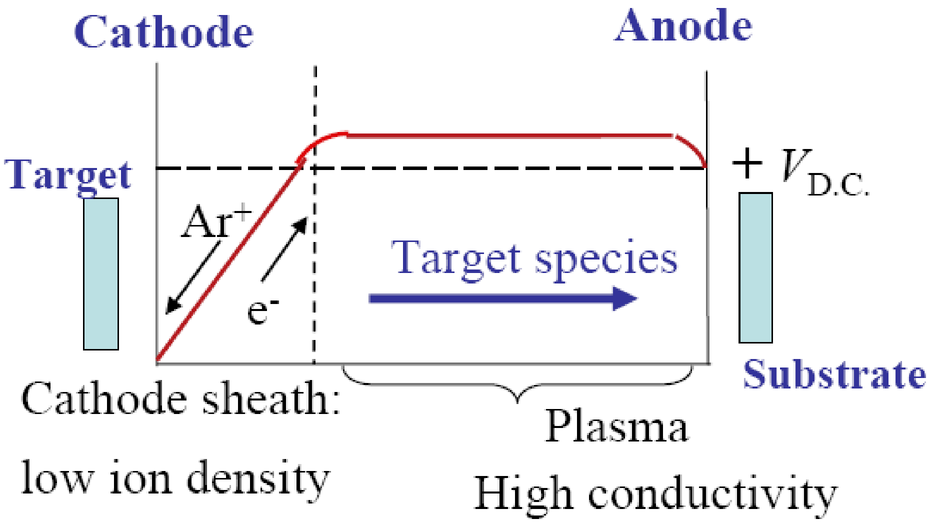


$J_{e^-}, v_{e^-} \gg J_{Ar^+}, v_{Ar^+} \Rightarrow$

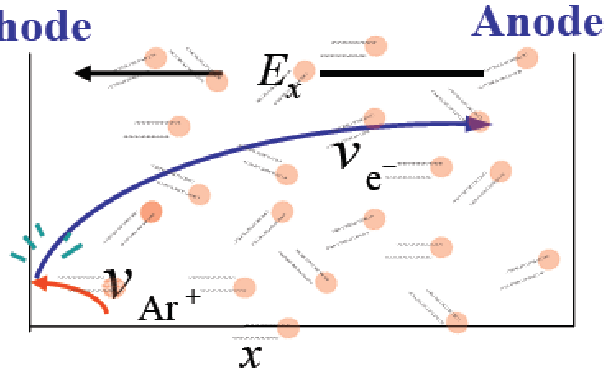
Surfaces in plasma charge negative, attract Ar^+ repel e^-

$\therefore$ *plasma* $\approx$ 10 V *positive*

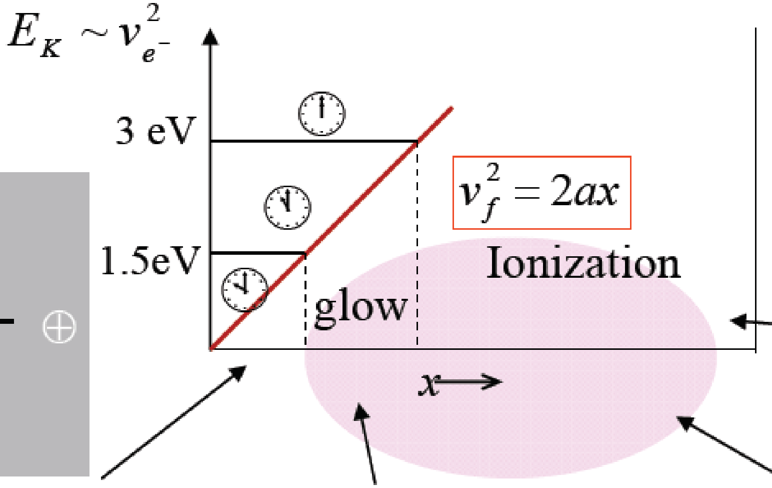
relative to anode



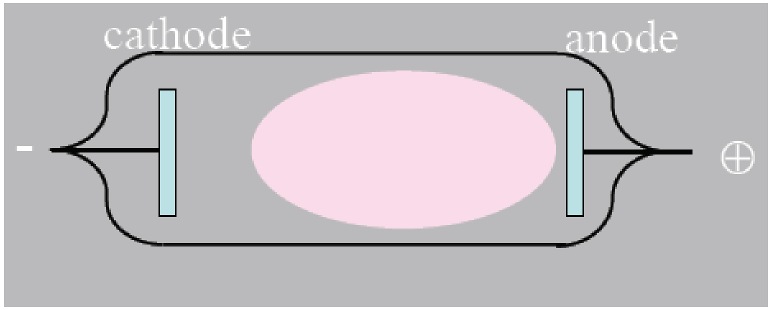
What about Glow?



Ar$^+$ impact on cathode => Lots more electrons, plus sputtered atoms



$v_f^2 = 2ax$



Faraday dark space

e⁻s swept out

$E_K^{e^-} \lesssim 1.5\text{eV}$

$1.5 \lesssim E_K^{e^-} \lesssim 3\text{eV}$

$E_K > 3\text{eV}$

Cathode dark space, no action

e⁻ - induced optical excitation of Ar ⇒ visible glow

=> ionization, High conductivity plasma

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Pressure range for normal glow-discharge plasmas

Necessary conditions:

If pressure is too low, λ is large, too few collisions *in plasma* to sustain energy

1) $\lambda < L$

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

so collisions exchange energy *within* plasma

If pressure is too high, λ is small, very little acceleration between collisions

2) E_K > ionization potential of Ar^+

$$\boxed{\frac{1}{2} m v_f^2 = 2ax \approx Eq\lambda}$$

High-density plasmas can sustain at lower pressures

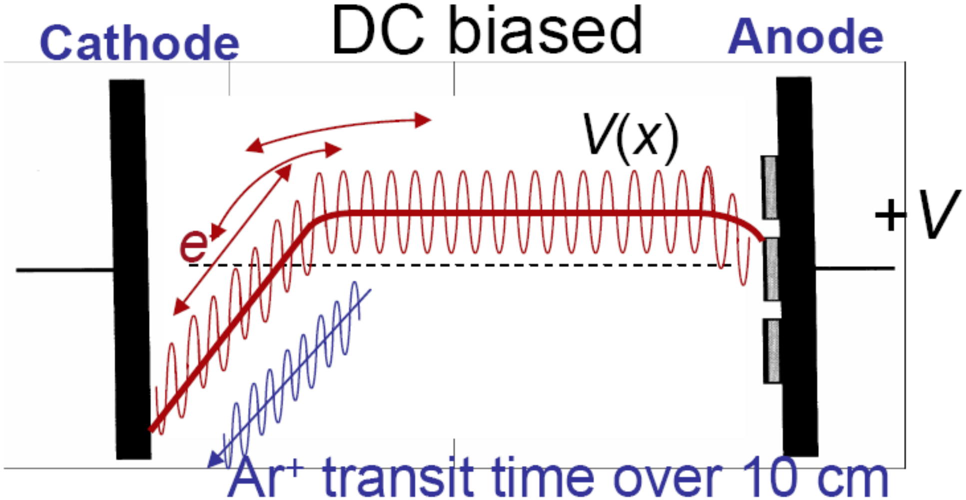
RF Plasma

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

e^- transit time over 10 cm:

$t \approx 10$ ns.

e^- follows RF field

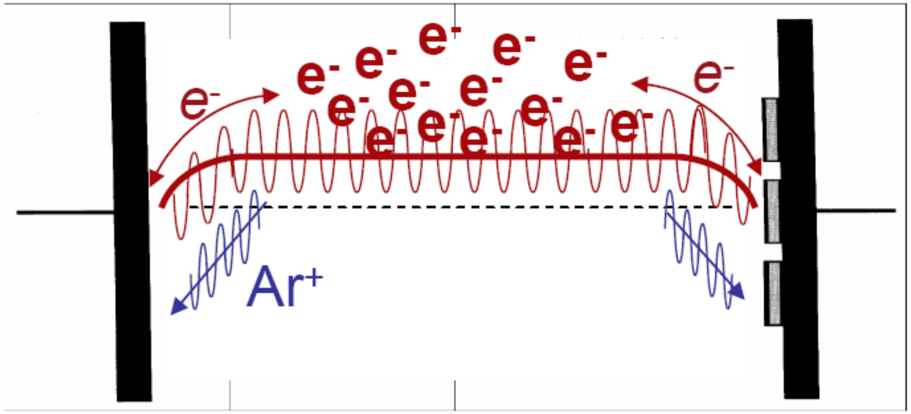


Ar^+ transit time over 10 cm

$t \approx 2$ μs

Ar^+ drifts with DC field

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



Plasma is conductive but not a good one

τ: average time between collisions

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

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

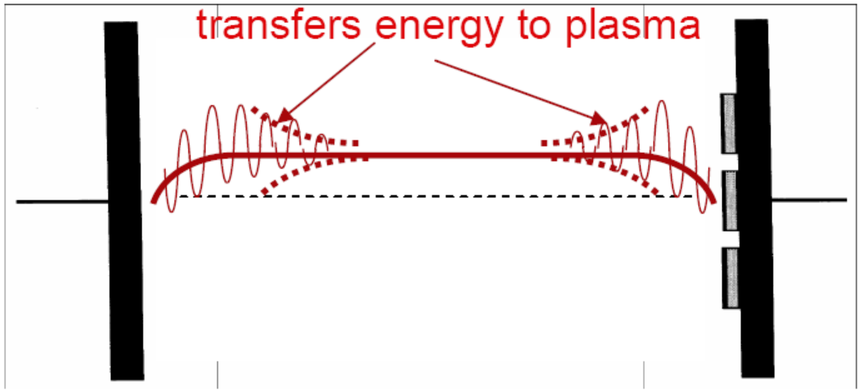
Is this a good metal? **No!**

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

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

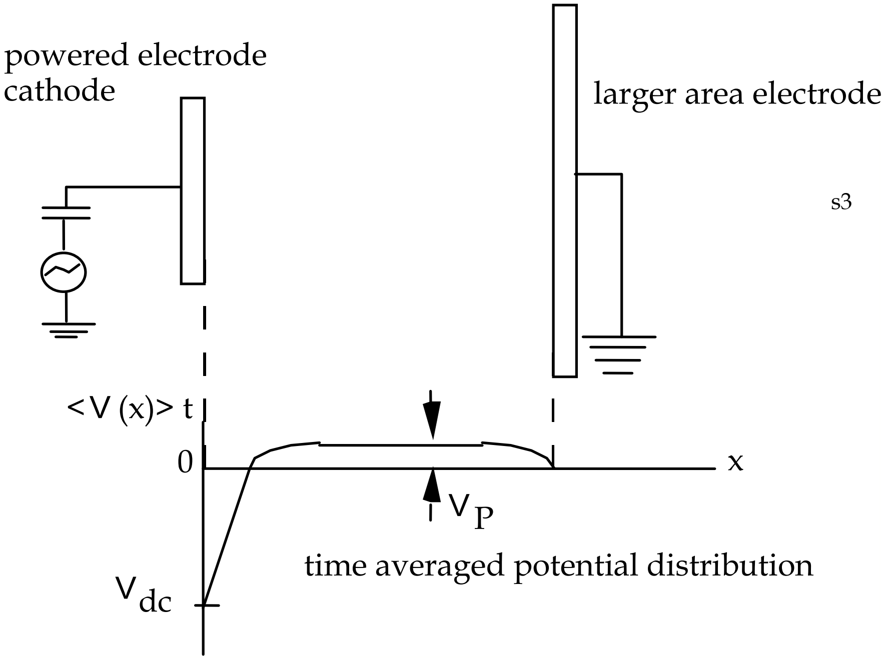
$$\boxed{\delta = \frac{1}{\sqrt{\mu\sigma\omega}} \approx 5\ \mathrm{mm}}$$

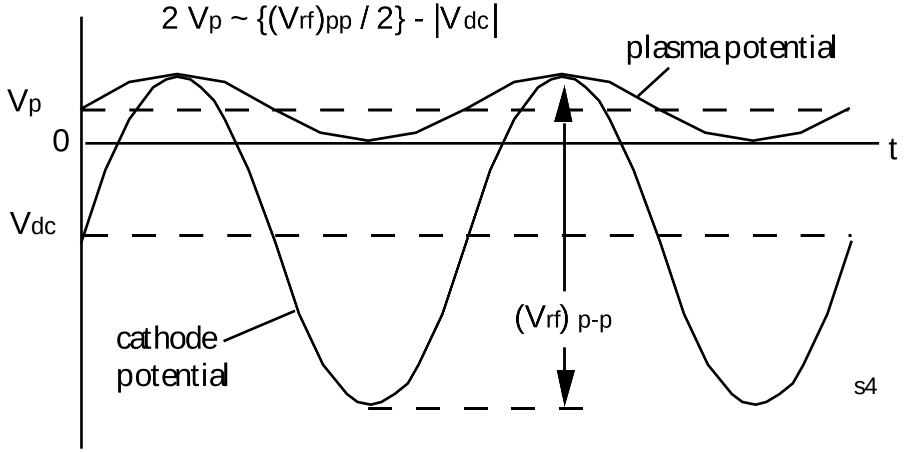
Energy pumped in from edges of plasma



This is where RF field transfers energy to plasma

Charge balance in RF plasma





RF plasma allows electrodes to be insulators