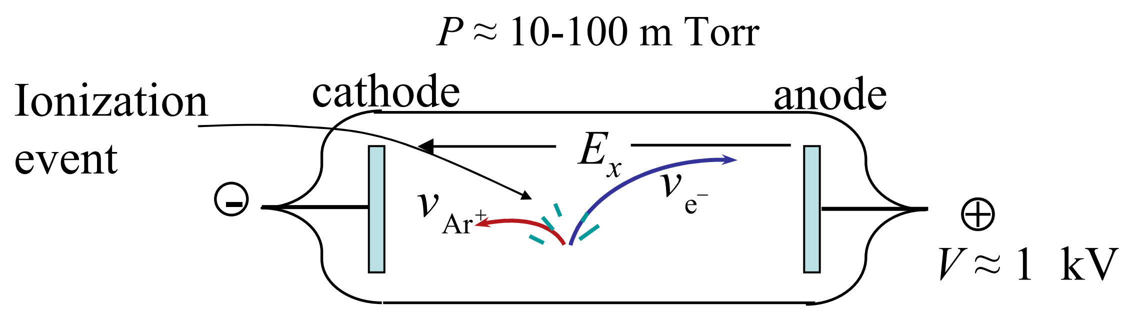
Physical Vapor Deposition (PVD): SPUTTER DEPOSITION

- We saw **CVD** — Gas phase reactants: $P_g \approx 1$ mTorr to 1 atm.
  Good step coverage, $T >> \mathrm{RT}$
- …**PECVD** — Plasma enhanced surface diffusion without need for elevated T
- We will see **evaporation:** (another PVD) — Evaporate source material, $P_{\mathrm{eq.vap.}}$ $P_g \leq 10^{-6}$ Torr
  Poor step coverage, alloy fractionation: $\Delta P_{\mathrm{vapor}}$
- We will see **Dry etching** — Momentum transfer and chemical reaction from plasma to remove surface species
- Now **sputter deposition**. Noble or reactive gas $P \approx 10$ -100 mTorr

What is a plasma?

What is a plasma? A gas of ionized particles, typically noble gas (e.g. $Ar^+ + e^-$)

Ionization potential of Ar ≈ 16 eV

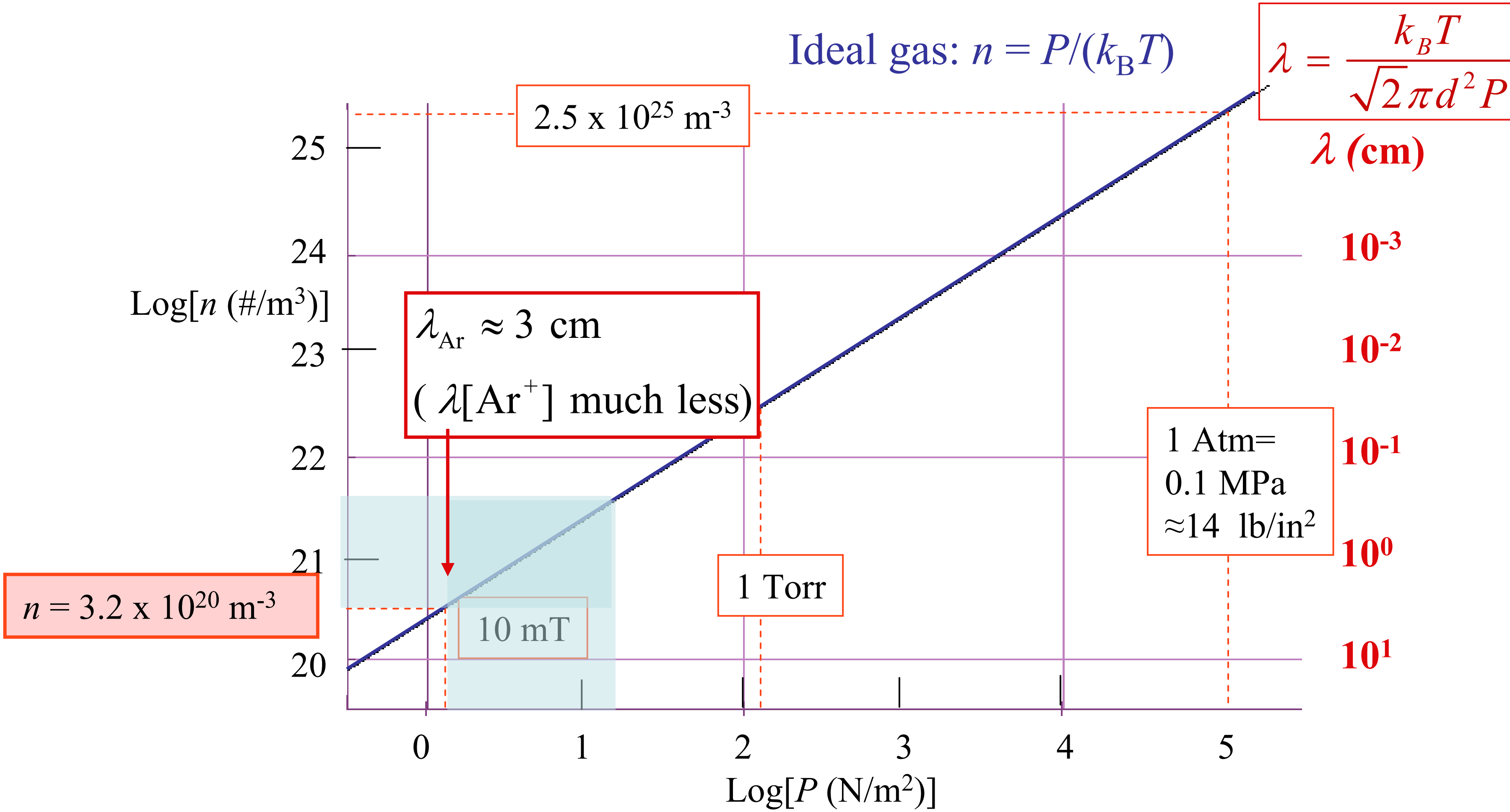


Plasma is only self-sustaining over a range of pressures:

typically 1 or 10 mT > P > 100 mT.

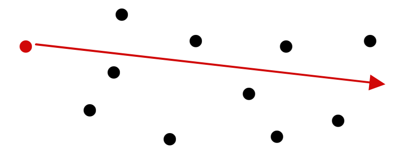
To understand "Why this pressure range?", we need to understand what goes on inside a plasma?

First, what is molecular density at 10 mT?



At 10 mT, molecular spacing ≈ $n^{-1/3}$ = 0.15 microns. Is this = λ ?

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



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

$\lambda_{\mathrm{Ar}} \approx 3$ cm

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

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

---

What's final velocity of ions at $x = \lambda$? ***E*** field accelerates Ar^+, e^- between collisions.

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

$v_{\mathrm{Ar}} \approx 4 \times 10^5$ m/s | $v_{e^-} \approx 2 \times 10^7$ m/s,

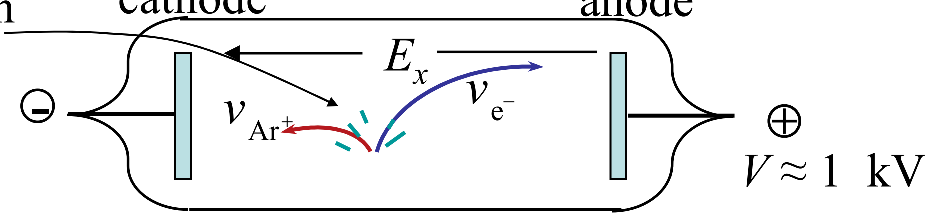
(only 0.1% to 1% of n_{Ar} are ions):

Be clear about different velocities:

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

$$v \approx \sqrt{\frac{3k_B T}{m_{Ar}}}$$

So we have: low-vel. **Ar**$^+$ high vel. ***e***$^-$



The plasma is highly conducting due to electrons:

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

Thus $J_{e-} \gg J_{Ar+}$

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

Plasma is self-sustaining only for 1 or 10 mT < P < 100 mT.

"Why this pressure range?"

Necessary conditions:

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

1) $\lambda < L$

so collisions exchange energy *within* plasma

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

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

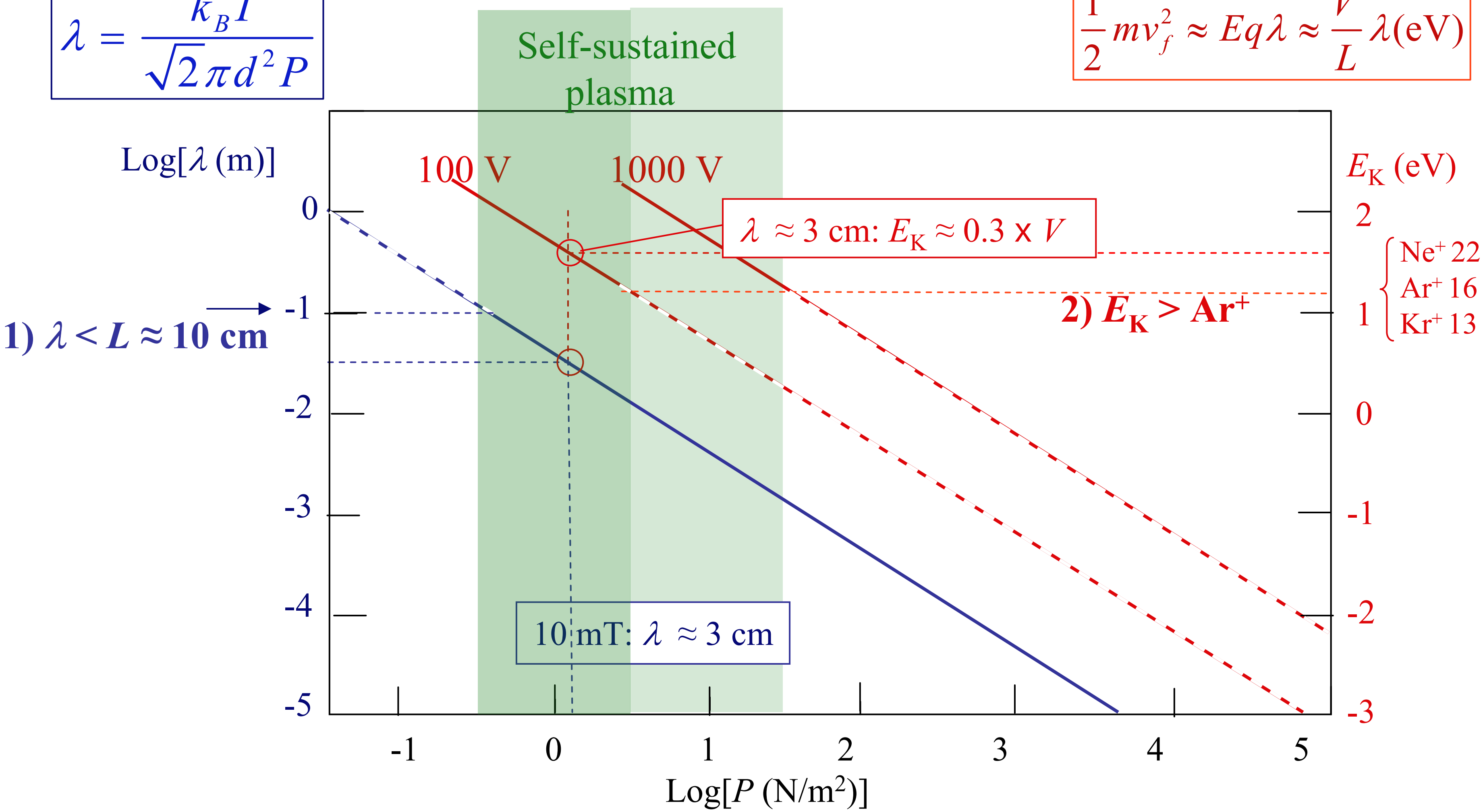
2) E_K > ionization potential of Ar^+

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

Plasma is self-sustaining only for 1 or 10 mT < P < 100 mT.

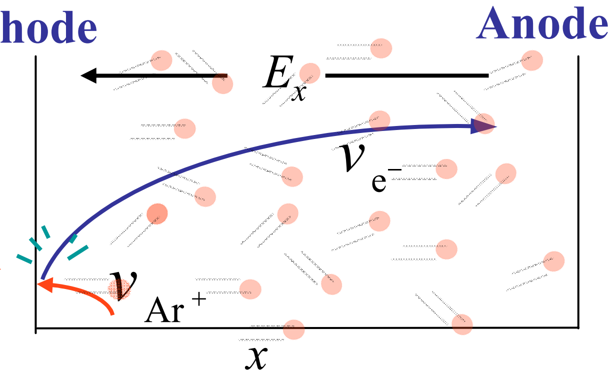
$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 P}$$

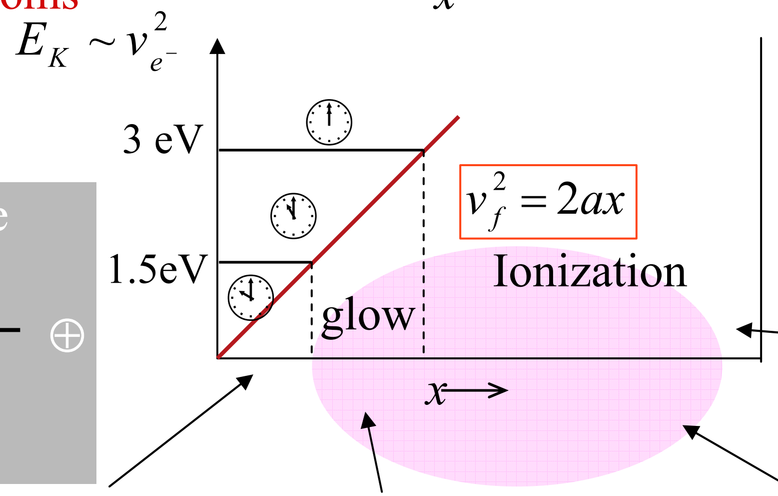
$$\frac{1}{2} m v_f^2 \approx Eq\lambda \approx \frac{V}{L}\lambda(\text{eV})$$

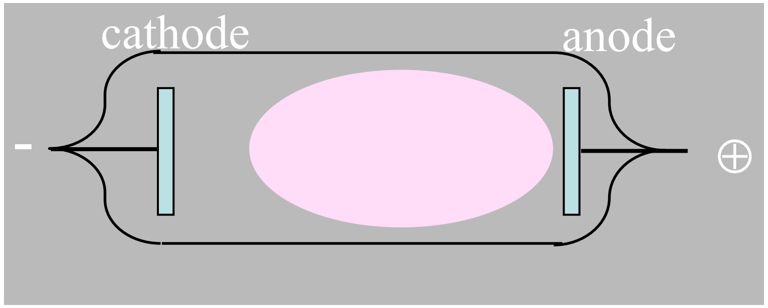


What about Glow?

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







Faraday dark space

e^-s swept out

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

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

$E_K > 3\text{eV}$

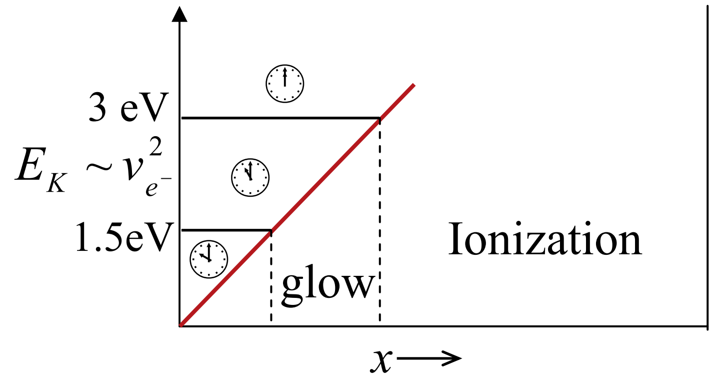
Cathode dark space, no action

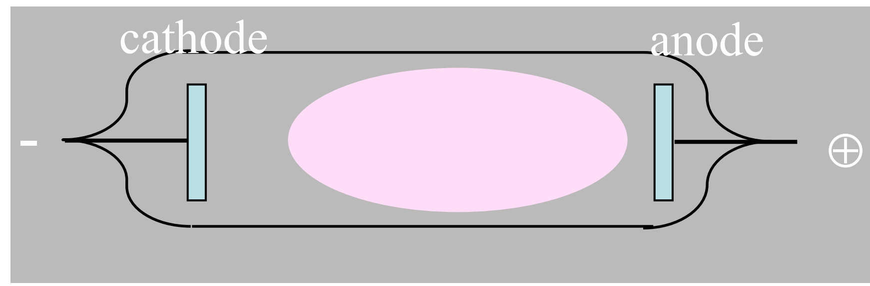
e^- - induced optical excitation of Ar $\Rightarrow$ visible glow

=> ionization, High conductivity plasma

Inside a plasma

(D.C. or "cathode sputtering")



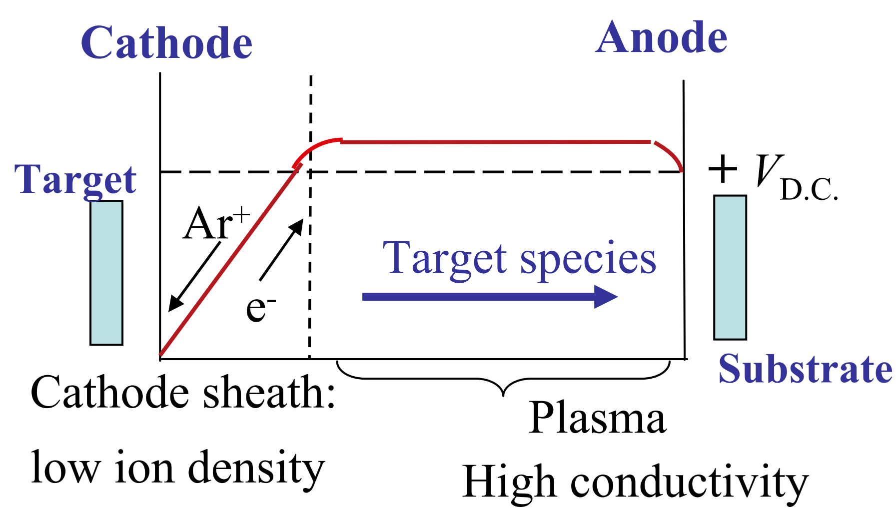


$J_{e^-}, v_{e^-} >> J_{Ar^+}, v_{Ar^+} \Rightarrow$

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

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

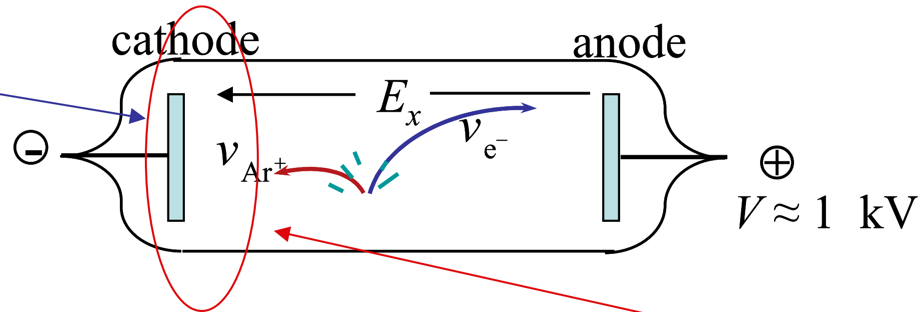
relative to anode



Which species, e^- or Ar^+ , is more likely to dislodge an atom at electrode ?

$P \approx$ 10-100 m Torr

Cathode is "target", source material



Sputter removal (etching) occurs here

At 1 keV, $v_{Ar+} = v_e/43$

Momentum transfer:

$$\begin{cases} p_e = mv \\ P_{Ar} = MV = 1832mv/43 \approx 43p_{e-} \end{cases}$$

No surprise.

from ion implantation,

most energy transfer when:

i.e. incoming particle has mass close to that of target.

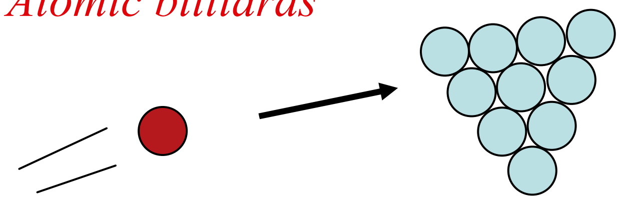
$$\Delta E = E_1 \frac{4M_1M_2}{(M_1 + M_2)^2}$$

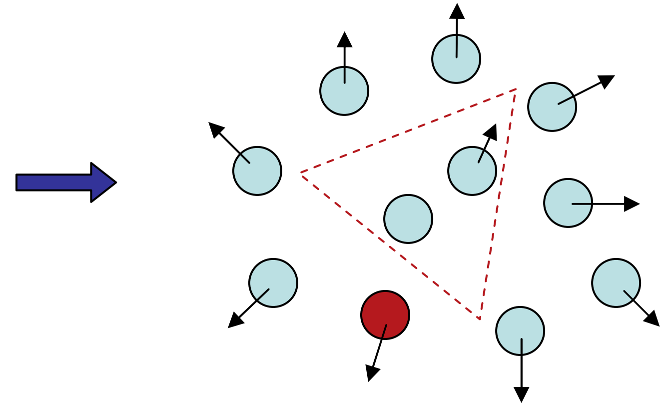
Sputtering process

Ar^+ impact, momentum transfer at cathode $\Rightarrow$ 1) e^- avalanche and

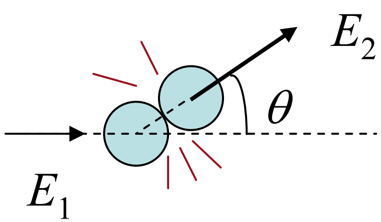
2) released target atoms, ions.

Atomic billiards





Elastic energy transfer



$$\frac{E_2}{E_1} \propto \frac{4M_1M_2}{(M_1+M_2)^2}\cos^2\theta$$

E_2 greatest for $M_1 \cong M_2$

For e^- hitting anode, substrate, $M_1 << M_2$ $\quad \frac{E_2}{E_1} \approx \frac{4M_1}{M_2}$ (small)

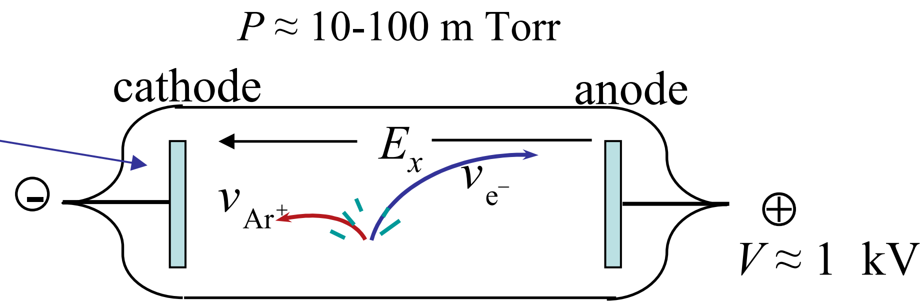
But e^- can give up its E_K in ***in***elastic collision:

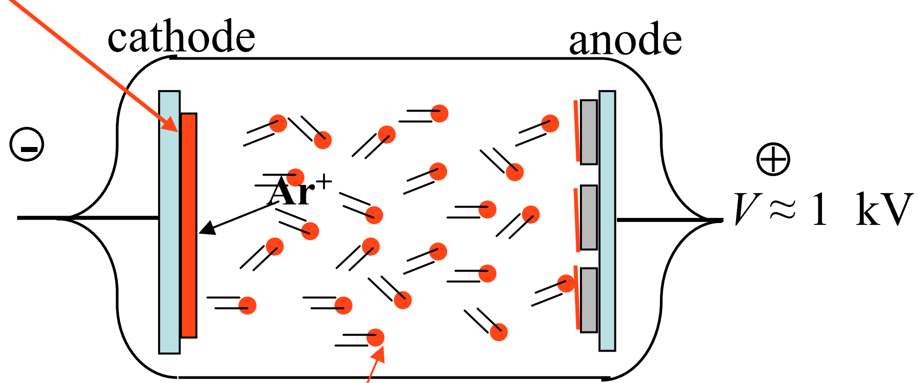
$$\frac{1}{2}m_e v_e^2 \Rightarrow \Delta U$$

Excitation of atom or ion

Sputtering process: *ablation of target*

Cathode
is "target",
source material





Momentum transfer of Ar^+

on cathode erodes cathode atoms

$\Rightarrow$ flux to anode, substrate.

Mostly-neutral
source atoms
(lots of *e*'s around)

Target material (cathode)
must be conductive
…or must use ***RF*** sputtering
(later)

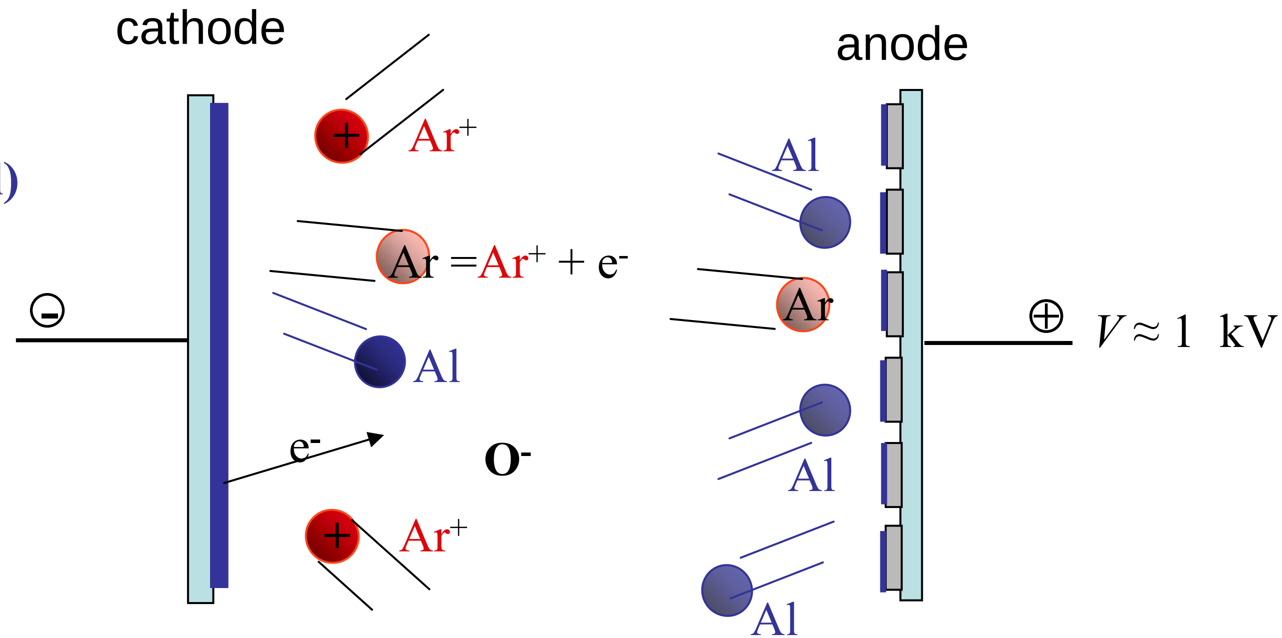
How plasma results in *deposition*

1) Ar^+ accelerated to cathode

5) Flux => *deposition* at anode:
Al, some Ar,
some impurities

2) Neutral target species (Al) kicked off;

3) Some Ar, Ar^+ and e^- also.



4) e^- may ionize impurities (e.g. O => O^-)

6) Some physical resputtering of film (Al) by Ar

Sputtering rate **of source material in target is key parameter.**

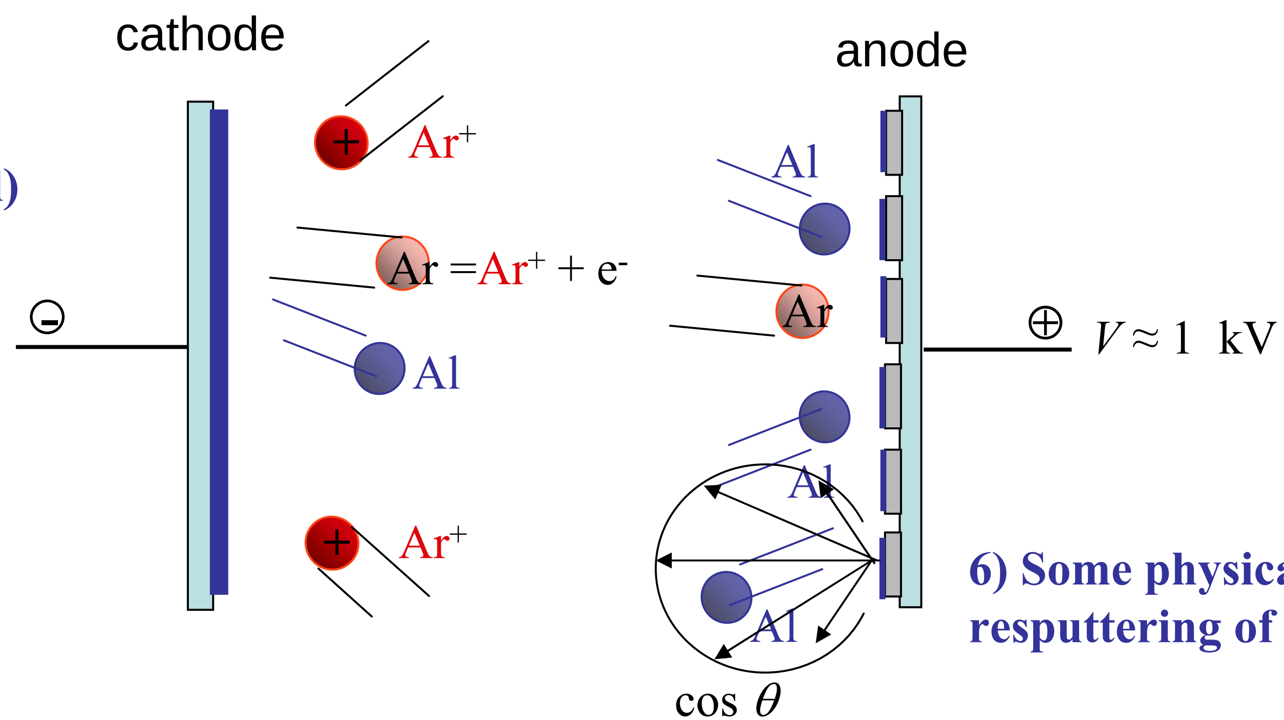
Typically 0.1 - 3 target atoms released/Ar incident

Sputtering rates vary little from material to material.

Vapor pressure **of source NOT important**

(this differs greatly for different materials).

2) Neutral target species (Al) kicked off.



6) Some physical resputtering of Al by Ar

Sputtering yield

$$S = \text{Sputtering yield} = \frac{\text{\# atoms, molecules from target}}{\text{\# incident ions}}$$

$$S = \sigma_0 n_A \frac{\overline{E}_2}{4E_{\text{thresh}}} \times \left[1 + \sqrt{\ln\left(\frac{E_2}{E_b}\right)} \right]$$

σ_0: πd^2

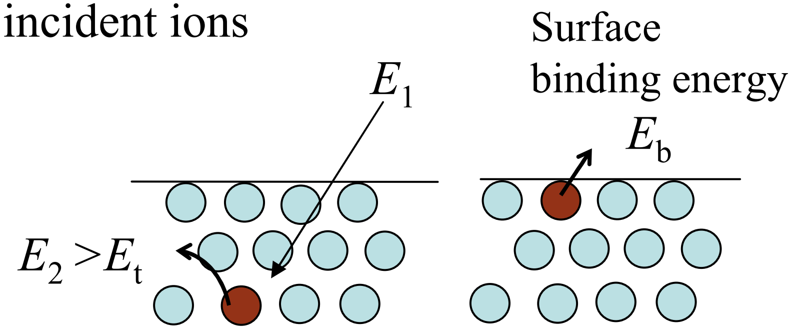
n_A: # / area

excited in each layer;

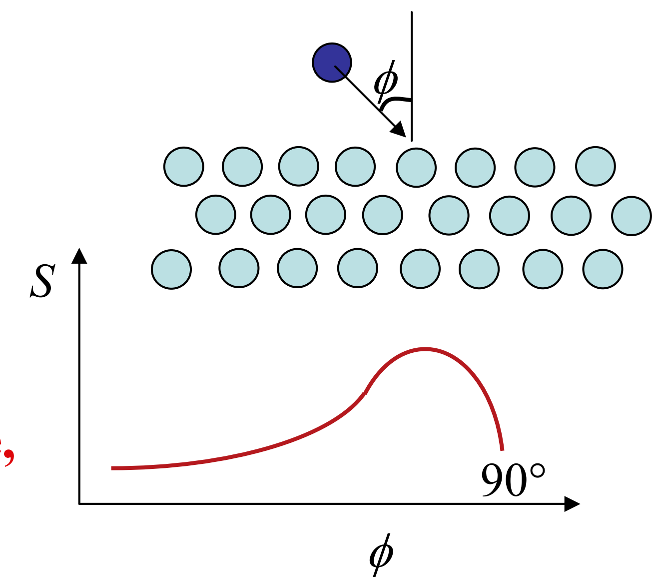
E_{thresh} = energy to displace interior atom

Random walk to surface;

E_b = surface binding energy



$$\frac{E_2}{E_1} \propto \frac{4 M_1 M_2}{(M_1 + M_2)^2} \cos^2 \theta$$



Oring, Fig. 3.18

Sputter rate depends on angle of incidence, relative masses, kinetic energy.

Figure removed for copyright reasons.

Table 3-4 in Ohring, M. *The Materials Science of Thin Films*. 2nd ed. Burlington, MA: Academic Press, 2001. ISBN: 0125249756.

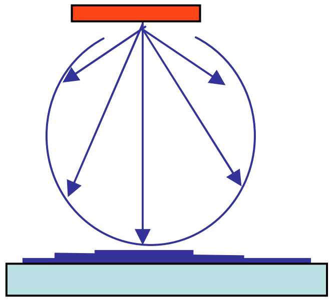
Figure removed for copyright reasons.

Figure 12.13 in Campbell, S. *The Science and Engineering of Microelectronic Fabrication*. 2nd ed. New York, NY: Oxford University Press, 2001. ISBN: 0195136055.

Sputter yield vs. ion energy, normal incidence

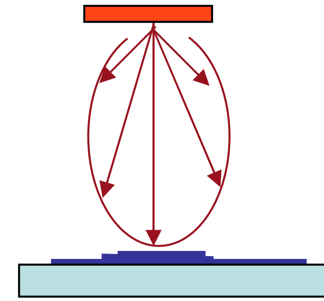
Sputtering miscellany

Isotropic flux:
$\cos\,\theta$ = normal component of flux



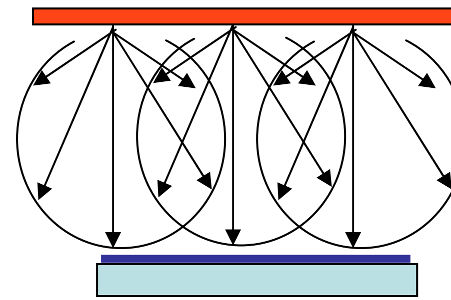
Higher P

Anisotropic flux:
$\cos^n\,\theta$: more-narrowly directed at surface
(surface roughness)
Poor step coverage.



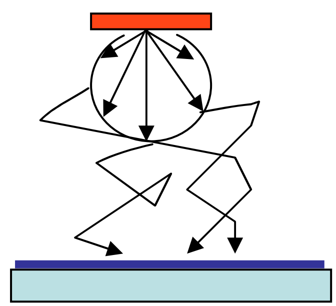
Lower P

Large target, small substrate
Moving substrates
} => Good step coverage, more uniform thickness



Higher pressure => shorter λ,
better step coverage
…but more trapped gas

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



p	λ (cm)
10 mT	2
1 mT	20

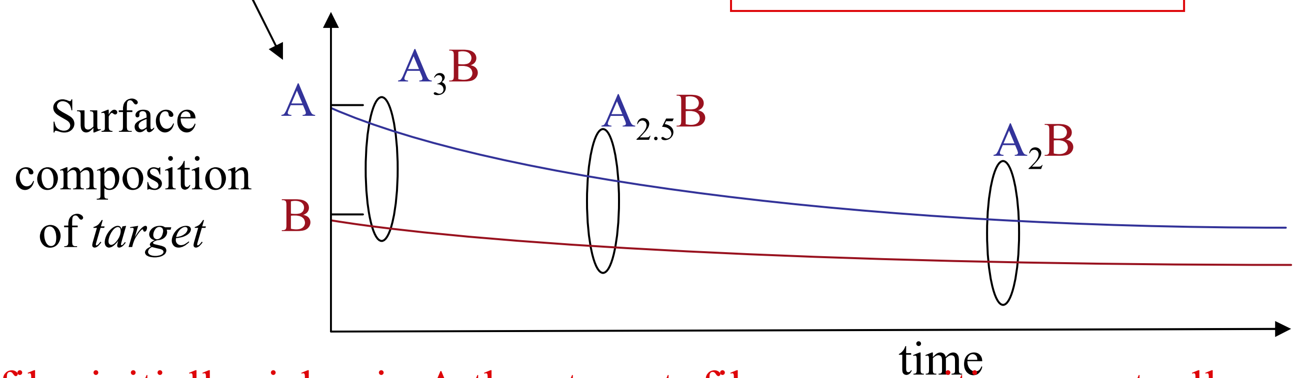
Target composition vs. film composition

Sputtering removes outer layer of target;

can lead to problem with multi-component system, but only initially

Initial target composition A_3B

If sputter yield A > B



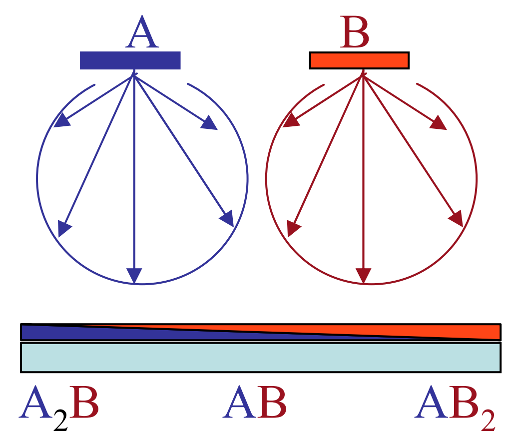
Deposited film initially richer in A than target; film composition eventually correct.

Another approach:

Co-sputtering => composition control;

multiple targets & multiple guns.

Also can make sample "library".

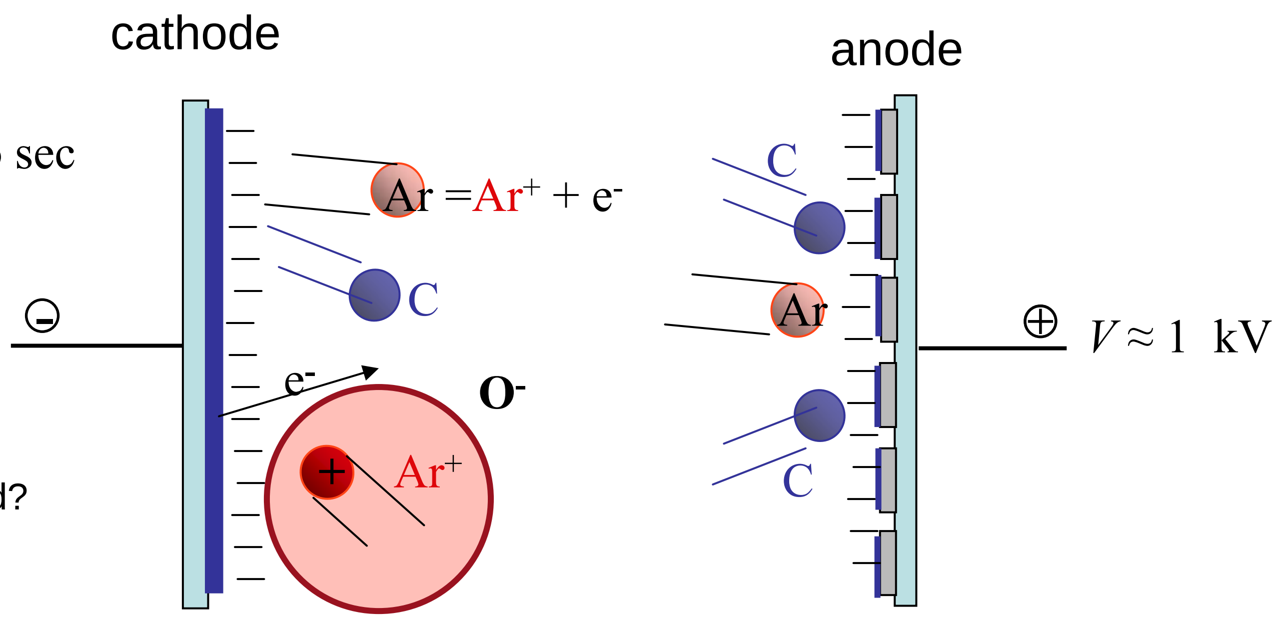


Varieties of sputtering experience

D.C. sputter deposition: Only for conducting materials.

if DC sputtering were used for insulator. e.g. carbon, charge would accumulate at each electrode and quench plasma within 1 - 10 mico-sec.

t < 1 micro sec



What does 1 microsec tell you about ion speed? (>10^6 cm /sec)

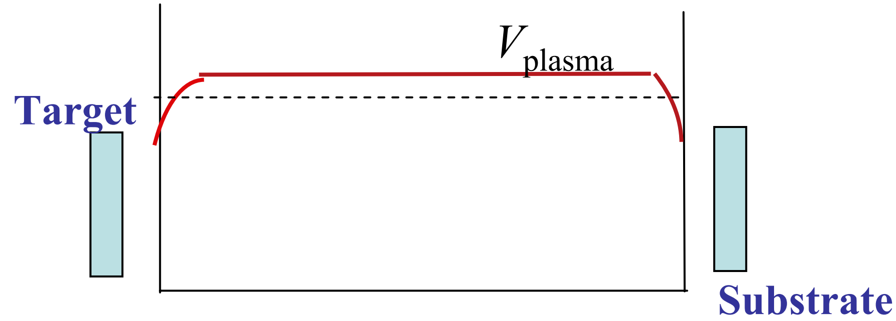
- **Therefore, use RF plasma…**

RF -sputter system is basically a capacitor with gas dielectric. Energy density ↑ as *f* ↑

◆ RF plasma sputtering

Plasma conducts at low f $\omega_p \sim 10^7 s^{-1}$

Thus, $V = 0$ *in plasma*



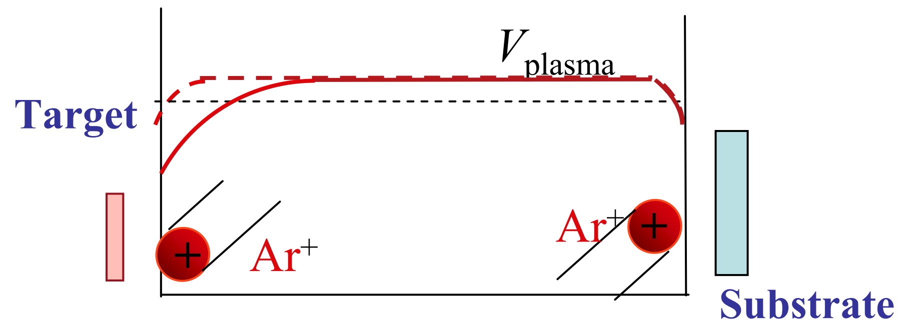
Plasma potential still $V > 0$ due to high e^- velocity, (-) charging of surfaces.
Potential now symmetric.

Mobility of target species (concentration gradient)still => sputtering in 1/2 cycle:

$$v \le \sqrt{\frac{2eV}{M}} \approx 7 \times 10^4 \ m/s$$

Smaller target => higher field

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^m \qquad m \approx 1,2$$



Some re-sputtering of wafer

F.C.C. reserves: 13.56 MHz for sputtering

Varieties of sputtering experience

- **RF *Bias* sputtering**

  Negative wafer bias enhances re-sputtering of film

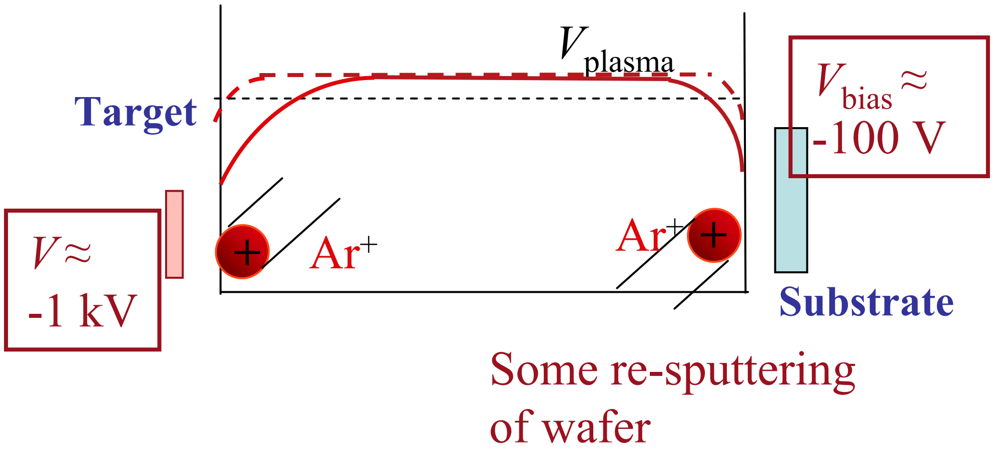
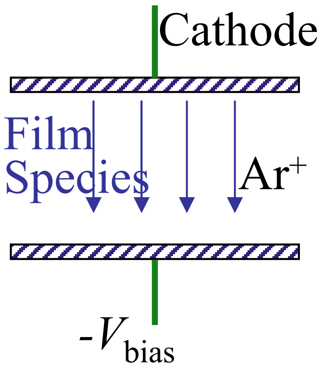


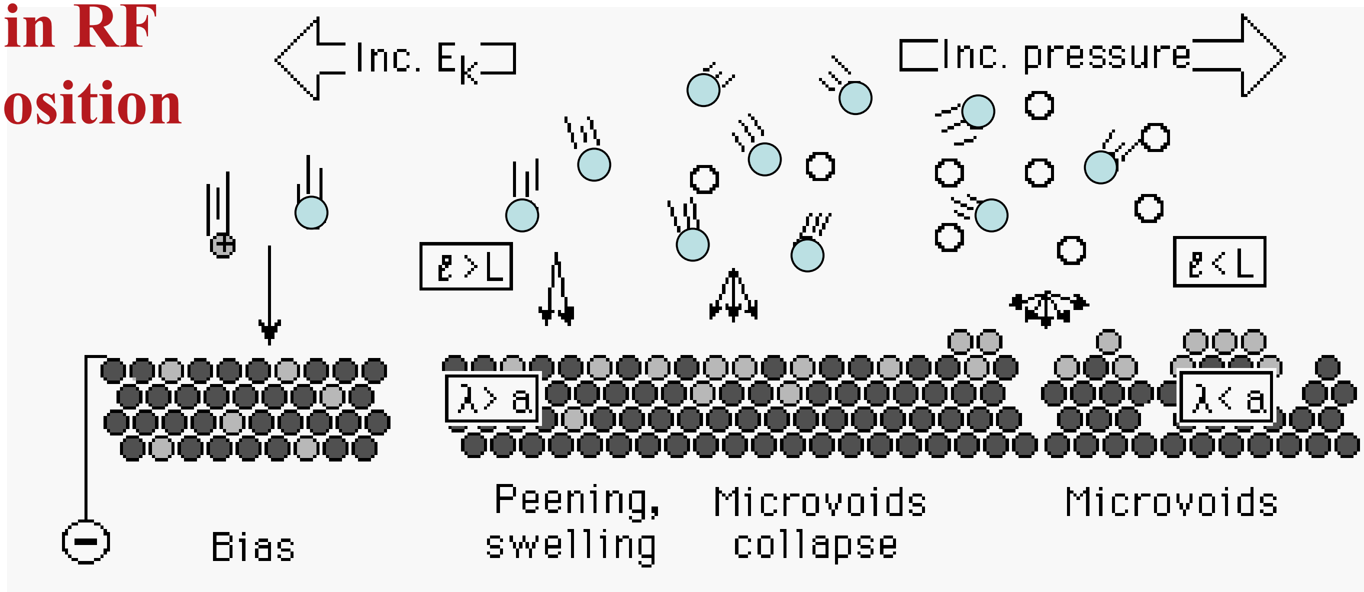
Figure removed for copyright reasons.

Figure 3-24 in Ohring, 2001.

Bias is one more handle for process control.
Used in SiO_2: denser, fewer asperities.
Bias affects stress, resistivity, density, dielectric constant…

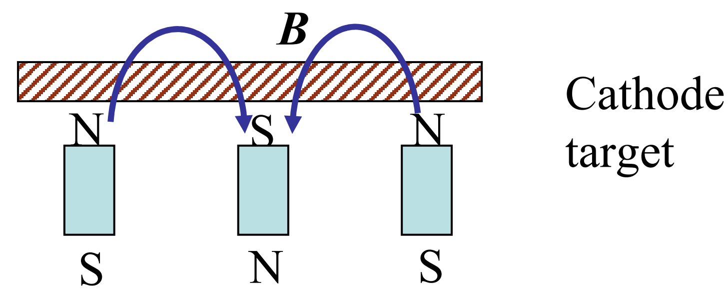
Film stress in RF sputter deposition





Varieties of sputtering experience

◆**Magnetron sputtering** **use magnets**

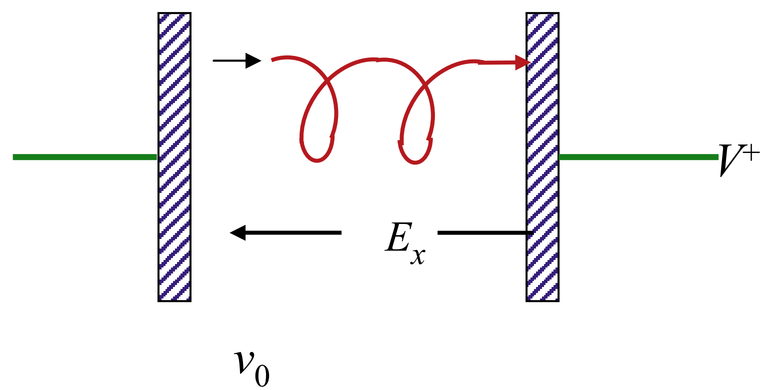


$$\vec{F} = q\left(\vec{v} \times \vec{B}\right) + E_x q \qquad F = \frac{mv^2}{r}, \quad r = \frac{mv}{qB}$$

- $v_z B_x \Rightarrow F_y \Rightarrow \mathrm{v_y}$
- $v_y B_x \Rightarrow F_z \Rightarrow \mathrm{v_z}$

} Ions spiral around ***B*** field lines

$v \approx 6 \times 10^6$ m/s for electron, $r < 1$ mm for 0.1 T

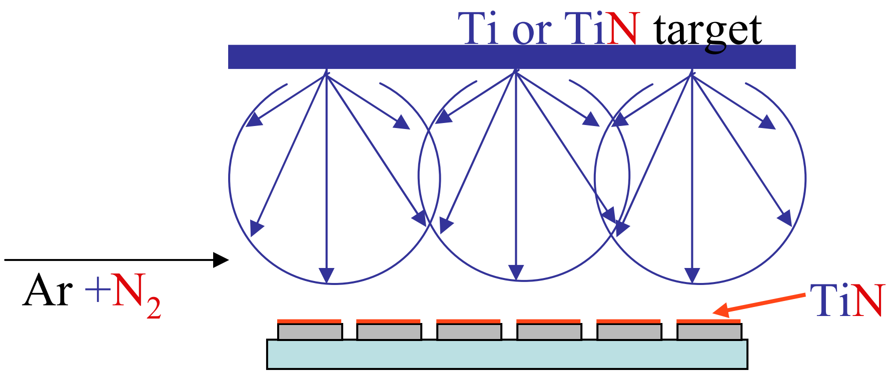


B field enhances time of e^- in plasma

$\Rightarrow$ more ionization, greater Ar^+ density.

- **Reactive sputter deposition**: Mix reactive gas with noble gas (Ar or Ne).

  analogous to PECVD



Also useful for oxides: SiO_x, TiO, CrO…

other nitrides: SiN, FeN,…

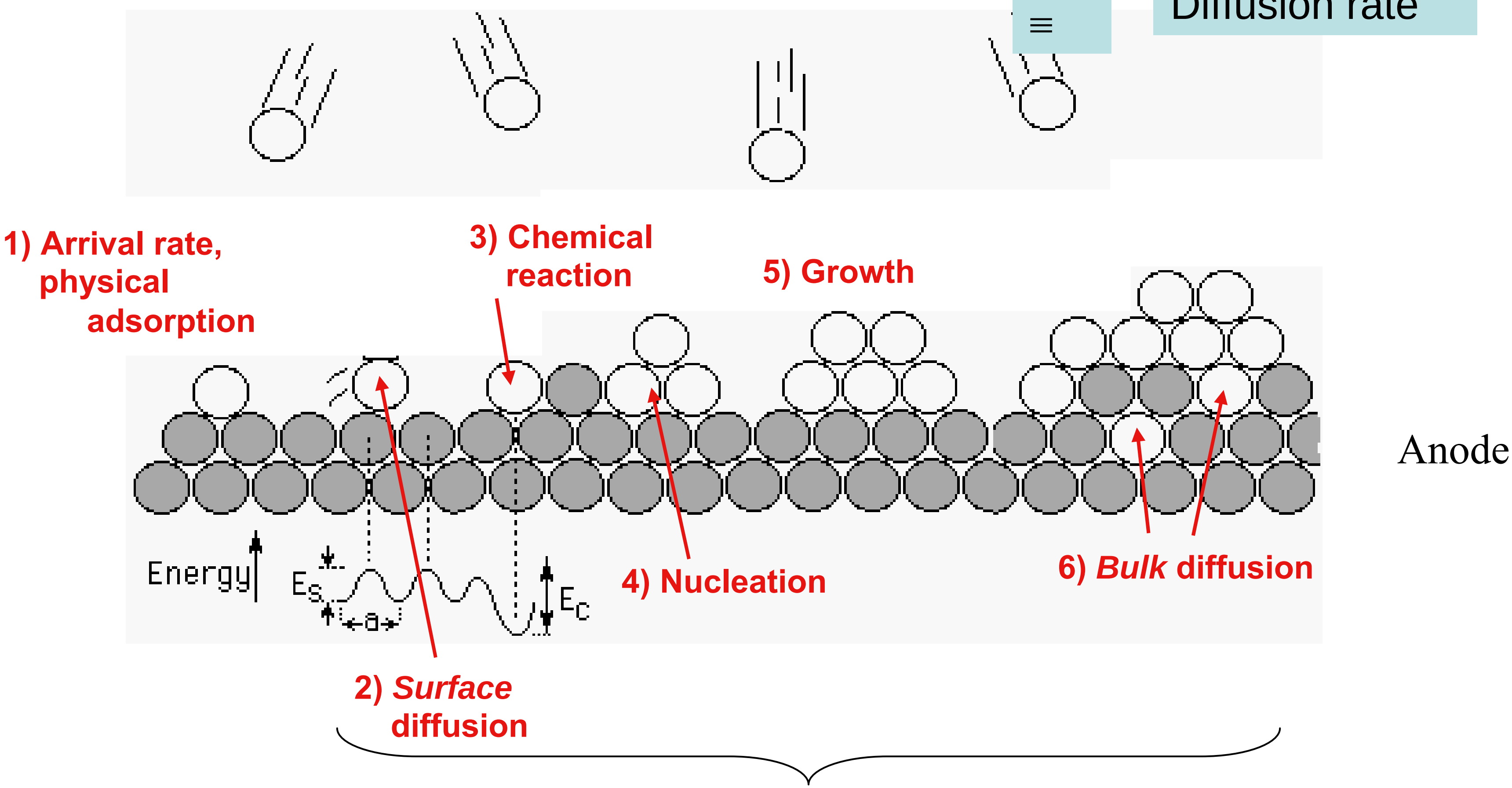
Figure removed for copyright reasons.

Figure 12.27 in Campbell, 2001.

Resistivity and composition of reactivity sputtered TiN vs. N_2 flow.

Thin film growth details (R < 1)

$$R \equiv \frac{\text{Rate of arrival}}{\text{Diffusion rate}}$$



If R > 1, these processes have reduced probability

- **Sputtering metals** Can use DC or RF

- **Sputter alloys, compounds** Concern about different sputter yield S

e.g.	Al	Si
$S =$	1.05	0.5

But S does not vary as much as $P_{eq.vap}$ which controls evaporation

Sputter target T $<<$ T_{evap}

Sputter target T: No diffusion, surface enriched in low S components

T_{evap}: High diffusion, composition change, species distributed over entire source

Figure removed for copyright reasons.

Table 3-7 in Ohring, 2001.