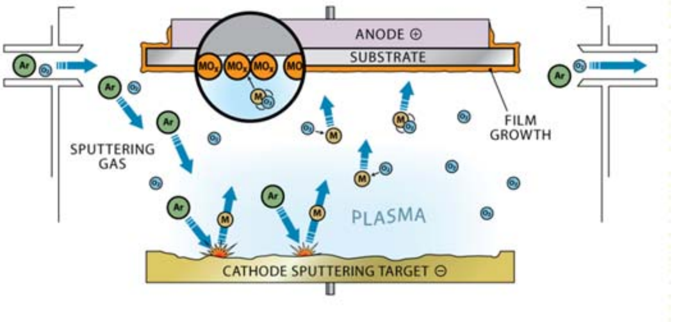
Chap. 4 DC PLASMA AND DISCHARGES

4.1 INTRODUCTION

- Sputtering: a process where material (target) is ejected from the surface by particle bombardment with sufficient kinetic energy.
- Sputter deposition proceeds under a typical vacuum of 10^{-1} to 10^{-4} torr. The bombarding particles are generally ions of a heavy inert gas, most commonly argon. The ejected species is primarily in atomic form. The substrates are positioned facing the target so that the sputtered species can be uniformly coated on its surface.



Sputtering

- Sputter deposition is done in a vacuum chamber 10^{-1} to 10^{-4} torr) as follows:
  - Plasma is generated by applying the DC or RF signal producing energetic ions.
  - Target is bombarded by these ions (usually Ar^{+}).
  - Ions knock the atoms from the target.
  - Sputtered atoms are transported to the substrate where deposition occurs.

- Wide variety of materials can be deposited because material is put into the vapor phase by a mechanical rather than a chemical or thermal process (including alloys and insulators).
- Excellent step coverage of the sharp topologies because of a higher chamber pressure, causing large number of scattering events as target material travels towards wafers.
- Film stress can be controlled to some degree by the chamber pressure and power.

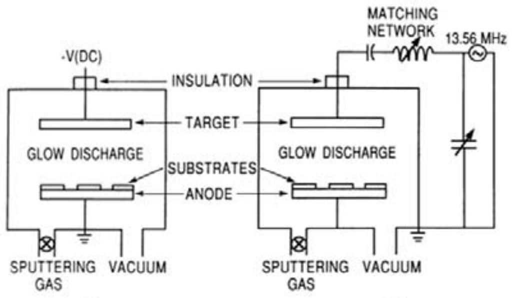


Figure 4-1 Schematics of simplified sputtering systems: (a) dc, (b) RF.

4.2 PLASMAS, DISCHARGES, AND ARCS

Source: http://ece.uwaterloo.ca/~bcui/

DC plasma

Plasma is ionized gas, with nearly equal number of ions and electrons, plus neutrals (un-ionized molecules including those at ground state and excited state; free radicals such as atomic O, H, F – but no free radicals for Ar plasma).

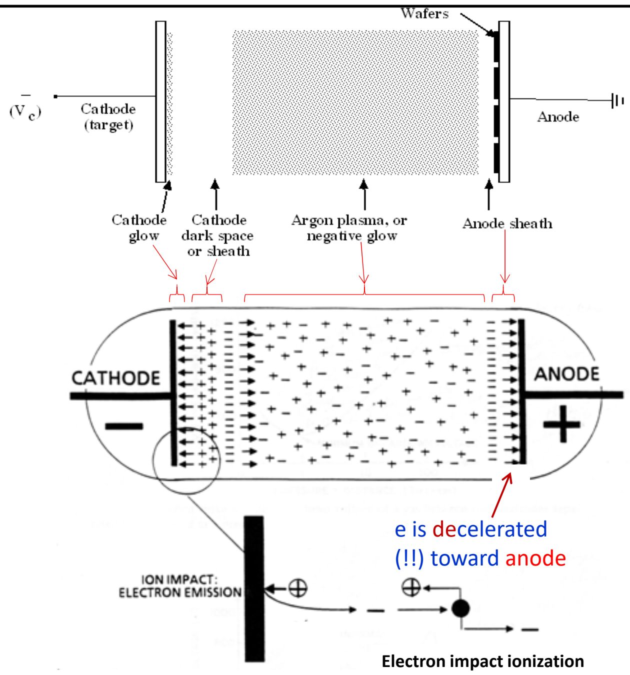
Glow is due to de-excitation of excited Ar.

So glow only exists where there are lots of electrons to excite Ar.

Cathode glow region: very close to cathode, secondary electrons are created by Ar bombardment of target material.

Cathode dark space/sheath: electrons pass too fast with little excitation.

Anode sheath: electrons lost to anode due to its faster *random* movement.



5

Explanation of DC plasma structure

Different velocities in a plasma:

Thermal energy random movement of Ar – 400 m/sec, order $(k_BT/m_{Ar})^{1/2}$.

Thermal energy random movement of electron – 10000 m/sec.

Velocity of Ar with energy 100eV – 20000 m/sec.

Velocity of electrons with energy 100eV – 6000000 m/sec.

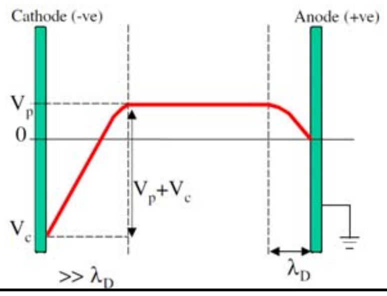
Thus plasma is highly conducting due to fast electrons – very little voltage drop in the plasma area where electrons are rich.

Voltage drop is only possible near the electrodes where electrons may lost to the electrode.

Even without applied voltage (assume plasma still exist), voltage drop may still exist due to faster *random* electrons movement that leads to their lost to electrode.

Therefore, the plasma is always positively biased relative to any electrode or anything (floating or not) inside the plasma.

This positive bias will accelerate positive Ar ion to strike the electrode.
But the bias V_p near the anode is very small (~10V), so no significant sputtering of the substrate.
The total bias (V_p plus applied voltage) is very high, leading to sputtering of cathode (target).



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Requirement for self-sustained discharge (plasma)

Ions make (secondary) electrons when they bombard the target, and electrons make ions when they collide with Ar → self sustained discharge.

Condition for *sustaining* plasma: pd > 0.5 (cm·Torr).
For instance, typical target-substrate spacing d ~ 10cm, need p > 50mTorr
(actually sputter deposition is usually conducted at <10mTorr, due to magnetron…).

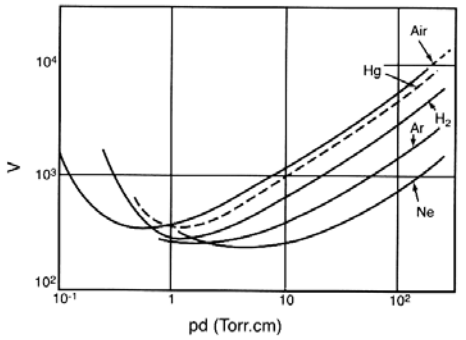


Figure 2.7 The dc breakdown voltage as a function of gas pressure *P* and electrode spacing *d* for plane parallel electrodes in air and some other gases. Such curves are determined experimentally and are known as *Paschen curves*.

Condition for *igniting* the plasma.

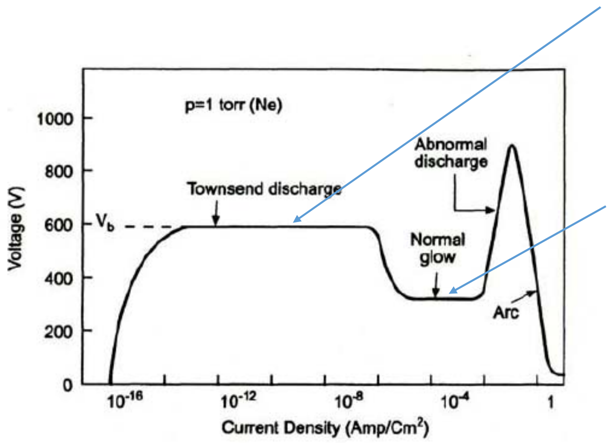
Too large P×d leads to too many collisions that prevent electron energy buildup.

Too small P×d, there will be too few collisions (electron just goes to the wall without ionizing a molecule or atom), and too few ions to bombard and generate secondary electrons.

Once the plasma is ignited, it is very conductive, thus voltage drops to order 100 V only.

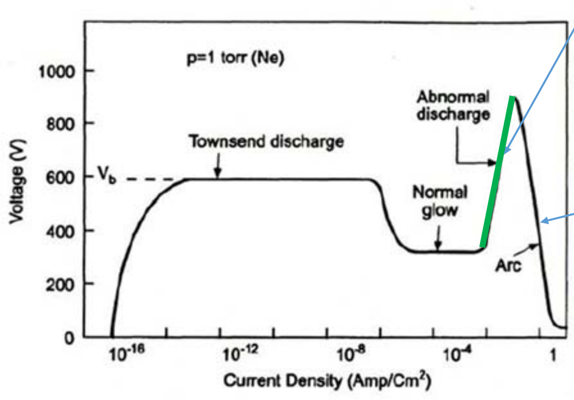
7

4.2.3 TYPES AND STRUCTURES OF DISCHARGES



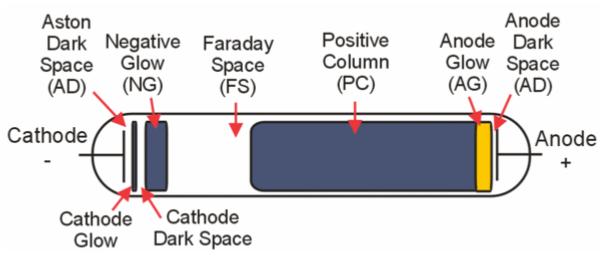
- **Townsend discharge**
  - A tiny current flows initially due to the small number of charge carriers in the system.
  - With charge multiplication, the current increases rapidly, but the voltage, limited by the output impedance of the power supply, remains constant.
- **Normal glow**
  - When enough electrons produce sufficient ions to generate the same number of initial electrons, the discharge becomes self-sustaining.
  - The gas begins to glow now and the voltage drops accompanied by a sharp rise in current.
  - Initially, ion bombardment of the cathode is not uniform but concentrated near the cathode edges or at other surface irregularities.
  - As more power is applied, the bombardment increasingly spreads over the entire surface until a nearly uniform current density is achieved.

STRUCTURES OF DISCHARGES



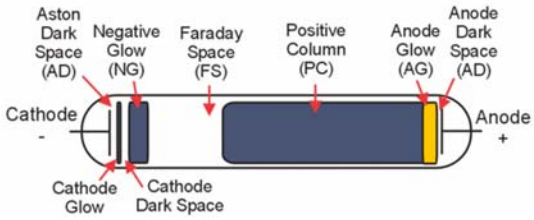
- **Abnormal discharge**
  - A further increase in power results in both higher voltage and cathode current-density levels.
  - The abnormal discharge regime has now been entered and this is the operative domain for sputtering and other discharge processes such as plasma etching.
- **Arc**
  - At still higher currents, the cathode gets hotter. Now the thermionic emission of electrons exceeds that of secondary-electron emission and low-voltage arcs propagate.
  - Arc is a self-sustained discharge that supports high currents by providing its own mechanism for electron emission from negative or positive electrodes.

DC Glow Discharge Tube



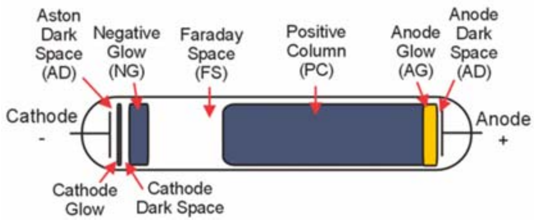
http://en.wikipedia.org/wiki/Electric_glow_discharge

Regions in the DC Glow Discharge Tube



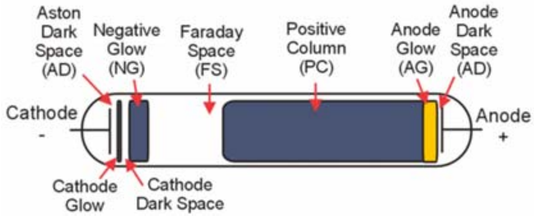
- **Cathode**
- **Aston dark**
  - The Aston dark space is very thin and contains both low energy electrons and high energy positive ions, each moving in opposite directions.
- **Cathode glow**
  - Beyond the Aston dark the cathode glow appears as a highly luminous layer that envelops and clings to the cathode.
  - De-excitation of positive ions through neutralization is the probable mechanism of light emission here.

Regions in the DC Glow Discharge Tube



- **Cathode dark (Crookes)**
  - Next to cathode glow is the cathode dark space, where some electrons are energized to the point where they begin to impact-ionize neutrals; other lower energy electrons impact neutrals without ion production.
  - Because there is relatively little ionization this region is dark.
  - Most of the discharge voltage is dropped across the cathode dark space.
  - Cathode dark space is commonly referred to as the cathode sheath.
  - The resulting electric field serves to accelerate ions toward their eventual collision with the cathode.

Regions in the DC Glow Discharge Tube



- **Negative glow**
  - Here the visible emission is apparently due to interactions between assorted secondary electrons and neutrals with attendant excitation and de-excitation.
  - During sputtering the substrate is typically placed inside the negative glow before the Faraday dark space so that the latter as well as the positive column do not normallt appear.

$$\frac{dV}{dx} = -E$$

$$\frac{dE}{dx} = \frac{1}{\varepsilon} q(N^{+} - N^{-})$$

$$N^{+} - N^{-}$$

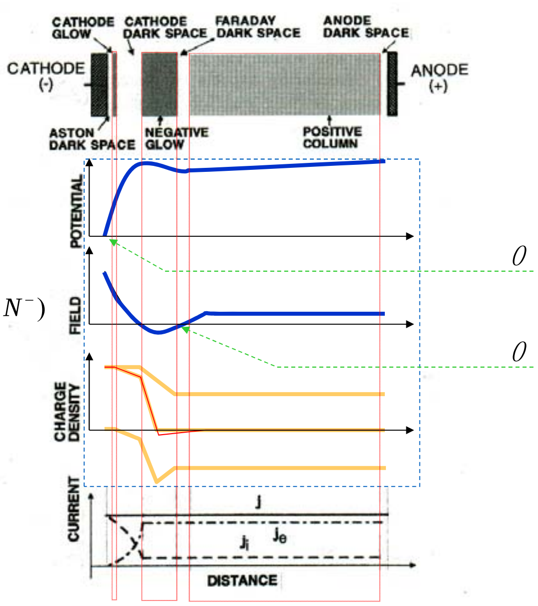


Figure 4-3 Structure of a DC glow discharge with corresponding potential, electric field, charge, and current distributions.

4.3 FUNDAMENTALS OF PLASMA PHYSICS

Source :http://gmankey.people.ua.edu/uploads/8/1/4/9/81492902/09sputterdeposition.ppt

PLASMA PHYSICS

Plasma species: electron (n_e), ions (n_i), and neutral gas (n_o)
Electron has highest velocity
Electrically neutral: $n_e = n_i$
Degree of gas ionization: $f_i = n_e/(n_e+n_o)$
$f_i = 10^{-4}$ for glow discharge

Particle energies and temperature:
For glow discharge:
Electron energy = 1 to 10 eV (typically 2 eV)
Effective characteristic temperature $T_e = E/k_B = 23000$ K
Neutral gas energy = 0.025 eV, ($T_o = 293$ K)
Ion energy = 0.04 eV ($T_i = 500$ K), acquired from electric field.
Low pressure glow discharge is a nonequilibrium cold plasma.
(if in equilibrium: $T_i = T_o = T_e = T$)

Motion in Plasma Species

$$j = \frac{n\overline{v}}{4} q$$

Electrical current density (j) — Particle flux ($\frac{n\overline{v}}{4}$) — Charge (q)

$$\Phi = n\sqrt{\frac{M}{2\pi RT}} \int_0^\infty v_x \exp(-\frac{Mv_x^2}{2RT}) dv_x = n\sqrt{\frac{RT}{2\pi M}} = \frac{n\overline{v}}{4}$$

$$\because \overline{v} = \sqrt{\frac{8k_B T}{\pi m}}$$

Surface are charged negatively due to greater electron bombardment. $v_e > v_i$

Charging of Surface in a Plasma

$$\overline{v} = \sqrt{\frac{8k_B T}{\pi m}} \qquad k_B = 1.38 \times 10^{-23} m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$$

$$\begin{cases} m_e = 9.1 \times 10^{-28} g \\ T_e = 23000K \end{cases} \longrightarrow v_e = 9.5 \times 10^7 cm/s$$

$$\begin{cases} m_{i(Ar)} = \frac{40}{6.02 \times 10^{23}} = 6.64 \times 10^{-23} g \\ T_i = 500K \end{cases} \longrightarrow v_e = 5.2 \times 10^4 cm/s$$

- The implication of this calculation is that an isolated surface within the plasma charges negatively initially because of the greater electron bombardment.
- Subsequently, additional electrons are repelled while positive ions are attracted.
- Surface continues to charge negatively at a decreasing rate until the electron flux equals the ion flux and there is no net current.

Mobility in an Electric Field

Mobility: velocity per unit electric field $\mu = v / \mathsf{E}$

Electric force — Frictional drag

$$m\frac{dv}{dt} = |q|\mathsf{E} + m[\frac{\partial v}{\partial t}]_{coll}$$

$$= |q|\mathsf{E} + mv\nu \qquad \because [\frac{\partial v}{\partial t}]_{coll} = v\nu$$

Collision frequency

In the steady state, $\frac{dv}{dt} = 0 \rightarrow \quad v = \frac{|q|\mathsf{E}}{m\nu}$

$$\mu = \frac{|q|}{m\nu} \qquad (\because \mu = v / \mathsf{E})$$

Typical mobilities for gaseous ions at 1 torr and 273 K range from ~ 4 × 10^2 cm^2/V-s (for Xe^+) to 1.1 × 10^4 cm^2/V-s (for H^+).

Diffusion

$$J_e = -n_e\mu_e\mathsf{E} - D_e\frac{dn_e}{dx}$$

$$J_i = n_i\mu_i\mathsf{E} - D_i\frac{dn_i}{dx}$$

Charge Neutrality, $J_e = J_i = J, n_e = n_i = n$

Electric field developed by separation of charge $\mathsf{E} = \frac{(D_i - D_e)}{n(\mu_e + \mu_i)}\frac{dn}{dx}$

- An electric field develops because the difference in electron and ion diffusivities produces a separation of charge.
- Physically, more electrons than ions tend to leave the plasma, establishing an electric field that hinders further electron loss but at the same time enhances ion motion.

Ambipolar diffusion coefficient $D_a = \frac{(D_i\mu_e - D_e\mu_i)}{(\mu_e + \mu_i)}$

Both ions and electrons diffuse faster than intrinsic ions do.

Electron Motion in Combined Electric Field

$\vec{B}$ *and* $\vec{\mathsf{E}}$ *are parallel*

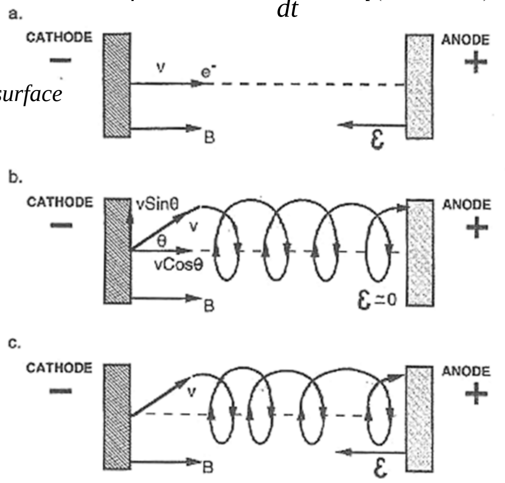
Lorentz force $\vec{F} = \frac{m d\vec{v}}{dt} = -q(\vec{\mathsf{E}} + \vec{v} \times \vec{B})$

$\vec{v}_e$ *normal to the target surface*

$\vec{v}_e$ *at an angle* θ *to* $\vec{B}$

$\vec{\mathsf{E}} = 0$

$\vec{v}_e$ *at an angle* θ *to* $\vec{B}$



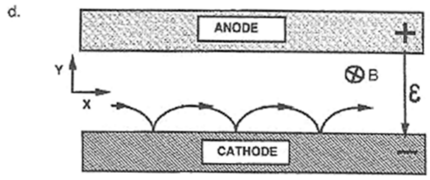
$$q \cdot v \sin\theta \cdot B = \frac{m(v\sin\theta)^2}{r}$$

$$\rightarrow r = \frac{mv\sin\theta}{qB}$$

Clearly, magnetic fields prolong the electron residence time in the discharge and enhance the probability of ion collisions.

Electron Motion in Combined Electric Field

$\vec{B}$ *and* $\vec{\mathsf{E}}$ *are perpendicular*



Electrons emitted normally from the cathode ideally do not even reach the anode but are trapped near the electrode where they execute a periodic hopping motion over its surface.

$$m_e \frac{d^2x}{dt^2} = qB\frac{dy}{dt}$$

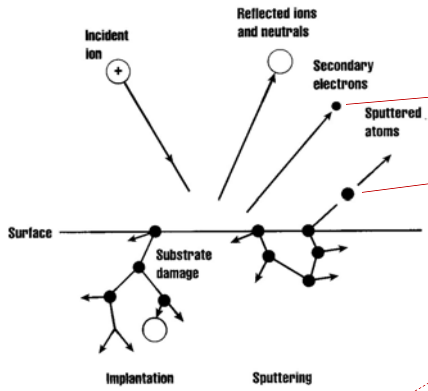
$$m_e \frac{d^2y}{dt^2} = q\mathsf{E} - qB\frac{dx}{dt}$$

$$m_e \frac{d^2z}{dt^2} = 0$$

4.5.2 SPUTTERING

NE 343: Microfabrication and Thin Film Technology
Instructor: Bo Cui, ECE, University of Waterloo, bcui@uwaterloo.ca
Textbook: Silicon VLSI Technology by Plummer, Deal, Griffin

Sputtering process



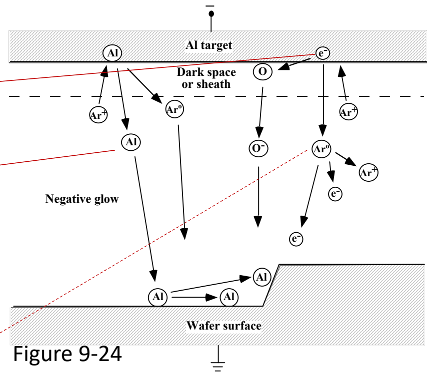


Figure 9-24

After collision ionization, there are now TWO free electrons.
This doubles the available electrons for ionization.
This ongoing doubling process is called "impact ionization", which sustains a plasma.

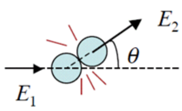
On the left side, sputter off an Al atom.
On the right side, generate secondary electrons, which are accelerated across the sheath region and 1) ionize/excite an Ar; or 2) ionize an impurity atom, here O, to generate O^- (for Ar, always positive ion Ar^+). This O^- is accelerated toward substrate and may go into the film (bad).

Sputtering process

- Energy of each incoming ion is 500-1000eV. Energy of sputtered atoms is 3-10eV.
- Thus, the sputtering process is very inefficient from the energy point of view, 95% of incoming energy goes to target heating & secondary electron.
- High rate sputter processes need efficient cooling techniques to avoid target damage from overheating (serious problem).
- The sputtered species, in general, are predominantly neutral.
- The energy of the ejected atoms shows a Maxwellian distribution with a long tail toward higher energies.
- The energies of the atoms or molecules sputtered at a given rate are about one order of magnitude higher than those thermally evaporated at the same rate, which often lead to better film quality.
- However, since sputtering yields are low and the ion currents are limited, sputter-deposition rates are invariably one to two orders of magnitude lower compared to thermal evaporation rates under normal conditions.

4.5.2.2 Sputter Yields

Elastic energy transfer



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

E_2 is greatest for $M_1=M_2$.
There is also inelastic energy transfer, which leads to secondary electrons emission…

$$\mathrm{Y} = \frac{\text{sputtered atoms}}{\text{bombing ions}} = \alpha \frac{\mathrm{Mm}}{(\mathrm{M}+\mathrm{m})^2}\frac{\mathrm{E_m}}{\mathrm{U_M}}$$

M : mass of target atom

m : mass of bombing ion

E_m : kinetic energy of bombing ion

U_M : Bonding energy of target metal

α : depends on striking /incident angle

- Sputter yield Y: the number of sputtered atoms per impinging ion.
- Obviously, the higher yield, the higher sputter deposition rate.
- Sputter yield is 1-3: not too much difference for different materials.
- The sputter yield depends on: (a) the energy of the incident ions; (b) the masses of the ions and target atoms; (c) the binding energy of atoms in the solid; and (d) the incident angle of ions.
- The yield is rather insensitive to the target temperature except at very high temperatures where it show an apparent rapid increase due to the accompanying thermal evaporation.

Dependence of sputter yield on ion energy

A threshold energy for the release of an atom from the target exists, below which the atom is not "sputtered". This threshold energy is:

$$E_{threshold} = \frac{\textit{Heat of Vaporization}}{\gamma(1-\gamma)}$$

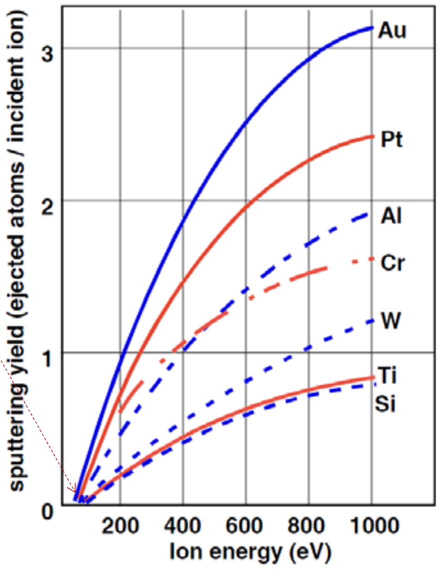
$$\textit{where } \gamma = \frac{4M_1M_2}{(M_1+M_2)^2}$$

(E_{th} very high when $M_1 \approx M_2$ or they are very different?)

The yield increases with the energy.

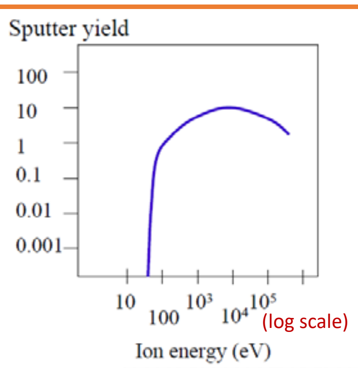
For higher energies, the yield approaches saturation, which occurs at higher energies for heavier bombarding particles.
e.g.: Xe^+ ~100keV and Ar^+ ~20KeV for saturation.

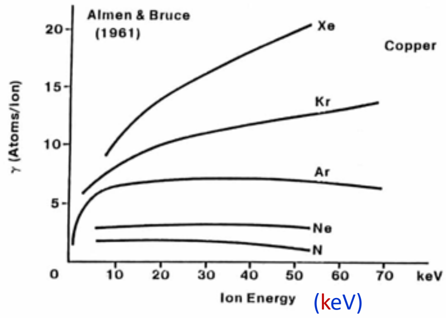
Sometimes, at very high energies, the yield decreases because of the increasing penetration depth and hence increasing energy loss below the surface, i.e. not all the affected atoms are able to reach the surface to escape.



27

Dependence of sputter yield on ion energy





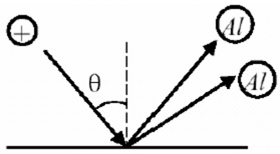
Sputtering yields of the noble gases on copper, as a function of energy.

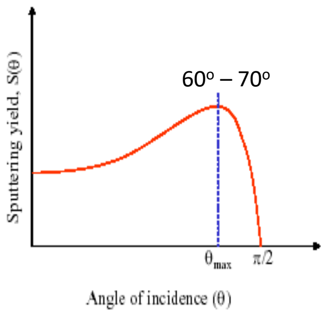
Table 11-2 SPUTTER YIELDS FOR METALS IN ARGON (ATOMS/ION)

Target	At.Wt./Dens.	100 eV	300 eV	600 eV	1000 eV	2000 eV
Al	10.0	0.11	0.65	1.2	1.9	2.0
Au	10.2	0.32	1.65	2.8	3.6	5.6
Cu	7.09	0.5	1.6	2.3	3.2	4.3
Ni	6.6	0.28	0.95	1.5	2.1	
Pt	9.12	0.2	0.75	1.6		
Si	12.05	0.07	0.31	0.5	0.6	0.9
Ta	10.9	0.1	0.4	0.6	0.9	
Ti	10.62	0.08	0.33	0.41	0.7	
W	14.06	0.12	0.41	0.75		

28

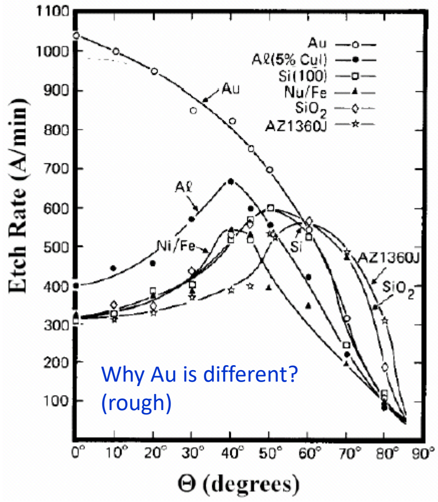
Dependence of sputter yield on ion incident angle





The yield increases as $(\cos\theta)^{-1}$ with increasing obliqueness (θ) of the incident ions.

However, at large angles of incidence the surface penetration effect decrease the yield drastically.

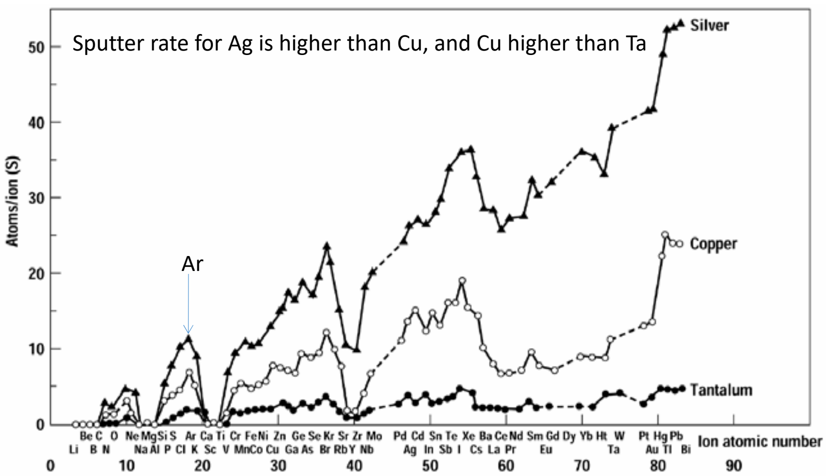


29

Dependence of sputter yield on ion mass

Sputter increases with ion mass.

Sputter yield is a maximum for ions with full valence shells: noble gasses such as Ar, Kr, Xe have large yields.



30

Sputter yield of elements at 500eV

Gas	He	Ne	Ar	Kr	Xe
Element					
Be	0.24	0.42	0.51	0.48	0.35
C	0.07	—	0.12	0.13	0.17
Al	0.16	0.73	1.05	0.96	0.82
Si	0.13	0.48	0.50	0.50	0.42
Ti	0.07	0.43	0.51	0.48	0.43
V	0.06	0.48	0.65	0.62	0.63
Cr	0.17	0.99	1.18	1.39	1.55
Cu	0.24	1.80	2.35	2.35	2.05
Fe	0.15	0.88	1.10	1.07	1.00
Ni	0.16	1.10	1.45	1.30	1.22
Nb	0.03	0.33	0.60	0.55	0.53
Mo	0.03	0.48	0.80	0.87	0.87
Pd	0.13	1.15	2.08	2.22	2.23
Ag	0.20	1.77	3.12	3.27	3.32
Ta	0.01	0.28	0.57	0.87	0.88
W	0.01	0.28	0.57	0.91	1.01
Re	0.01	0.37	0.87	1.25	—
Os	0.01	0.37	0.87	1.27	1.33
Ir	0.01	0.43	1.01	1.35	1.56
Pt	0.03	0.63	1.40	1.82	1.93
Au	0.07	1.08	2.40	3.06	3.01
Au	0.10	1.3	2.5	—	7.7
Pb	1.1	—	2.7	—	—