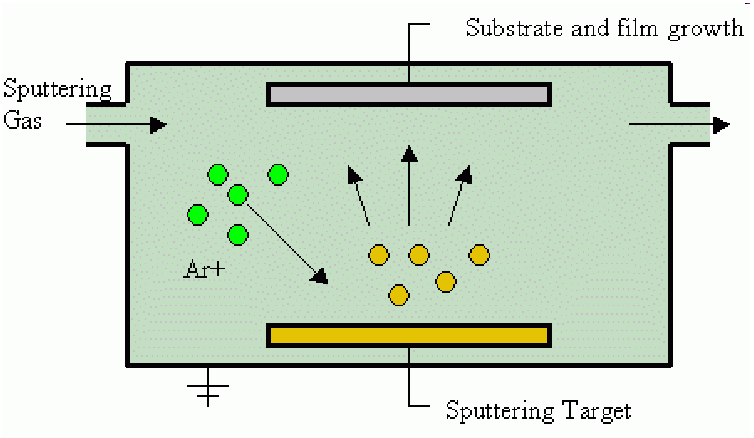
Sputtering

Vacuum Evaporation Recap

- Use high temperatures at high vacuum to evaporate (eject) atoms or molecules off a material surface.
- Film uniformity can be an issue.
- Alloy evaporation is very complicated and in most cases, not possible.
- Must stay below the melting temperature of the evaporant.

Sputtering

- A stream of charged particles (ions) is used to remove (sputter) atoms from a target.
- The sputtered atoms then travel to the substrate and form a film.
- The important aspects of this method are:
    - Generating and controlling the ion stream.
    - Interaction of the ions with the target.
    - Deposition on the substrate.



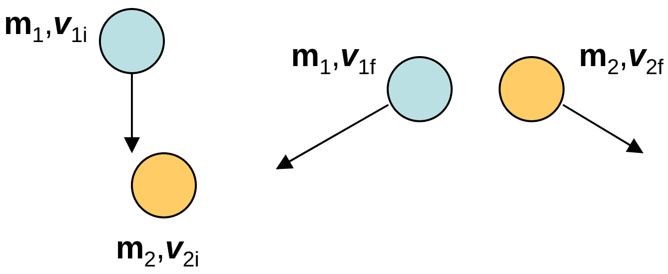
Advantages

- Not a line of sight method
  - Can use diffusive spreading for coating
  - Can coat around corners
- Can process alloys and compounds.
  - High temperatures are not needed
- Can coat large areas more uniformly.
- Large target sources mean less maintenance.

How Ions Sputter Atoms

- When ions collide with surface atoms on the target, the energy transfer can knock some of these atoms off the surface.
- The key principle is energy and momentum conservation.
- In any collision, momentum is conserved.
- If the collision is elastic, kinetic energy is also conserved.
- The energies required for sputtering are much higher than lattice bonding or vibrational energies, therefore collisions can be considered elastic.

Momentum and Energy



Momentum

$$\mathbf{p} = m\mathbf{v}$$

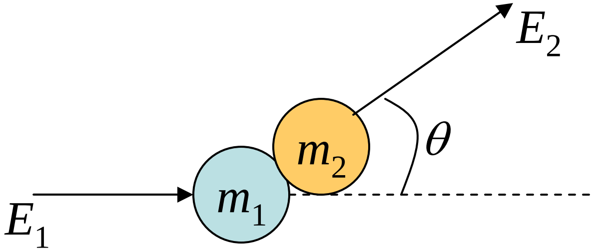
Kinetic Energy

$$K = \frac{1}{2} m v^2$$

$$\mathbf{p}_i = m_1 \mathbf{v}_{1i} + m_2 \mathbf{v}_{2i} \quad = \quad \mathbf{p}_f = m_1 \mathbf{v}_{1f} + m_2 \mathbf{v}_{2f}$$

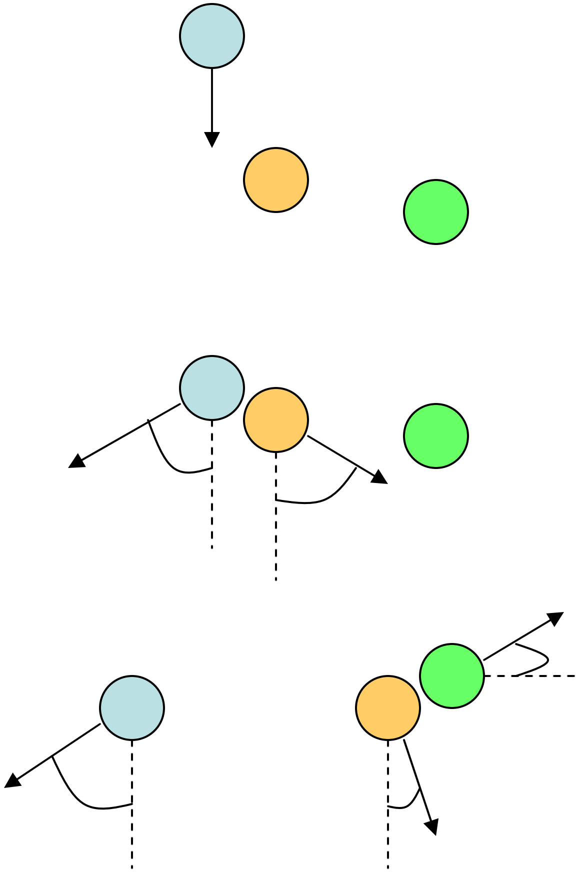
$$K_i = \frac{1}{2}\left(m_1 v_{1i}{}^2 + m_2 v_{2i}{}^2\right) \quad = \quad K_f = \frac{1}{2}\left(m_1 v_{1f}{}^2 + m_2 v_{2f}{}^2\right)$$

- Maximum energy transfer in such a collision occurs when the masses are equal.



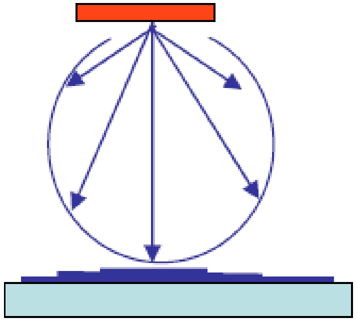
$$\frac{E_2}{E_1} \propto \frac{4 m_1 m_2}{\left(m_1 + m_2\right)^2} \cos^2 \theta$$

Direction of Emission

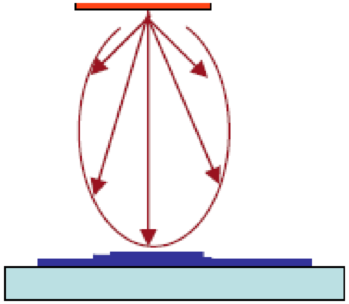


- For normal incidence of ions, the primary collision can not eject an atom off the surface.
- However, the secondary collision can.
- At oblique incidence, primary collisions can result in ejection.
  - Think billiard balls.

Angular Distribution of Ejected Atoms



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



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

What Else Can Occur?

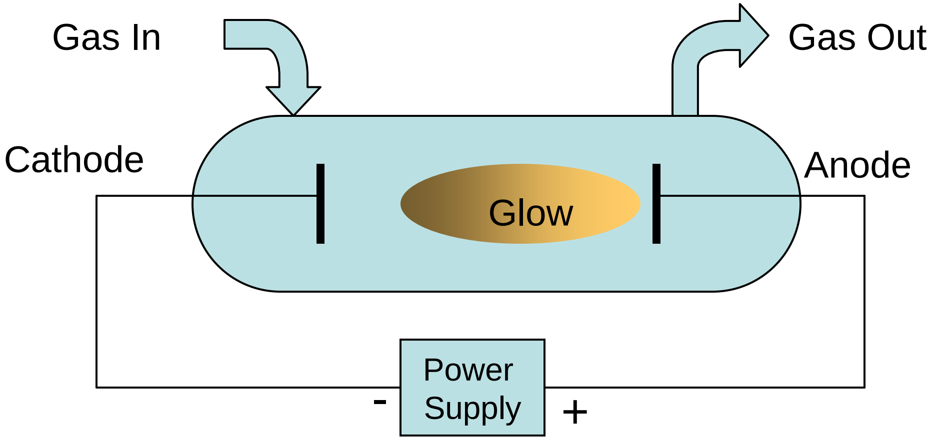
- The ion can bounce back.
- The ion can be reflected by a grazing collision.
- The ion can become deeply embedded in the target (implantation).
- The ion can be absorbed on to the surface (adsorption).
- Electrons can be emitted from the surface and interact with both the ion and the sputtered atoms.
- Ideally, we would like a bounce back with electron emission (see later).

Generating and Controlling the Ions

- Ions can be generated by the collision of neutral atoms with high energy electrons.
- The interaction of the ions and the target are determined by the velocity and energy of the ions.
- Since ions are charged particles, electric and magnetic fields can control these parameters.
- To establish the electric field, we need a positive and negative terminal.
- In sputtering, the target is the cathode (negative) and the substrate is the anode (positive).
- Of course the ions do not behave independently but really form a gas of charged particles called a **plasma**.

Plasma

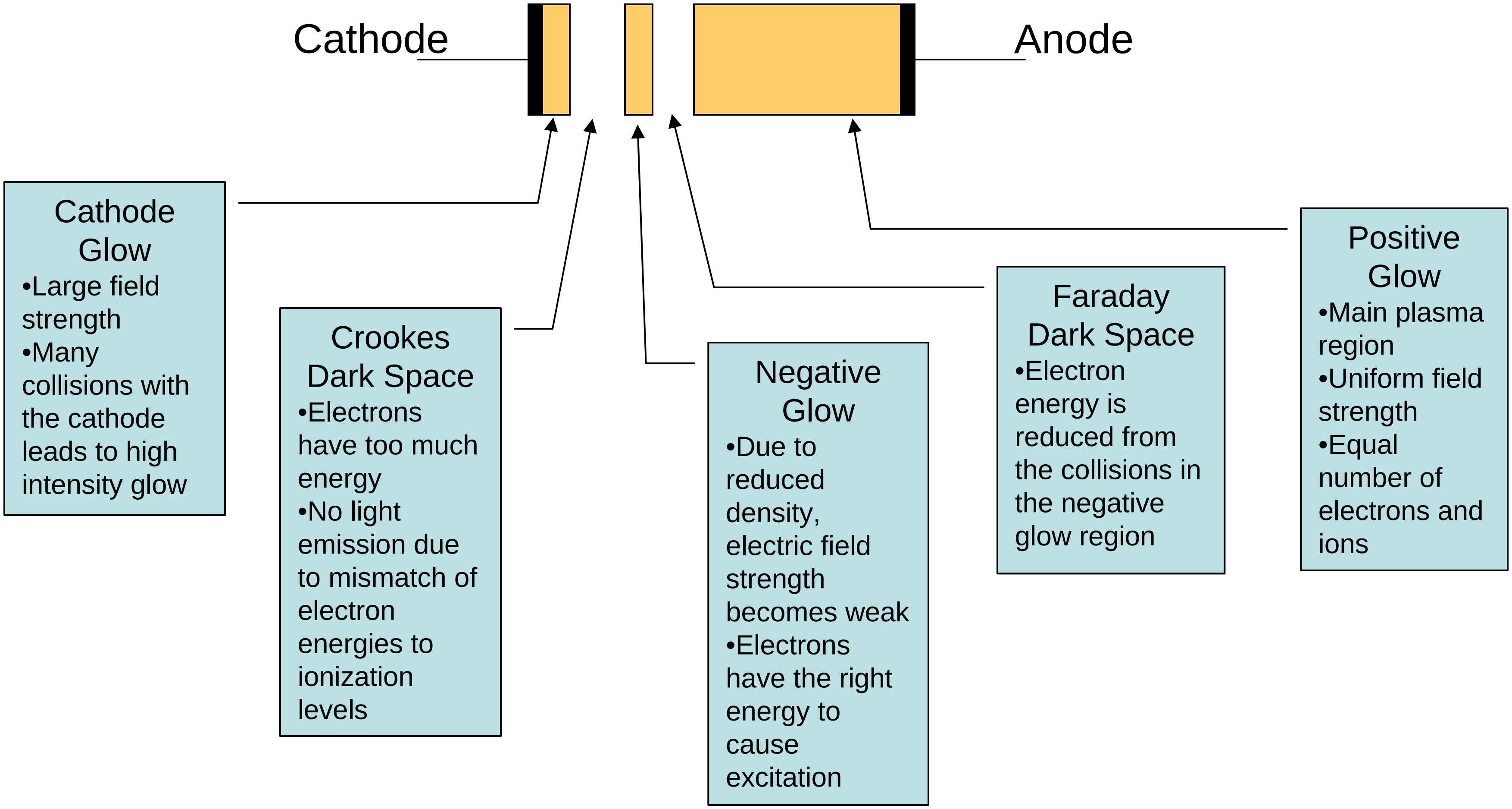
- A plasma is a gas of charged particles (electrons, ions).
- A plasma can be created by the cascading collisions of electrons with neutral gas molecules or atoms.



Glow Discharge Formation

- Consider an electron between the anode and the cathode.
- The electron will be accelerated toward the anode.
  - The more it accelerates, the more energy it will have. This depends on the anode-cathode voltage and the distance it travels between collisions.
- On the way it can collide with a gas atom.
  - If the energy of the electron is large enough, it can kick one of the atom’s electrons out and ionize it.
- The ionized atom (positively charged) will be accelerated towards the cathode.
- As the ion slams into the cathode, it will kick off more electrons (secondary emission).
- Some of the electron-ion collisions will not be energetic enough to kick an electron off the atom but will be enough to emit a photon which results in the “glow”.

The Glow Discharge



Cathode

Anode

Cathode Glow
- Large field strength
- Many collisions with the cathode leads to high intensity glow

Crookes Dark Space
- Electrons have too much energy
- No light emission due to mismatch of electron energies to high ionization levels

Negative Glow
- Due to reduced density, electric field strength becomes weak
- Electrons have the right energy to cause excitation

Faraday Dark Space
- Electron energy is reduced from the collisions in the negative glow region

Positive Glow
- Main plasma region
- Uniform field strength
- Equal number of electrons and ions

Plasma Pressures

- Unless there are enough collisions, the plasma will quickly die.
- In order to have a self-sustaining plasma, each electron has to generate enough secondary emission.
- Since we want collisions to occur, the pressure can not be too low.
    - The mean free path should be a tenth or less than the typical size of the chamber.
- Also, since we want the electrons to gain enough energy between collisions, the pressure can not be too high.
- This means discharge tube pressures around 10-1000 mTorr.

Ion Energies

- < 5 eV : Physisorption or reflection
- 5 - 10 eV : Surface damage and migration
- 10 - 30 eV : Sputtering
- > 30 eV : Ion implantation

$$E_T = \frac{4 m_{ion} m_{target}}{\left(m_{ion} + m_{target}\right)^2} E_{ion} = \gamma_m E_{ion}$$

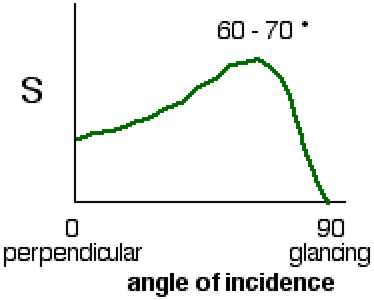
Energy transferred to the target

Other Factors

- Angle of incidence
- Subsequent behavior of ions
- Path and energy of freed ions
- Binding energy of target atoms

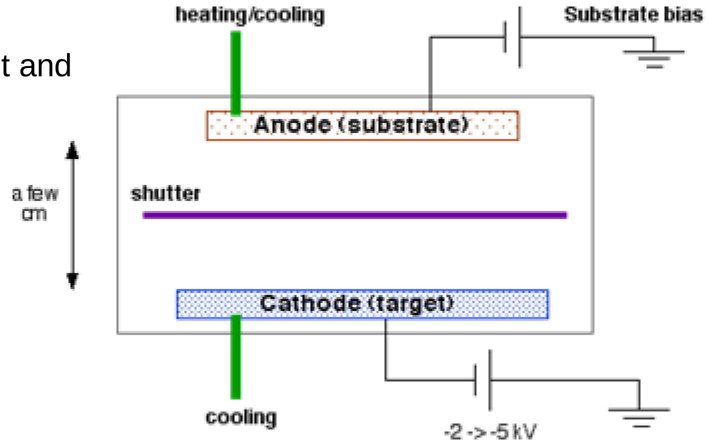
Sputter Yield

- The process is characterized by **sputter yield** (S)
- S = number ejected / number incident
- S depends on
  - target material
  - binding energy
  - mass of atoms
  - sputtering gas
  - mass of atoms (S increases for heavier gasses)



Some Parameters

- **Argon Pressure**
  - optimum deposition rate around 100 mTorr
  - compromise between
    - increasing number of Ar ions
    - increasing scattering of Ar ions with neutral Ar atoms
  - if you can increase the number of ions without increasing the number of neutrals, you can operate at lower pressures
- **Sputter voltage**
  - maximize sputter yield (S)
  - typically -2 to -5 kV
- **Substrate Bias Voltage**
  - substrate is being bombarded by electrons and ions from target and plasma
    - sputtering film while you deposit
  - neutral atoms deposit independently
  - put negative bias on the substrate to control this
  - can significantly change film properties
- **Substrate temperature**
  - control with substrate heater
  - heating from deposited material
    - increases with increasing sputter voltage
    - decreases with increasing substrate bias
- **Particle Energy**
  - increases with increasing sputter voltage
  - decreases with increasing substrate bias
  - decreases with increasing Ar pressure

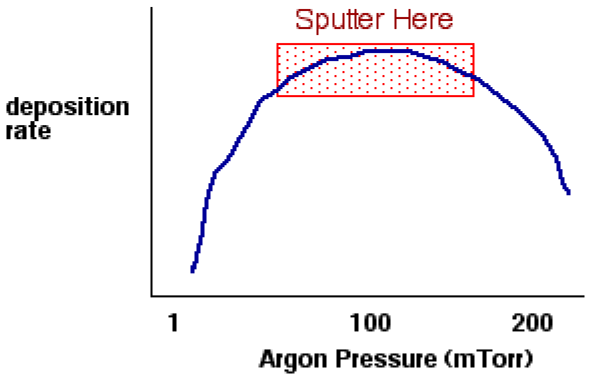


Deposition

- Sputtered atoms from the target make their way on to the substrate through diffusion.
- Ions and neutralized gas atoms may also embed on the substrate as impurities.
- The ions incident on the substrate may also re-sputter the surface.
- Chemical reactions may occur.

Deposition Rate

- It is proportional to the sputtering yield.
- An optimum pressure exists for high deposition rates.
  - Higher pressure means more collisions and ions.
  - Lower pressure means less scattering.



Composition Issues

- If a target is made up of several atoms with different sputtering yields, initial film composition can be off.
- This will eventually correct itself as the amount of the faster sputtering component at the target reduces.

Step Coverage and Film Uniformity

- Angular distribution of sputtering depends on the pressure.
- Lower pressures result in a more directed flow which results in less uniform films.
- Higher pressures result in more isotropic flow and better coverage.
- Uniform films also require larger targets.