Sputtering (cont.)

Sputtering Summary

- Create an ionic plasma by applying a high voltage to a glow tube.
- Ions bombard the target material at the cathode.
- Target atoms are ejected (sputtered) from the cathode by energy and momentum transfer.
- Sputtered atoms from the target are deposited on to the substrate (anode).

Keys to Proper Sputtering

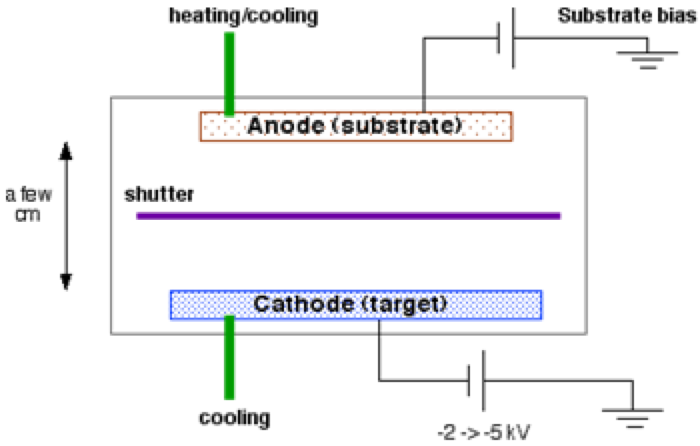
- The right choice of ions
  - The atomic weights of the ions and the target atoms should be close.
- The right pressure for a sustainable plasma
  - 10-1000 mTorr
- The right cathode voltage so that the ions have the right energy for sputtering
  - E_{ion} ~ 10-30 eV and V_{cath} ~ 2-5 kV
- The right substrate voltage and temperature for a clean film
- The right angle for high sputter yield
  - 60° - 70° from normal

Glow Discharge Sputtering

- As the gas molecules are ionized and energized by collisions, eventually they will have enough energy to cause ejection of atoms from the cathode surface.
- This is not a very efficient system (ionic MFPs are very low due to their high mass).
- The film quality is not very good due to the high pressures required to maintain the glow.

DC Sputtering

- Initially pump system down to 10^{-6} – 10^{-7} Torr for purity.
- Then let in controlled amount of the gas to be ionized (generally Argon).
- Eventually the chamber pressure will be around 1 – 100 mTorr.
  - This number is determined by the pressure required to have a sustainable plasma given the chamber dimensions.
- The main control is the energy of the ions.
  - They need to be in the right range for sputtering.
- Can only be used to deposit conducting films.
  - If insulators are used, charge accumulation in the electrodes will eventually quench the plasma.



Limitations of DC Sputtering

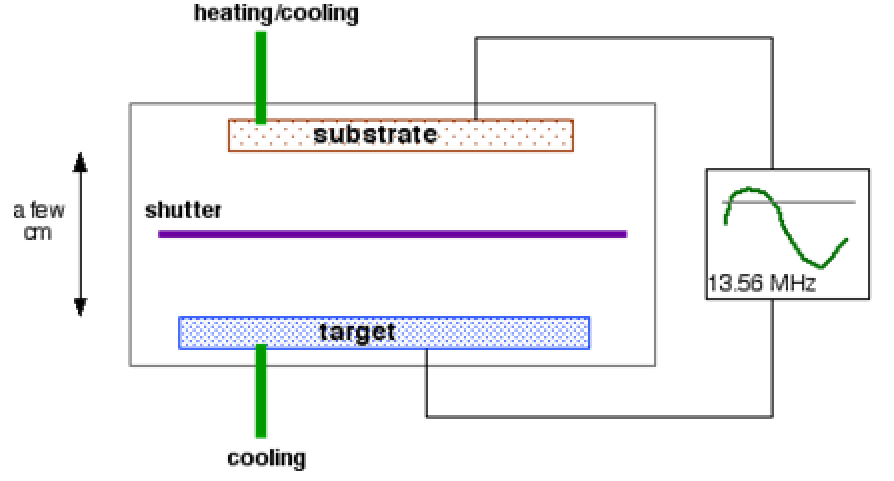
- The high pressures required to achieve a plasma can degrade film quality.
- Can only be used for conductive films.
  - If insulating targets are used, the negative charge applied to the cathode will be neutralized by the positively charged plasma ions and quench the plasma.
- Only a small fraction of the gas is converted to ions.

Substrate Biasing

- Applying a small negative voltage to the substrate (50 – 300 V)
- Removes physisorbed (adsorbed) contaminants such as Oxygen
- Also, by increasing the energy of the surface atoms enhances diffusion
  - This improves adhesion, nucleation and crystal structure.

RF Sputtering

- Instead of applying a DC voltage to the cathode, apply a voltage oscillating at radio frequency (RF).
- Typically around 13.5 MHz.
- The heavy and slow ions can not react fast enough to this oscillation.
- However the light and fast electrons can.
- On the positive cycle, electrons are attracted to the cathode, creating a negative bias (think of it as replenishing the negative charge on the target surface).
- On the negative cycle ion bombardment continues.



Cathode Voltage in RF Sputtering

n_e: density of electrons
v_e: velocity of electrons
n_i: density of ions
v_i: velocity of ions

Δt: duration the cathode is negative
τ: duration of one oscillation cycle
γ_e: Townsend Coeff. (number of secondary electrons)

$$Dose_+ = q \cdot n_e \cdot v_e \cdot \Delta t$$

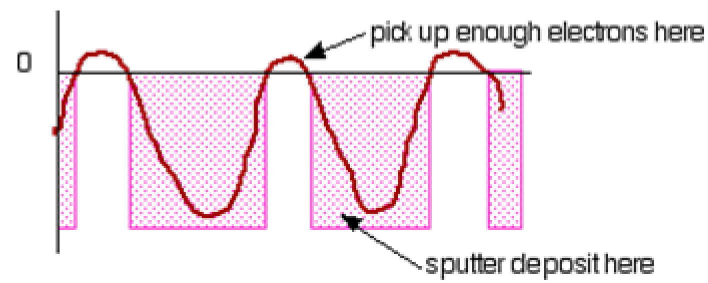
Dose of electrons that hit the cathode when it is positive

$$Dose_- = q \cdot n_i \cdot v_i \cdot (1 + \gamma_e) \cdot (\tau - \Delta t)$$

Dose of ions that hit the cathode when it is negative

$$\frac{\Delta t}{\tau} = \frac{1}{1 + \frac{v_e}{v_i (1 + \gamma_e)}}$$

Fraction of the time the cathode is positive



With plausible numbers
(v_e = 9.5x10^7 cm/s, v_i = 5.2x10^4 cm/s, γ_e = 0.1) → $\frac{\Delta t}{\tau} \approx 10^{-3}$

target	**-**	**-**	**-**	**+**	**-**	**-**	**-**	**+**	**-**
substrate + chamber	**+**	**+**	**+**	**-**	**+**	**+**	**+**	**-**	**+**

Advantages

- By avoiding a constant negative voltage on the cathode, ion buildup is prevented for insulating targets.
- Can operate at lower pressures (as low as 1 mTorr) while still sustaining a plasma.

Magnetron Sputtering

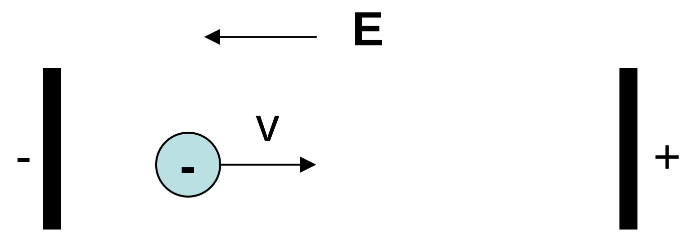
- Plasma generation is an inefficient process.
  - Less than 0.1% ionization rate
- Can increase chamber pressure
  - Degrade film quality, lose plasma
- Solution: Use secondary electrons more efficiently to generate plasma.

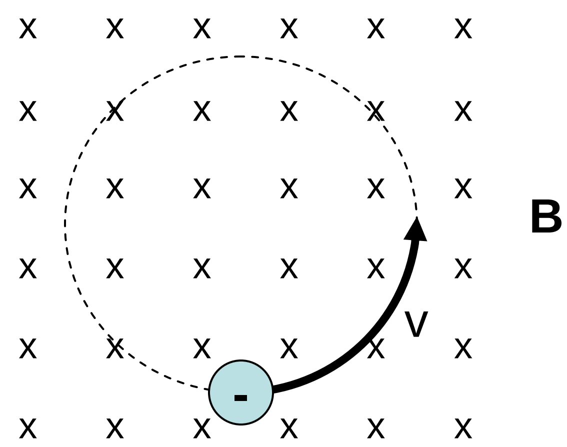
Magnetron Sputtering

- Normally once an electron is kicked out of the surface it travels more or less in a straight line between collisions.
- Under the influence of the cathode-anode voltage, it will drift towards the anode.
- If we can confine the electrons near the cathode, their high density will increase the plasma density and make for more efficient sputtering.

Lorenz Forces

- An electron in motion can be affected by both electrical and magnetic fields.
- An electric field changes the speed of the electron along the direction of the field.
- A magnetic field changes the direction of the electron about the direction of the magnetic field.

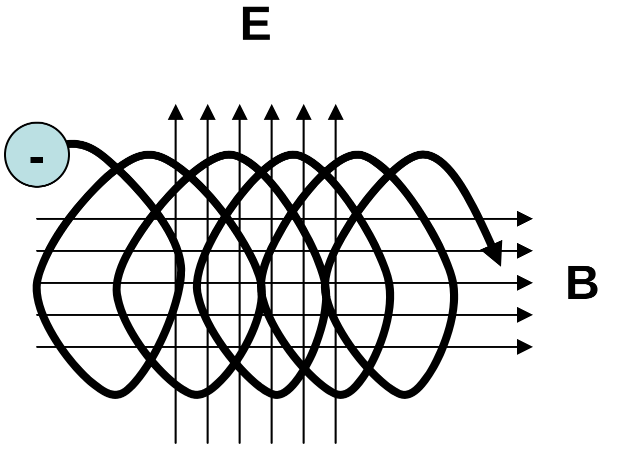




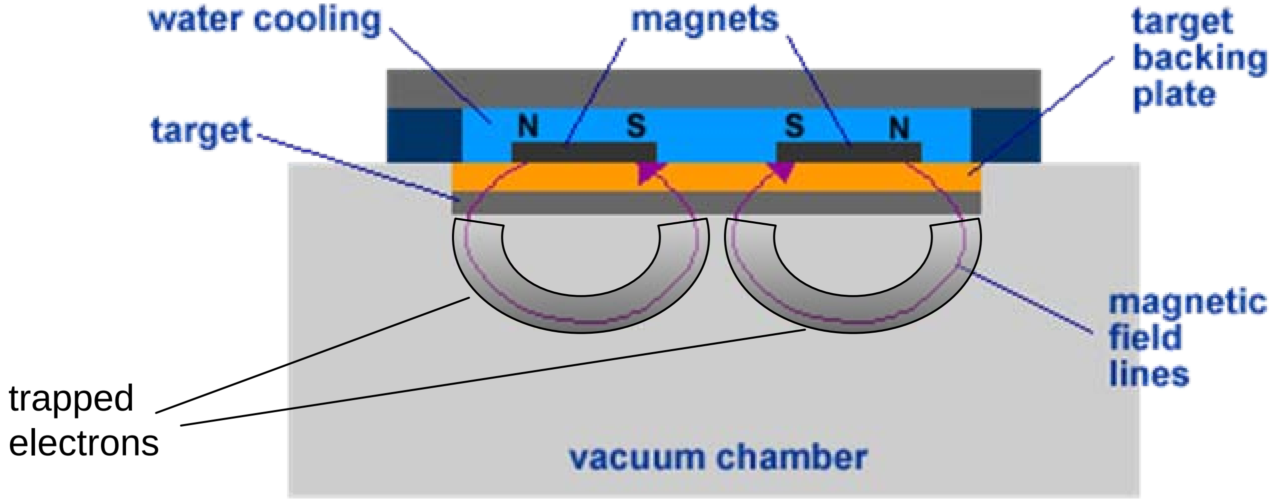
$$\mathbf{F} = q_e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) = m_e\mathbf{a}$$

Helical Motion

- If the electric and magnetic fields are crossed (perpendicular to each other), then the trajectory of the electron is a helix.
- If the magnetic field bends, the helix also bends confining the electrons to it.



The Magnetron



- A series of magnets with alternating polarity are attached to the back side of the target in a circular fashion.
- The magnets create curved magnetic field lines which confine the secondary electrons to them.
- The highly concentrated electron gas collides with the ions near the target and create a denser plasma without the need for higher pressures.
- Plasma densities can be increased by two orders of magnitude.

Practical Considerations

- A stationary magnetic field will produce permanent regions where the plasma is strong
- This will create erosion rings on the target.
- This affects film uniformity and requires frequent replacement of the target.
- To avoid this oddly shaped and rotating magnetron rings are used.

Sputtering of Alloys

- Alloy sputtering is a self-regulating process.
- If the sputter yield of one species (A) is larger than the other (B), then the surface will initially be depleted of A.
- Now, since the surface has more of B, more of it will sputter off.
- An equilibrium will be reached around the stochiometric ratio.

Reactive Sputtering

- A combination of physical and chemical deposition.
- Used to deposit compounds (oxides, nitrides).
- Add a reactive gas (oxygen, nitrogen) to the inert gas flow.
- The reactive gas goes in to a chemical reaction with the sputtered atoms.
- If the sputtering rate is faster than the chemical reaction rate, then the reaction will take place on the substrate.
- Adjust gas flow to get good stochiometry (chemical composition).
- Examples: Al_2O_3, AlN, TiO, TiN, SiO_2

Issues with Reactive Sputtering

- As more and more reactive gas is introduced into the system, target oxidation or nitridation can occur.
- This leads to drastically reduced sputter yields and deposition rates.
- The oxidation/nitridation is a runaway process. Beyond a critical gas pressure, it progresses rapidly.
- Best oxide films are obtained just below this critical point.
- One solution is to oscillate the cathode voltage like RF sputtering but at a lower frequency (~100 KHz).