Sputtering of Thin Films

Hassaan Majeed

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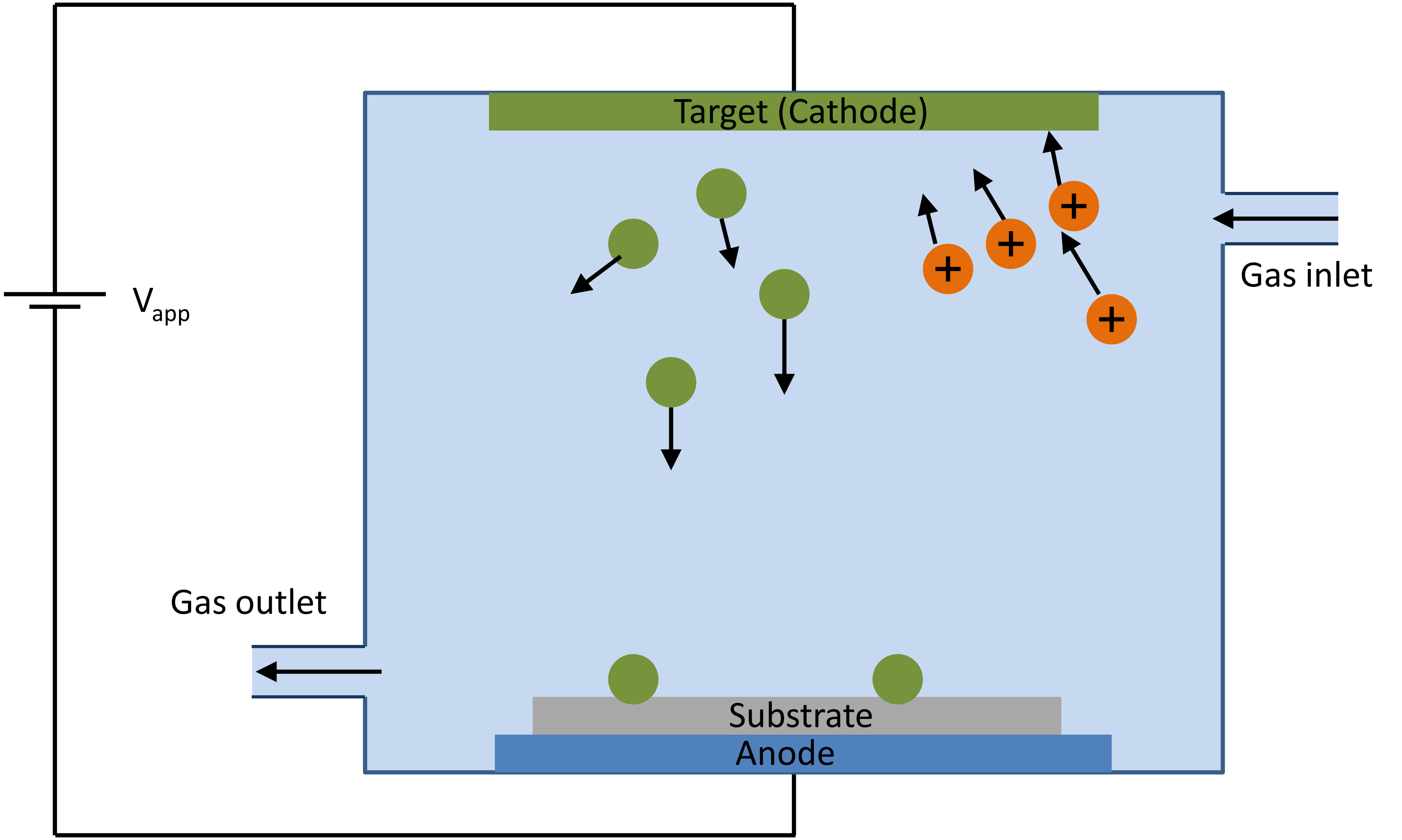
Introduction: Overview of the process

- A gaseous plasma is generated by applying an electric field inside a vacuum chamber filled with a heavy inert gas such as Argon, at a specific pressure
- The inert gas ions accelerate under the field towards the cathode which is made of the source material (called the target)
- Momentum transfer from the bombarding ions to the surface atoms of the target results in their ejection
- The ejected atoms diffuse towards the substrate (attached to the anode) and are deposited

Introduction: Schematic

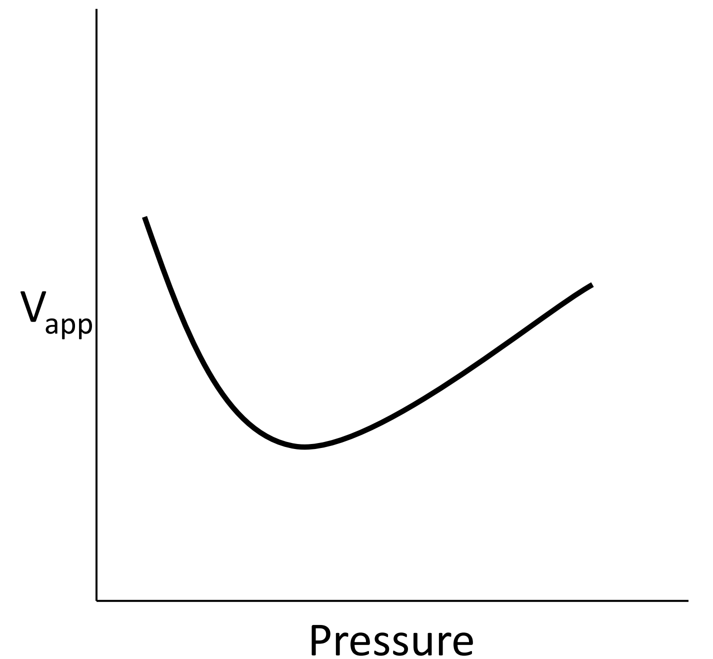


Step 1: Plasma generation and control

- Plasma is formed by the ionization of Argon due to the electric field
- This process begins when a stray free electron from the cathode is accelerated towards the anode
- On its way the electron encounters a neutral Argon gas atom and collides with it to produce a positively charged ion and two more free electrons
- The newly generated free electrons go on to ionize more Argon atoms resulting in a cascading effect
- This continues until the gas breaks down
- The break down voltage depends on the Argon pressure and distance between the cathode and the anode

Step 1: Plasma generation and control

- Plasma generation is optimized by determining the gas pressure required for maximum efficiency
- If the pressure is too low, there aren't enough collisions between electrons and atoms to sustain a plasma
- If the pressure is too high there too many collisions and the electrons do not have enough time to gain energy in order to ionize atoms
- Mean free path for the electron should be a tenth or less than the typical size of the chamber
- Typical pressure ranges of 10-1000 mTorr and plasma densities of 10^{10} to 10^{12} cm^3



Step 2: Ion-Surface Interaction

- When ions bombard the cathode surface, several possible interactions can take place:
  - Reflection
  - Adsorption
  - Sputtering
  - Ion implantation
  - Electron and photon emission
  - Chemical reactions

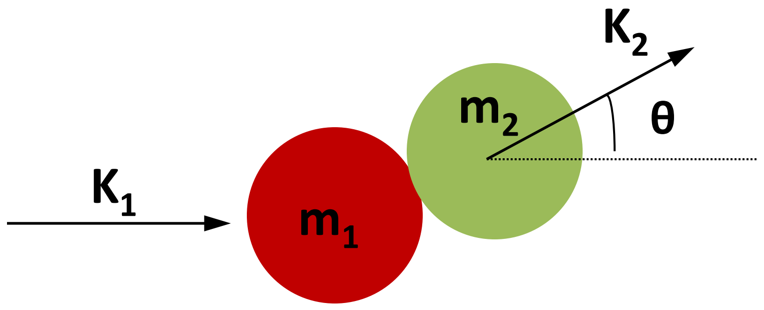
- The type of interaction is dictated by the energy of the ion-beam:
  - Less than 5 eV => Adsorption or reflection
  - 5 – 10 eV => Surface damage and migration
  - 0.01 – 3 keV => Sputtering
  - > 10 keV => Ion implantation

Step 2: Ion-Surface Interaction

- High energy ions sputter atoms by transferring energy greater than the binding energy of the target surface atoms and knocking them out
- The key principles are energy and momentum conservation
- Momentum is conserved in any collision whereas in an elastic collision kinetic energy is also conserved
- The energy at which sputtering occurs is higher than the lattice bonding or vibrational energies that are responsible for inelastic interactions
- Sputtering collisions can, hence, be considered elastic

Step 2: Ion-Surface Interaction

$$\frac{K_2}{K_1} \propto \frac{4m_1 m_2}{(m_1 + m_2)^2} \cos\theta$$



- Maximum transfer of energy in the horizontal direction takes place at $m_1 = m_2$
- For this reason heavy inert gases such as Ar and Kr are used during sputtering

Step 2: Ion-Surface Interaction

- For most sputtering systems, the kinetic energy of incident ions is in a regime known as the “knock-on energy regime”
- In this regime, ions have enough kinetic energy to cause secondary collisions and tens to hundreds for atoms are dislodged for every ion
- During energy transfer, the ions also excite electrons from the target material
- These “secondary electrons” are then accelerated towards the anode and participate in plasma generation by ionizing the sputtering gas. Their generation yield is important in sustaining a plasma

Step 2: Ion-Surface Interaction

- Sputter yield is defined as:

$$S = \frac{Number\ of\ Sputtered\ atoms}{Number\ of\ incident\ ions}$$

- The sputter yield depends on:
  - Type of target atom
  - Binding energy of target atom
  - Incident ion energy
  - Angle of incidence
    - In general from 0 – 50 deg the yield varies linearly with angle of incidence

Step 3: Deposition

- Sputtered atoms make their way to the substrate through diffusion
- Ions and neutral sputtering gas atoms may also embed on the substrate as impurities
- Substrate re-sputtering may also take place due to any ion flux
- Chemical reactions are also possible

Step 3: Deposition

- Rate of deposition is proportional to sputtering yield
- Optimum pressure exists for high deposition rate:
  - Pressure should not be too low as that reduces ions and collisions
  - Should not be too high as that causes scattering
- Control parameters to vary deposition rate include
  - Sputtering power or current
  - Distance between cathode and anode

Step 3: Deposition

- Film uniformity depends on:
  - Pressure
  - Incident ion energy
  - Size of target

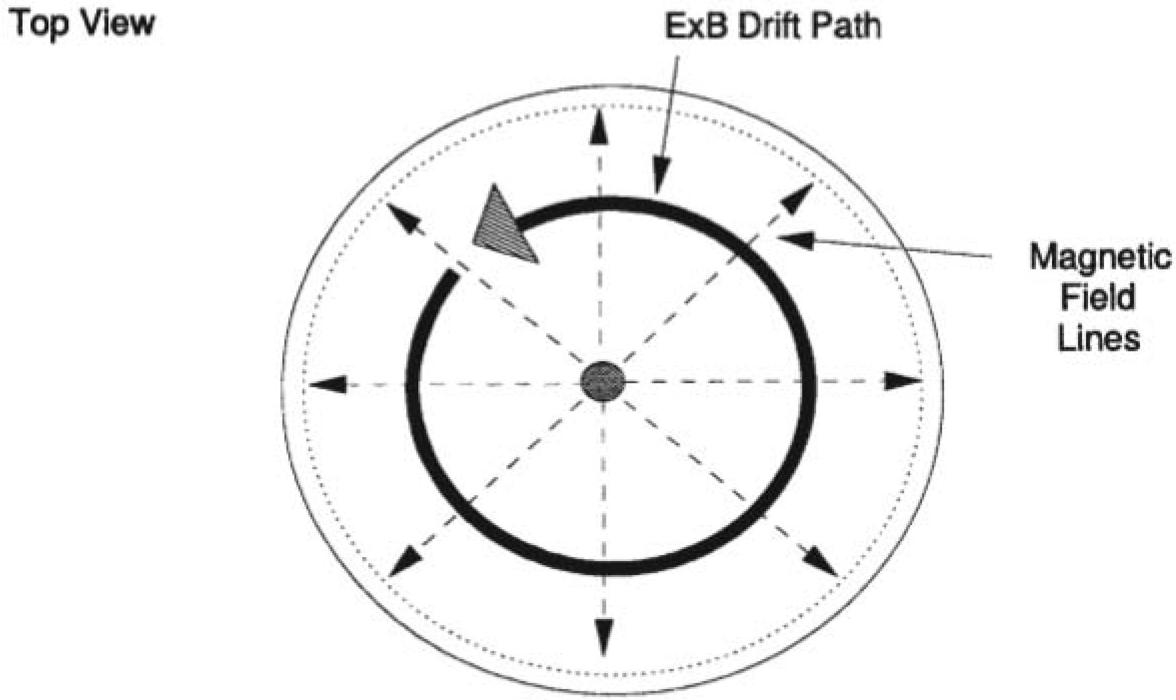
Variations: DC and RF Sputtering

- DC or diode sputtering
- RF sputtering
  - Power supply operated at high frequency
  - For a small portion of the cycle the direction of ion and electron flow is reversed
  - Prevents charge build-up on insulating surfaces
  - Allows reactive sputtering
  - Interaction path of electron with gas is increased leading to denser plasma and faster sputtering

Variations: Magnetron Sputtering

- Magnetron sputtering
  - Static magnetic field is configured in the cathode location
  - Secondary electrons, generated by ion bombardment are constrained to flow perpendicular to the E x B
  - In the correct configuration, the secondary electrons follow a current loop called the “drift ring” parallel to the cathode surface

Variations: Magnetron Sputtering



Variations: Magnetron Sputtering

– Secondary electrons are confined within a region near the cathode
– They cause ionization in the vicinity of the cathode to generate a dense plasma in the drift ring
– Sputtering yield is increased
– Substrate heating is reduced

Animation

- http://www.ajaint.com/whatis.htm

References

[1] K. Seshan, "Handbook of thin-film deposition processes and techniques: principles, methods, equipment and applications", Intel Corporation, 2002

[2] Sputter coating technical brief, Quorum Technologies, URL: http:///www.quorumtech.com

[3] http://www.ajaint.com/whatis.htm