Magnetron discharges

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Application of the magnetron sputtering

- Technological coatings
- Medical coatings
- Decorative coatings
Motivation - Physical vapour deposition

- Physical vapour deposition (PVD)
  - a name for several vacuum deposition methods used to deposit thin films by the condensation of a vaporized form of the chosen film material onto a substrate

- Various techniques
  - Cathodic arc deposition
  - Electron beam PVD
  - Evaporation
  - Pulsed laser deposition
  - Sputter deposition
Why to choose sputtering?

- **Advantages**
  - Use for deposition of materials with high melting points
  - Deposited films have a composition close to the composition of source material
  - Typically better adhesion
  - Suitable for ultra high vacuum (UHV) applications
  - Compatibility with reactive gases

- **Disadvantages**
  - Contamination problems
  - No possibility of layer-by-layer deposition
  - Inert gases are built into the growing films
DC discharge

Magnetron – the apparatus

Particle trajectories in magnetron

Types of magnetrons

Special case of magnetron sputtering: HiPIMS

Significance of the target material ionisation
Introduction - Glow discharge

- A lot of dark and light regions indicate a complicated behaviour of the discharge
  - Cathode sheath (Crooks dark space)
    - Most of the voltage drop
    - Discharge maintained by secondary electrons accelerated by the sheath
  - Negative glow
    - Bright glow due to ionisation and excitation
    - Dissipation of electron energies
- Positive column
  - Power lost per electron-ion pair created going to excitation, ionisation, kinetic energy of ions and electrons
Voltage current characteristic of the DC discharge

- V-I characteristic provides an overview of different discharge regimes possible
- For the application glow discharge and arc discharge are widely used in industry

Limitations of the glow discharge

- The discharge is maintained by secondary electron emission from the cathode through the ionisation.
- However, operating pressures must be relatively high, $p > 4$ Pa, so that secondary electrons are not lost to the anode or side walls.
- This pressure is higher than optimum for deposition.
- The drawback of the DC glow discharge is the low sputtering power efficiency, which is decreasing with increasing energy.
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Significance of the target material ionisation
First magnetron concept

- Idea is to confine the electrons in order to operate the discharge more efficiently
- Induced magnetic field along the target surface confines the electrons and enhances the ionisation

John A. Thornton, 1976
Flat target magnetron concept

- Permanent magnets placed behind the cathode in order to confine the electrons and enhance the ionisation
Sputtering mechanism

- Negative bias on the target attracts ions that sputter the target material and generate secondary electrons.
- Secondary electrons are confined near the target by the magnets.
- Energetic sec. $e^-$ ionise both inert gas and sputtered atom.
- Created ions accelerated towards the target in continuous process.
- Sputtered atoms and ions diffuse towards the substrate.

http://www.directvacuum.com/sputter.asp
Sputtering mechanism

- Material from the target gets ejected/sputtered by impinging positive ion from the plasma accelerated in the cathode sheath
- Different sputtering regimes possible:
  - Single knock on regime (a)
  - Linear cascade regime (b)
  - Collision spike regime (c)

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Significance of the target material ionisation
Charged particle confinement

- Larmor radius is a function of the kinetic energy of the particle and the strength of the magnetic field:

  \[ r = \frac{mv}{qB} \]

- Particle is magnetised when the Larmor radius is much smaller to the size of the chamber.

- For typical deposition chambers target-substrate distance is of order of 10 cm.

- For a particle with Larmor radius smaller than 0.5 cm (gyrating diameter 1 cm) we can say it is magnetised.

Charged particle confinement

Ion energy distribution function (IEDF)

![Graph of Ion Energy Distribution Function (IEDF)]

Electron energy distribution function (EEDF)

![Graph of Electron Energy Distribution Function (EEDF)]

Except very close to the target, ions are not magnetised

Except very close to the target, electrons are magnetised

ExB drift

- The voltage is applied to the target, creating the electric field perpendicular to the target.

- Combination of the static magnetic field and the electric field perpendicular to the target will generate ExB drift of the charged particles.

- Generated azimuthal current can be up to 25 times higher than a discharge current.

Electron transport

- Electrons confined in within the closed magnetic field region are subjected to the cross field transport.
- In contrast to classical diffusion, $D = \frac{\lambda^2}{\tau}$ ($\lambda$ is the mean free path, and $\tau$ is the inverse of collision frequency).
- The electrons obey Bohm diffusion: $D_{Bohm} = \frac{1}{16} \frac{k_B T}{eB}$.

Chapman, Glow Discharge Processes, Wiley
Electron trajectories

Simulation of the electron trajectories without →

and with scattering →

Balanced/unbalanced magnetrons

Balanced

Unbalanced I
outer magnets
weaker than
inner magnets

Unbalanced II
outer magnets
stronger than
inner magnets

Tunable Unbalanced Magnetrons

Externally mounted set of coils is used to generate induced magnetic field that alters the static magnetic field and consequently the electron trajectories.

Planar Magnetron

- Two predominant types of planar magnetron
  - circular magnetron
  - rectangular magnetron

[Chapman, Glow Discharge Processes]
Target utilisation of the magnetron targets

- Due to the confinement of the electrons by the magnetic field, a preferential sputtering area occurs.
- Fixed magnetic fields result in the limited target utilisation.
Rotating Cylindrical Magnetrons

- 90% target utilisation
- Possible higher discharge power due to efficient cooling

[Leroy et al., DRAFT, Belgium]
Another method is the double ring magnetrons with additional magnet set in the middle.
Solutions for the magnetic targets (Ni, Fe and alloys)

Magnetic targets absorb and disturb the magnetic fields. One of the solutions -> enhanced magnetic field
Multiple Sources
Large Magnetron Sputtering Systems

Applied ATON PVD 5.7, substrates 5.7m$^2$ in area

PIA|nova®
DC discharge

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Significance of the target material ionisation
Why are metal ions significant for the film growth?

- **Ions** - biasing the substrate allows to fine tune the kinetic energy of ions arriving to the substrate

- **Metal ions** – they are desirable building blocks of the film while Ar ions are deteriorating the film properties

The idea is to develop magnetron into an ion source. By ionising the sputtered material it is possible to improve control of the deposition process.

Example: high power impulse magnetron sputtering (HiPIMS)

- For more ions we require higher power
- In order to increase power but not to overheat the target short pulses of high power are applied to the target

Typical discharge parameters

- Peak powers – up to kW/cm²
- Peak current density ~ 1 A/cm²
- Frequency – 10 to 1000 Hz
- Pulse duration – 10 to 500 µs


Current-Voltage characteristic

- Demonstrating the difference in power output between DC and HIPIIMS
- Discharge currents 2 orders of magnitude higher for HiPIMS discharge compared to DC discharge

![Voltage-Current Characteristic of the DC Low Pressure Electrical Discharge Tube](image)

DC and HIPIIMS discharge with Cr target
Ability to achieve higher current is very important since the plasma density increases linearly with the discharge current.
Optical emission spectroscopy

- OES result reveals lower intensity of Ar lines, and significant increase of both Ti atom and ion emission lines, indicating dominance of metal ions and atoms.
Optical absorption spectroscopy

- Ion-to neutral ratio increases for higher discharge currents
- Results show decay of the ratio, however with ratio of 1 measured even at 900 μs after the end of the discharge

Multiple ionisation detected

- Using Mass-spectrometer quadruple charged particles have been detected
- Indicating presence of electrons with energies of 43.3 eV – the ionisation energy of Ti$^{3+}$

Mass spectrometry DC and HIPIMS

- Comparison of the IEDFs no significant change is observed for Ar ions
- However comparing the data of the Ti IEDF, there is a clear difference in the high energy part of the IEDF with high energy tail of Ti ions with energies up to 100 eV present in case of HIPIMS discharge

Influence of the pressure and the distance on the IEDF of metal ions

- Two images show dependence of the ion energy distribution function of Ti\(^+\) ions on distance and pressure
- Longer distances -> high collision probability, less energetic ions
- Higher pressure -> more collisions, higher thermalisation

Plasma density

- Plasma densities of more than $10^{19}$ m$^{-3}$ have been reported during plasma on time

Spokes in HiPIMS

- High plasma densities result in inhomogenous plasma emission patterns – commonly known as spokes.

180 us

1.5 A/cm²

Al target
Plasma investigation of HIPIMS

- HIPIMS discharge generates a great deal of ions.
- The ratio of ions to neutrals is above 1 for considerable time after the pulse, indicating high fraction of ionised target material.
- Multiple charged ions have been observed.
- Distance and pressure strongly influence the IEDF reaching the substrate.
- High plasma densities up to $10^{19}$ m$^{-3}$. 
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Significance of the target material ionisation
Fundamental growth processes

- Graphic showing fundamental grow processes:
  - Nucleation
  - Island growth
  - Impingement and coalescence of islands
  - Formation of polycrystalline islands and channels
  - Development of a continuous structure

Structure zone models

- Structure zone diagrams present a convenient way to illustrate a structure of the polycrystalline film depending on the deposition parameters

Structure zone diagram

- Expansion of the Thornton’s diagram including information on kinetic energy of arriving ions

- Ion irradiation

- Interruption of columnar growth and re-nucleation

- Featureless morphology

Influence of the ion bombardment

- TaN grown by DC
- The ratio of ions to neutrals arriving to the substrate was varied while keeping other parameters fixed
- TEM images reveal less porosity and denser coatings

[Shin C-S. et al. J. Appl. Phys. 92, 5084 (2002)]
Influence of the ion bombardment

- 160 eV – defects and renucleation are more pronounced
- 120 eV – no voids along the boundaries, and some indication of intergranular damage
- 80 eV – dense columns with open column boundaries

Influence of the ion bombardment – TiN, Ni and V

- TiN deposited
  - < 15 eV – no atomic displacement
  - 15 – 100 eV – surface displacement
  - > 100 eV – surface and bulk displacement

- Valid for Nickel and Vanadium
  - < 23 eV – no atomic displacement
  - 23 – 55 eV – surface displacement
  - > 55 eV – surface and bulk displacement

[Eriksson F. et al., Thin Solid Films 500, 84 (2006)]
Deposition of trenches

- Cu atom dominated plasma
  - strong shadowing effect
- Cu ions dominated plasma
  - reduced shadowing effect

Trench filling limitation

- Debye length $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$, defines the sheath thickness
- Ta films deposited on the trench
- HiPIMS films exhibit smoother surfaces and no preferential growth.

Particle flux

HiPIMS coatings

- \((\text{Cr}_{0.5}\text{Al}_{0.45}\text{Si}_{0.05})\text{N}\) grown by HiPMS showing a high thickness uniformity around the cutting edge.

Both experiments and simulations show implantation in the steel substrate to a maximum of approximately 4 nm.

However....

- Deposition rate in HIPIMS is lower compared to deposition rate of DC

Summary

- Magnetron sputtering is a response on the requirements of industry for low pressure high power discharges.
- Magnetic configuration of the magnetron depends on the geometry of the deposition chamber.
- For improved tailoring of the film properties without macroparticles HiPIMS was introduced.
- The ions are important for tailoring of the deposited films since deposition of dense coatings is possible due to enhanced adatom mobility.
Thank you for your attention!