Langmuir probe study of the plasma parameters in the HiPIMS discharge

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Outline

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- High power impulse magnetron sputtering discharge (HiPIMS)
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  - Plasma parameters in the HiPIMS discharge
    - Electron density
    - Electron energy distribution
    - Plasma potential
- Summary
Planar dc Magnetron Sputtering Discharge

- For a typical dc planar magnetron discharge:
  - pressure of 1 – 10 mTorr
  - a magnetic field strength of 0.01 – 0.05 T
  - cathode potentials 300 – 700 V
  - electron density in the substrate vicinity is $10^{15} – 10^{17} \text{ m}^{-3}$
  - low fraction of the sputtered material is ionized $\sim 1\%$
  - the majority of ions are the ions of the inert gas
  - the sputtered vapor is mainly neutral
Planar dc Magnetron Sputtering Discharge

The electron energy distribution is bi-Maxwellian
High Power Impulse Magnetron Sputtering (HiPIMS)

- In a conventional dc magnetron discharge, the power density is limited by the thermal load on the target.
- In a HiPIMS discharge, a high power pulse is supplied for a short period:
  - low frequency
  - low duty cycle
  - low average power
- The high power pulsed magnetron sputtering discharge uses the same sputtering apparatus except the power supply.
High Power Impulse Magnetron Sputtering (HiPIMS)

- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500 – 2000 V
  - Current densities of 3 – 4 A/cm²
  - Power densities in the range of 1 – 3 kW/cm²
  - Average power 200 – 600 W
  - Frequency in the range of 50 – 1000 Hz
  - Duty cycle in the range of 0.5 – 5 %
HiPIMS - Electron density - summary

The electron density versus time from the initiation of the pulse 9 cm below the target.

- The pulse is 100 $\mu$s long and the average power 300 W and the target made of tantalum.
- A strong initial peak appears.
- A second peak appears later in time at higher pressure.

(After Gudmundsson et al. (2002))
A monotonic rise in plasma density with discharge gas pressure (Gudmundsson et al., 2002)
and applied power (Alami et al., 2005)

A linear increase in electron density with increased discharge current (Ehiasarian et al., 2008)

The electron density depends on the target material
- Cr target gives higher density than Ti (Vetushka and Ehiasarian, 2008)

The peak electron density travels away from the target with fixed velocity (Gylfason et al., 2005)
HiPIMS - Experiment

- The goal of this work was to determine the temporal variation of the
  - electron energy
  - plasma potential
- In particular determine the electron energy distribution function (EEDF)
The pulse generator was SINEX 2 from Chemfilt Ionsputtering

- The exact pulse shape is determined by the load
  - the discharge formed
  - it depends on the gas type and gas pressure
- The average power was in the range 215 – 270 W, pulse length from 80 to 90 $\mu$s and repetition frequency was 50 Hz
A Langmuir probe was used to study the temporal and spatial variation of the plasma parameters:
- electron density
- electron energy
- plasma potential

The Langmuir probe:
- made of a stainless steel wire, 200 $\mu$m in diameter and 5 mm long

The voltage and current was measured with a 12-bit A/D converter.

For each voltage step, the current drawn by the probe was measured as a function of time.
Plasma parameters - Langmuir probe

- The EEDF was determined from the Druyvesteyn formula

$$g_e(V) = \frac{2m}{e^2 A} \left( \frac{2eV}{m} \right)^{1/2} \frac{d^2 I_e}{dV^2}$$

- The electron density

$$n_e = \int_0^\infty g_e(\mathcal{E}) \, d\mathcal{E}$$

- The effective electron temperature

$$T_{\text{eff}} = \frac{2}{3} \left\langle \mathcal{E} \right\rangle = \frac{2}{3} \frac{1}{n_e} \int_0^\infty \mathcal{E} g_e(\mathcal{E}) \, d\mathcal{E}$$

- The measured data was filtered

(Magnus and Gudmundsson, 2008)
The spatial variation of the electron density at 65 $\mu$s and 230 $\mu$s from the initiation for gas pressure of 5 mTorr.

- The pulse is 90 $\mu$s long and the average power 270 W and the target made of copper.
- The electron density is uniform along the radius of the discharge.
The spatial variation of the effective electron temperature at 65 $\mu$s and 230 $\mu$s from the initiation for gas pressure of 5 mTorr.

The pulse is 90 $\mu$s long and the average power 270 W and the target made of copper.

The effective electron temperature is uniform along the radius of the discharge.
HiPIMS - Plasma potential

The spatial variation of the plasma potential at 65 $\mu$s and 230 $\mu$s from the initiation for gas pressure of 5 mTorr.

The pulse is 90 $\mu$s long and the average power 270 W and the target made of copper.
The electron energy probability function (EEPf) under the race-track 100 mm below the target for an argon discharge at 3 (dashed) and 20 (solid) mTorr with a copper target.
HiPIMS - Electron energy

- The measured EEPF is Maxwellian-like during the pulse
  - high electron density leads to a Maxwellian-like low energy part of the EEPF
  - the depletion in the high energy part is due to the escape of high energy electrons to the chamber walls and inelastic collisions of high energy electrons
- The EEPF is more broad at low pressure and early in the pulse
HiPIMS - Electron energy

- Temporal variation of the effective electron temperature 100 mm below the target under the race-track ($r = 40$ mm)
- Argon discharge at 3 and 20 mTorr with a copper target
- The electron energy decreases with increased discharge pressure
HiPIMS - Electron energy

- During the initial stages of the pulse Ar\(^+\) ions dominate the discharge.
- Later in the pulse metal ions build up and become the abundant ion species.
- The high metal content is expected to cool the EEPF due to electron impact excitation and ionization of the metal atoms, that have much lower excitation thresholds and ionization potential than the argon sputtering gas.

From Bohlmark et al. (2006)

From Ehiasarian et al. (2002)
Summary

- We discussed Langmuir probe measurements of the plasma parameters of the high power impulse magnetron sputtering discharge (HIPIMS).

- The electron density
  - roughly 1 – 3 orders of magnitude higher than in a dc magnetron sputtering discharge.

- The electron energy distribution function (EEDF) is Maxwellian-like during the pulse.

- The electron energy
  - is below 1 V towards the end of the pulse probably due to high metal content in the discharge.
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Can be downloaded at

http://www.raunvis.hi.is/~tumi/hipims.html


