Langmuir probe study of the plasma parameters in the HiPIMS discharge

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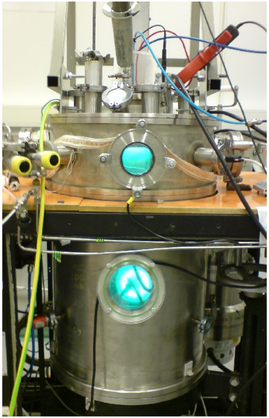
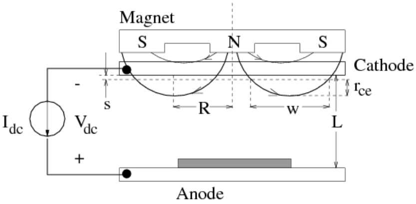
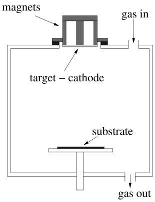
Outline

- dc Magnetron Sputtering Discharge
  - Electron density
  - Electron energy distribution
- High power impulse magnetron sputtering discharge (HiPIMS)
  - Summary of earlier work
  - Experimental apparatus and setup
  - Plasma parameters in the HiPIMS discharge
    - Electron density
    - Electron energy distribution
    - Plasma potential
- Summary



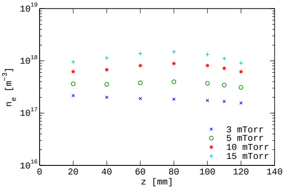
Planar dc Magnetron Sputtering Discharge

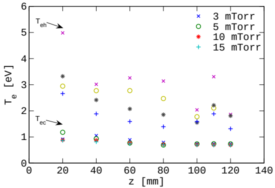


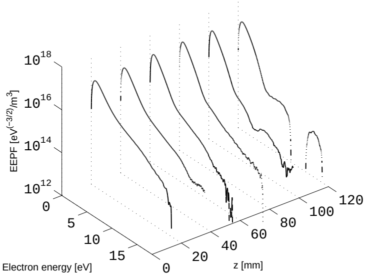


- For a typical dc planar magnetron discharge
  - pressure of 1 – 10 mTorr
  - a magnetic field strength of 0.01 – 0.05 T
  - cathode potentials 300 – 700 V
  - electron density in the substrate vicinity is $10^{15} - 10^{17}$ m^{-3}
  - low fraction of the sputtered material is ionized $\sim$ 1 %
 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

Planar dc Magnetron Sputtering Discharge





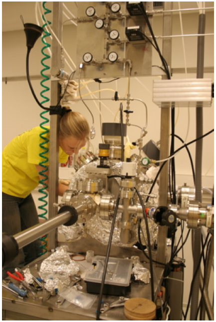


(From Sigurjonsson and Gudmundsson (2008))

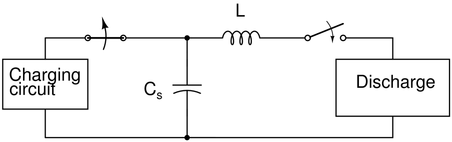
- The electron energy distribution is bi-Maxwellian

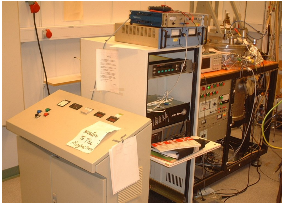
High Power Impulse Magnetron Sputtering (HiPIMS)

- 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



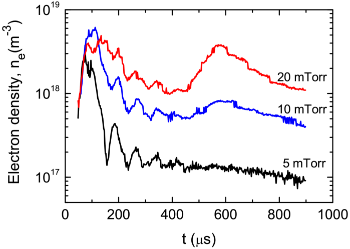
High Power Impulse Magnetron Sputtering (HiPIMS)





- The high power pulsed discharge operates with a
  - Cathode voltage in the range of 500 – 2000 V
  - Current densities of 3 – 4 A/cm^2
  - Power densities in the range of 1 – 3 kW/cm^2
  - 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

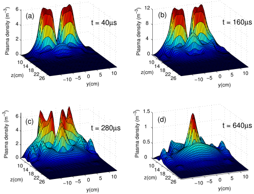


(After Gudmundsson et al. (2002))

- The electron density versus time from the initiation of the pulse 9 cm below the target
- The pulse is 100 μs 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

HiPIMS - Electron density - summary

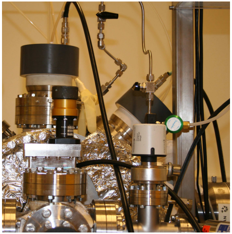
- A monotonic rise in plasma density
  - with discharge gas pressure (Gudmundsson et al., 2002)
  - applied power (Alami et al., 2005)
- A linear increase in electron density with increased discharge current (Ehiasarian et al., 2008)
- The electron density depends on the target material
  - Cr target 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)

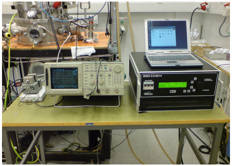


(After Bohlmark et al. (2005))

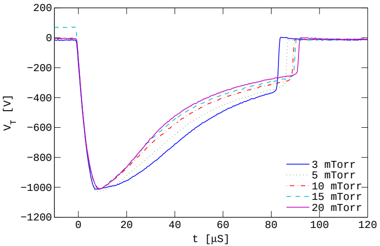
HiPIMS - Experiment

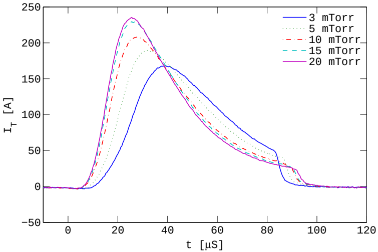
- The goal of this work was to determine the temporal variation of the
  - electron energy
  - plasma potential
- In particular determine the electron energy distribution function (EEDF)





HiPIMS - Power supply

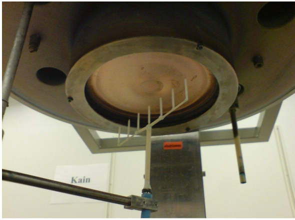


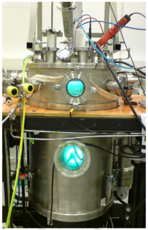


- The pulse generator was SINEX 2 from Chemfilt Ionsputtering
- The exact pulse shape is determined by the load
  - the discharge formed
  - it depends on the gas type and gas pressure
- The average power was in the range 215 – 270 W, pulse length from 80 to 90 μs and repetition frequency was 50 Hz

Plasma parameters - Langmuir probe

- 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 μm 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

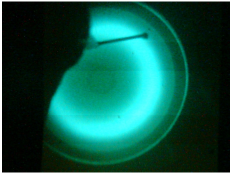
$$\mathrm{g_e}(V) = \frac{2m}{e^2 A}\left(\frac{2eV}{m}\right)^{1/2} \frac{d^2 I_\mathrm{e}}{dV^2}$$

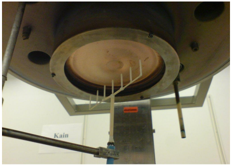
- The electron density

$$n_\mathrm{e} = \int_0^\infty \mathrm{g_e}(\mathcal{E})\, d\mathcal{E}$$

- The effective electron temperature

$$T_\mathrm{eff} = \frac{2}{3}\langle\mathcal{E}\rangle = \frac{2}{3}\frac{1}{n_\mathrm{e}}\int_0^\infty \mathcal{E}\,\mathrm{g_e}(\mathcal{E})\, d\mathcal{E}$$

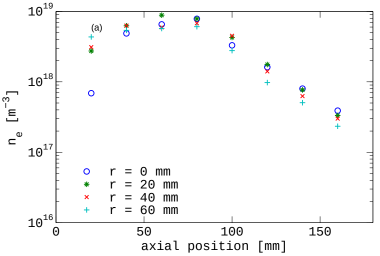




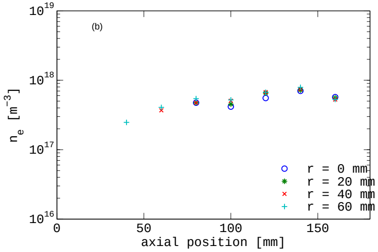
- The measured data was filtered

(Magnus and Gudmundsson, 2008)

HiPIMS - Electron density



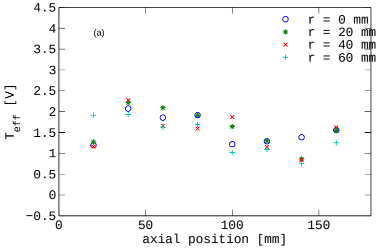
65 μs



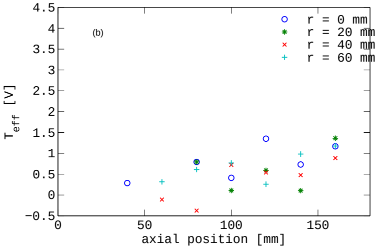
230 μs

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

HiPIMS - Electron energy



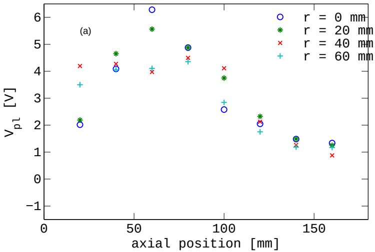
65 μs



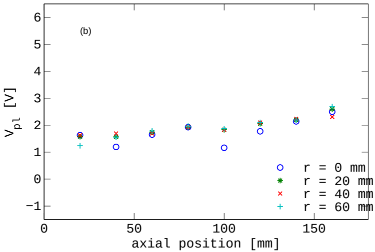
230 μs

- The spatial variation of the effective electron temperature at 65 μs and 230 μs from the initiation for gas pressure of 5 mTorr.
- The pulse is 90 μs 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



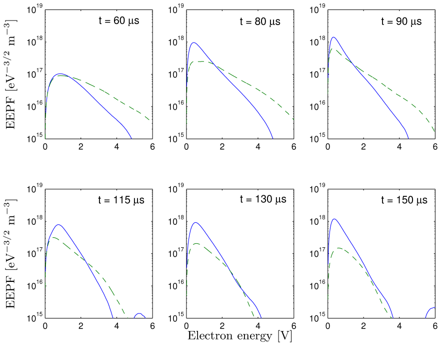
65 μs



230 μs

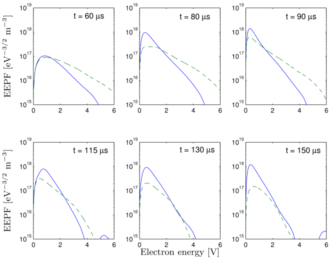
- The spatial variation of the plasma potential at 65 μs and 230 μs from the initiation for gas pressure of 5 mTorr.
- The pulse is 90 μs long and the average power 270 W and the target made of copper

HiPIMS - Electron energy



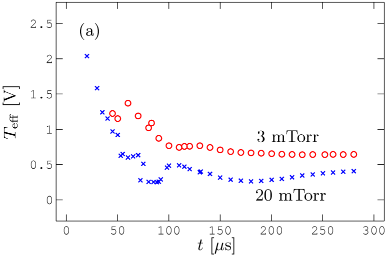
- The electron energy probability function (EEPF) under the race-track 100 mm below the target for an argon discharge at 3 (dashed) and 20 (solid) mTorr with a copper target

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

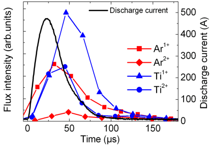
HiPIMS - Electron energy



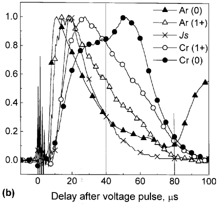
- Temporal variation of the effective electron temperature 100 mm below the target under the race-track ($r = 40$ mm)
- Argon discharge at 3 and 20 mTorr with a copper target
- The electron energy decreases with increased discharge pressure

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)



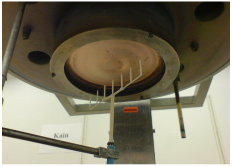
From Ehiasarian et al. (2002)

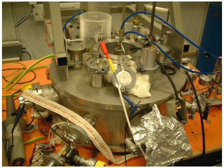
Summary

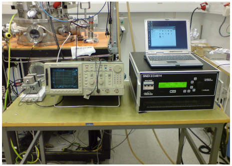
- We discussed Langmuir probe measurements of the plasma parameters of the high power impulse magnetron sputtering discharge (HIPIMS)

- 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

Acknowlegdements







Can be downloaded at

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

- The photographs were taken by Árni S. Ingason, Páll Sigurjónsson and Kristinn B. Gylfason.
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