Plasma parameters in a planar dc magnetron sputtering discharge of argon and krypton

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Abstract. The electron energy distribution function (EEDF) and plasma parameters in a planar dc magnetron sputtering discharge in argon and krypton were determined using a Langmuir probe. Two groups of electrons are observed in the discharge. The electron temperature of the cold electrons is roughly independent of the discharge pressure, while the electron temperature of the hot electrons decreases with increased discharge pressure. The electron density increases with increased pressure and is roughly a factor of 2 – 3 higher for a krypton discharge than for an argon discharge.

1. Introduction

The dc magnetron sputtering discharge has found widespread use in coating processes, particularly for deposition of thin metallic films. A typical dc planar magnetron discharge operates at a pressure of 1 – 10 mTorr with a magnetic field strength of 0.01 – 0.05 T and cathode potentials 300 – 700 V [1]. There have been a number of investigations of the spatial variation of the plasma parameters in a dc planar magnetron sputtering discharges [2, 3, 4, 5, 6]. Field et al. [5] find the electron density is highest in and near the magnetic trap above the etch region (race track) and is at a local minimum above the well region in the center of the cathode and near the edges of the cathode. Electron energy distribution functions (EEDF) are found to be either Maxwellian like or bi-Maxwellian like in nature, depending on pressure and spatial location [3, 6]. Maxwellian like electron energy distributions are found in or near the magnetic trap and bi-Maxwellian distributions are found further away from the cathode target [3]. The electron temperature and the electron density decrease with distance from the cathode target [2]. Outside the magnetic trap the plasma potential is generally found to have weak dependence on spatial location and pressure [3, 5].

Here we explore the spatial dependence of the electron energy distribution function (EEDF) and plasma parameters: electron density, electron temperature, and the plasma potential, in a planar dc magnetron sputtering discharge using a Langmuir probe. A comparison is made between argon and krypton sputtering gas.

2. Experimental apparatus and method

A Langmuir probe is used to measure the spatial variation of the electron energy distribution functions (EEDF) in a dc magnetron sputtering discharge. The Langmuir probe was made of a tungsten wire 127 μm in diameter and 5 mm long. A standard planar magnetron source was operated with a copper (Cu) target 76.2 mm in diameter. The sputtering-target, the cathode, was located inside a stainless steel chamber, 200 mm in diameter and 250 mm long. The magnetron is operated in a constant power mode at 100 W. The target voltage for the scan was in the range 380 ± 5 V to 450 ± 5 V, and the target current was in the range 220 ± 15 mA to 250 ± 10 mA. The circular water-cooling system cooled the coper (Cu) target while the sputtering was in progress. The base pressure was maintained below 10^{-7} Torr, with a turbo molecular pump. Argon (Ar) and krypton (Kr) of purity 99.9997 %, were used as discharge gases. The discharge was operated at four different pressures 3, 5, 10 and 15 mTorr.

The Langmuir probe was moved in 20 mm steps away form the cathode target along the discharge center axis in the range 20 mm to 120 mm from the target surface. The Langmuir probe current-voltage ($I-V$) characteristic was recorded, the current was monitored by measuring the voltage over an 10 Ω resistor as well as the voltage applied to the Langmuir probe. The probe current and voltage were collected with a 12-bit A/D converter and stored on a computer. The second derivative of the probe $I-V$ curve was obtained by numerically differenting and filtering [7] the measured $I-V$ curve to determine the electron energy distribution function (EEDF) from Druyvesteyn formula [8, p. 191]. The electron density was found by

$$n_{\mathrm{e}} = \int_0^{\infty} g_{\mathrm{e}}(\mathcal{E}) d\mathcal{E} \tag{1}$$

where $\mathcal{E}$ is the electron energy. The electron energy probability function (EEPF) is $g_{\mathrm{P}}(\mathcal{E}) = \mathcal{E}^{-1/2} g_{\mathrm{e}}(\mathcal{E})$. Kagan and Perel [9] showed that the magnetic field does not disturb the $I-V$ characteristic of a cylindrical Langmuir probe, if the probe radius is small, it is placed perpendicular to the field and the Larmor radius of the electrons is much larger than the probe radius. The magnetic flux density is below 30 mT at the target surface. Thus, the probe radius is much smaller than the Larmor radius of the electrons and the distortion of the low energy part of the $I-V$ characteristic can be considered negligible.

3. Results and discussion

Figure 1 shows the electron energy probability function (EEPF) for an argon discharge at 5 mTorr in the range 20 – 120 mm from the target surface. Two groups of electrons are apparent in the discharge. Similarly, two groups of electrons are apparent in the krypton discharge as shown in figure 2. Figure 3 shows the electron temperature versus distance from target along the center axis for argon discharge. It has a group of cold electrons with electron temperature in the range 0.6 – 1.2 eV and hot electrons with electron temperature in the range 1.3 – 5 eV. For both groups the electron temperature decreases with increased distance from the cathode target. The electron temperature of the cold electrons is roughly independent of the discharge pressure, while the electron temperature of the hot electrons decreases with increased discharge pressure. The plasma potential is in the range 1.4 – 1.8 V and is spatially uniform outside the magnetic trap in the range 20 – 120 mm and increases with increased discharge pressure. Thus, the cold electrons are trapped by this plasma potential. Figure 4 shows the electron temperature versus distance from target along the discharge center axis for krypton discharge. The krypton discharge has a group of cold electrons with electron temperature in the range 0.6 – 0.8 eV and a group of hot electrons with electron temperature in the range roughly 1 to 4 eV. Just as for the argon discharge, the electron temperature decreases with increased distance from the cathode target for both groups of electrons. The electron temperature of the cold electrons is roughly independent of the discharge pressure. The plasma potential is spatially flat in the range 1.35 – 2.2 V and increases with increased discharge pressure. The bi-Maxwellian like EEDF is commonly observed in the substrate vicinity in magnetron sputtering discharges [3, 6, 10]. Sheridan et al. [3] claim that the hot electrons are not energetic enough to be the ones

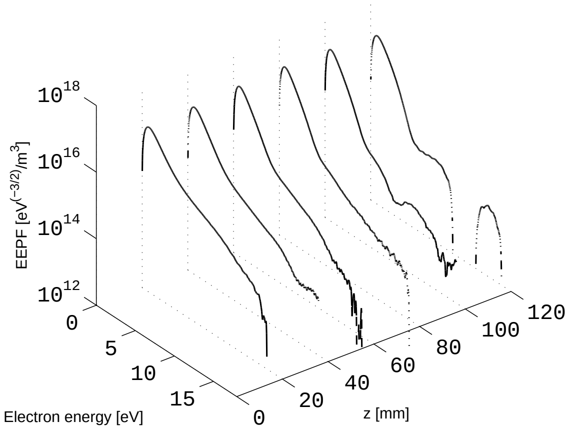

Figure 1. The electron energy probability function (EEPF) along the discharge center axis for argon discharge at 5 mTorr.

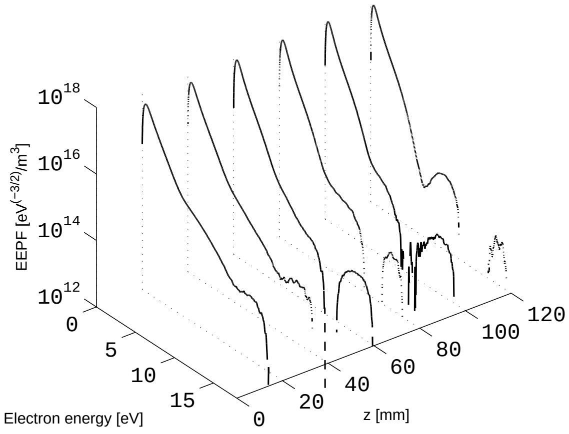

Figure 2. The electron energy probability function (EEPF) along the discharge center axis for krypton discharge at 5 mTorr

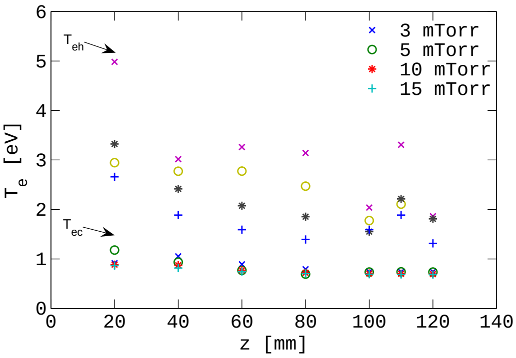

Figure 3. The electron temperature for hot electrons $T_{\rm eh}$ and cold electrons $T_{\rm ec}$ versus distance from target along the discharge center axis for argon discharge.

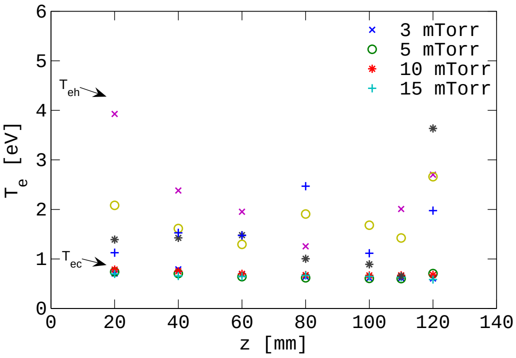

Figure 4. The electron temperature for hot electrons $T_{\rm eh}$ and cold electrons $T_{\rm ec}$ versus distance from target along the discharge center axis for krypton discharge.

emitted from the target, but are created in the magnetic trap in the cathode fall regions and drift to the downstream region under the influence of a diverging magnetic field [2, 10]. The low and flat distribution of the plasma potential traps the cold electrons. Thus, a bi-Maxwellian like electron energy distribution is observed in the downstream region. Figure 5 shows the electron density versus distance from target along the discharge center axis for an argon discharge. The electron density increases with increased pressure from about 2×10^{17} m^{-3} at 3 mTorr to 10^{18} m^{-3} at 15 mTorr. Furthermore, for pressures above 5 mTorr the electron density increases slightly with distance and peaks at roughly 80 mm from the target and then decreases again with further increase in distance. Figure 6 shows the electron density versus distance from target along the discharge center axis for krypton discharge. The electron density in a krypton discharge increases with increased pressure and is roughly a factor of 2 − 3 higher than for an argon discharge. Higher electron density is expected in a krypton discharge than for an argon discharge, since the ratio of electron impact ionization rate coefficient $k_{\mathrm{iz,Kr}}/k_{\mathrm{iz,Ar}} \approx 2.9$ for electron temperature of 2 eV and $k_{\mathrm{iz,Kr}}/k_{\mathrm{iz,Ar}} \approx 2.2$ for electron temperature of 3 eV [11].

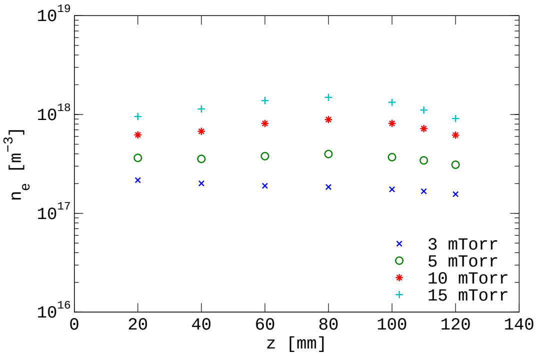

Figure 5. The electron density versus distance from target along the discharge center axis for argon discharge.

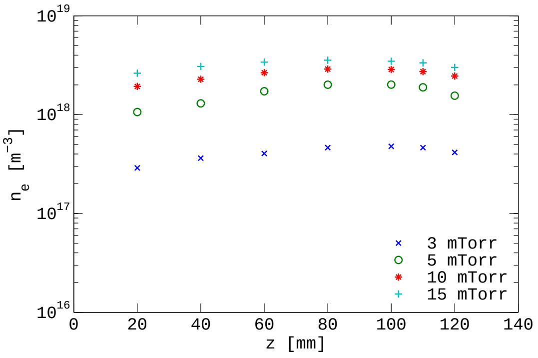

Figure 6. The electron density versus distance from target along the discharge center axis for krypton discharge.

4. Conclusion

The electron energy distribution function (EEDF) and plasma parameters were determined along the axis of planar dc magnetron sputtering discharge in argon and krypton. Two groups of electrons are observed in the discharge. The electron density increases with increased pressure an is roughly a factor of 2 − 3 higher for a krypton discharge than for argon discharge.

Acknowledgments

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