Correlation between plasma glow intensity distribution and sputtering profile in dc magnetron discharge

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Abstract. The correlation between the plasma glow intensity distribution and the target sputtering profile in an axially symmetric unbalanced dc magnetron discharge with copper cathode in argon is studied. At high pressures the argon atom and ion emission intensities are in good agreement with a sputtering profile. In case of low pressures, a satisfactory agreement is only for the ion emission. The best estimates of the sputtering profile can be obtained from the argon ion emission distribution at not too low pressures.

1. Introduction

The distribution of the ionic current density on the cathode is an important characteristic of the magnetron discharge. The presence of a strong arc-shaped magnetic field leads to the fact that the secondary electrons emitted from the cathode surface due to ion bombardment can be recaptured by the cathode and produce no ionization [1–3]. The probability of the electron returning to the cathode depends on the distribution of the magnetic field lines, the gas pressure, and the location of the electron emission on the cathode surface. For the electrons produced in the region of the maximum ion current density on the cathode the recapturing probability is close to one and they do not participate in ionization. The discharge is maintained by electrons that are emitted far from this region, where the ion current density is usually small. Recapturing can be the reason for the appearance of non-monotonic region on the current-pressure dependences at constant voltage in dc magnetron discharges [4, 5].

For a long time, it was believed that ionization in a magnetron discharge is carried out by the electrons created by secondary emission gaining energy in a thin cathode sheath (of thickness less than 1 mm), which is crossed by electrons without collisions, and where almost whole discharge voltage falls (hundreds of volts). Recently it was shown that the contribution of these high-energy electrons to ionization can be insignificant and the ionization is mostly produced by the electrons originated in the plasma pre-sheath—a region of the order of 1 cm where 10–20% of the discharge voltage drops [6, 7]. The pre-sheath electrons on average gain the energy corresponding to half the pre-sheath voltage and ionize the atoms, producing electrons that also gain energy and participate in ionization. Due to this cascade ionization a smaller number of secondary electrons is required to maintain the discharge.
Figure 1. Scheme of the experiment: 1—copper cathode; 2—ring-shaped grounded anode; 3—movable anode located 65 mm above the cathode; 4—most intensive part of plasma glow; 5—magnetic system; 6—photo camera; 7—interference filter; 8—shading screen.

Various methods are used to determine the ion current density on the cathode. It can be measured at a number of points of the cathode using electrical probes located on its surface [8]. On the entire surface the ion current density can be determined from the sputtering profile of the cathode. The sputtering depth should be too shallow to neglect the discharge changes induced by it. The accuracy also depends to some extent on the fraction of sputtered atoms returning to the cathode due to collision with gas atoms. The most convenient could be the method of determining the ion current density from plasma radiation. The essence of this method is that the volume distribution of the plasma glow correlates with the ionization rate distribution, which determines the ion flux density on the cathode surface. Assuming that the ions move from their birth point to the cathode along a straight line perpendicular to its surface, and neglecting ion losses, the ion current density distribution profile is found by integrating the ionization rate distribution along this line. The correlation between the atom and ion radiation and the cathode sputtering profile was reported in [9, 10], but in [9] the data were obtained only for a small number of points, and in [10] the question of accuracy was not considered. It should be noted that registration of small values of ion current density far from the sputtering maximum is important because, given recapturing effect, the secondary electrons from these regions can contribute the most to ionization. In a typical magnetron discharge with unbalanced magnetic system the plasma glow extends from the cathode to the anode, which leads to the question which part of this radiation correlates with the ion current density distribution and whether it is possible to use the assumption of rectilinear ion motion to the cathode.

The present work is devoted to the problem of determining the sputtering profile (that usually proportional to the ion current density profile) by the plasma emission in an axially symmetric unbalance dc magnetron discharge over a flat cathode.

2. Experiment

The experiments were carried out in a cylindrical vacuum chamber in which a magnetron sputter with a flat copper cathode of 55 mm diameter was located. The discharge maintained at a constant current in argon. The pressure was measured by a diaphragm transducer MKS Baratron 626B. The main elements of the setup are shown in figure 1, the detailed description can be found in [11]. The maximum value of the horizontal component of the magnetic induction on the cathode surface was 77 mT. The discharge glow was registered by a photo camera Canon 350D. To determine the intensity the raw 12-bit sensor data was used without color interpolation. The camera was located at a distance of 65 cm from the center of the discharge. The objective lens aperture was selected so that all parts of the discharge glow were in focus.

The main channels of ion production are ionization by electron impact of argon atoms in the ground state: e + Ar(3p⁶) → Ar⁺(3p⁵) + 2e (projectile electron energy E > 15.8 eV). The contribution of metastable states can be significant at low electron temperatures [12].
The discharge spectra showed that the radiation of exited copper atoms with low excitation energy gives the main contribution to the total emission of the plasma in visible spectrum (510.5, 521.8 and 515.3 nm lines). For this reason, the use of integral emission is not very suitable for estimating the spatial distribution of argon ions. The excited argon atoms, produced by electron impact from the ground state, \( e + \text{Ar} \rightarrow \text{Ar}^* + e \) \((E > 11.5 \text{ eV})\), and the excited argon ions, \( e + \text{Ar}(3p^6) \rightarrow \text{Ar}^+(3p^44p) + 2e \) \((E > 35.5 \text{ eV})\), also contribute to the total emission of the plasma. The emission of \( \text{Ar}^+ \) ions were registered by the ionic line of 487.9 nm using a narrow-band interference filter Thorlabs FL488-1 with a center wavelength of 488 nm and a transmission bandwidth ±0.5 nm. To register the emission of argon atoms, a red filter was used, which in combination with the red pixel filter of the camera sensor passed the radiation in the 650–700 nm band.

The glow intensity distribution of the magnetron discharge is highly inhomogeneous along the discharge gap: the region of the brightest glow is small and located near the cathode, while the regions of weak glow can extend up to the anode. The integral contribution to the ion current density from the regions of weak glow can be significant, especially far from the sputtering maximum. As noted above, the ion current from these regions can play a major role in maintaining the magnetron discharge. The dynamic range of the camera sensor is usually insufficient for simultaneous recording of strong and weak intensity. To solve this problem, an opaque screen was located about 11 cm from the camera lens, covering the lower part of the objective lens. The screen edge was parallel to the cathode surface. The unfocused image of the screen edge resulted in a gradient shading of the image on the camera sensor. The vertical position of the screen and its distance from the lens were selected to provide the necessary decrease of the intensity of the brightest part of the magnetron discharge near cathode surface. This technique allows recording a strong and weak part of the plasma glow simultaneously, greatly expanding the effective dynamic range of the camera. The light attenuation function of the shading screen is the result of a pixel-by-pixel division of two images of a uniformly illuminated white background, located at the center of the discharge region, obtained with and without the shading screen. This function is then used to restore the original intensity of the discharge glow. Since the interference filter diameter of 25.4 mm was much smaller than the diameter of the objective lens, it also introduced a radial shading of the image. Therefore, a light attenuation function was obtained for the filter with the shading screen, which was used to restore the original intensity.

Then the radial intensity distributions were calculated in cylindrical coordinates using the inverse Abel transform. The Fourier method was used which have the advantage of the absence of recurrent calculations procedure leading to accumulation of errors [13, 14].

To obtain the sputtering profile, the cathode was sputtered at constant pressure and current of the discharge. Then half of the cathode was removed and the radial sputtering profile was obtained from the image of the sputtered cathode cross-section.

3. Results and discussion
The copper target was sputtered at 2.4 and 8.9 mTorr in argon at 0.6 A constant current. During the sputtering the discharge voltage was decreased from 520 to 474 V at 2.4 mTorr and from 524 to 470 V at 8.9 mTorr. The corresponding normalized radial sputtering profiles are shown in figure 2.

Figure 3 shows the argon atom and ion emission distribution at 2.4 mTorr. The atom emission distribution has a larger width compared to the ion one, since the electron temperature in the magnetron discharge decreases with height above the cathode [15], and the threshold energy for producing excited atoms (11.5 eV) is much less than one for the excited ions (35 eV).

Assuming that the emission distribution correlates with the ion distribution and that the ions move to the cathode along straight lines perpendicular to its surface, the profile of the ion current
Figure 2. The normalized radial sputtering profiles obtained at 2.4 and 8.9 mTorr.

Figure 3. The argon atom (a) and ion (b) emission distribution at 2.4 mTorr.

density radial distribution on the cathode is found by integrating the emission distribution. The assumption of rectilinear ion trajectories may not hold for ions far from the cathode, where the vertical component of the electric field is near to zero. The comparison of the results of integrating the distributions of figure 3 along the vertical direction from the cathode surface to different heights with the sputtering profile is shown in figure 4. It is seen that the best correlation with the sputtering profile is achieved by integrating the ion emission distribution up to a height of 0.5 cm above the cathode. For the atom the correlation is worse, even the positions of the maxima are different.

The atom and ion emission distributions at 8.9 mTorr are shown in figure 5. A corresponding comparison of the integration results of these distributions in the vertical direction with the sputtering profile is shown in figure 6.

One can see that in the case of high pressure, the radial emission distributions better correlates with the sputtering profile. The distribution maxima do not coincide slightly with the sputtering profile maximum: the maximum of the ions is to the left, and the atoms to the right. The best agreement is achieved when the ion emission distribution is integrated up to a height of 1 cm.

Not very good correlation of the sputtering profile with the emission profiles in the case of low pressures is probably associated with a larger size of plasma glow in the vertical direction. In the case of a magnetron discharge with an unbalanced magnetic system with a stronger outer pole, the radial coordinates of the regions at which the magnetic field lines are parallel to the
Figure 4. Comparison of the radial sputtering profile (sput.) at a pressure of 2.4 mTorr with the radial emission distributions of argon atoms (Ar) and ions (Ar$^+$), obtained by integrating the corresponding distributions of figure 3 in the vertical direction from 0 to various $h$: 0.25 (a), 0.5 (b), 0.75 (c) and 1 cm (d).

Figure 5. The argon atom (a) and ion (b) emission distribution at 8.9 mTorr.

cathode decrease with height above the cathode. The plasma tends to concentrate in these regions. As a result, the radial coordinates of the regions of the greatest plasma concentration decrease with the height. The ions produced in these regions, reaching the cathode, lead to a broadening of the sputtering profile in the region of small radii. However, in this case the ion
Figure 6. Comparison of the radial sputtering profile (sput.) at a pressure of 8.9 mTorr with the radial emission distributions of argon atoms (Ar) and ions (Ar$^+$), obtained by integrating the corresponding distributions of figure 5 in the vertical direction from 0 to various $h$: 0.25 (a), 0.5 (b), 0.75 (c) and 1 cm (d).

Trajectories could be different from the straight lines perpendicular to the cathode. In addition, the inverse Abel transform used to reconstruct the radial distribution has less accuracy in the region of small radii.

4. Conclusion
The problem of determining the sputtering profile by the emission distribution of the argon plasma in an axially symmetric unbalanced dc magnetron discharge investigated. The use of a special shading screen increases the effective dynamic range of the camera, allowing simultaneous registering of the strong light intensity near the cathode and the weak one far from the cathode. Integral emission of the plasma in the case of a discharge over a copper cathode is not suitable for determining the sputtering profile, since the emission of sputtered copper atoms contribute the most to the integral emission. The emission of argon atoms is in good agreement with the sputtering profile at high pressures and diverges noticeably at the low pressures.

Thus, it is shown that the argon ion emission can be used to estimate the sputtering profile (and the ion current profile) in a dc magnetron discharge if the pressure is not low. At low pressures, only the coincidence of the maxima of sputtering and emission profiles can be expected.
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