Effect of interelectrode distance on dc magnetron current–pressure characteristics

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Abstract. The current–pressure ($I$–$P$) non-monotonic characteristic in the magnetron discharge dc in argon at different interelectrode distances was investigated. The ion spatial distribution was obtained with optical emission spectroscopy and the characteristic dimensions of the discharge structure in near cathode region were determined. It is shown that decreasing the distance between electrodes does not affect the shape and position of the nonmonotonic part of $I$–$P$ characteristic until this distance become comparable with the dimensions of the ionization region near cathode. The existence of non-monotonic part of $I$–$P$ characteristic is determined by the processes in the near cathode region and is probably unrelated with the cold electron transfer in the rest of the plasma.

1. Introduction

In dc magnetron discharge under certain conditions, the non-monotonic region is observed on current-to-pressure ($I$–$P$) dependence. The physical reasons of its occurrence are not very clear. In [1, 2] the dc magnetron discharge over a rectangular magnetron with a copper cathode was studied. The non-monotonic region on $I$–$P$ dependence was observed at pressures of about 100 mTorr. The authors [1, 2] relate the existence of the region with non-ionizing inelastic collisions of electrons with atoms in the cathode sheath. We have previously obtained [3, 4] the $I$–$P$ dependencies with non-monotonic region around 3 mTorr in axially symmetric magnetron discharge with a copper cathode. At such low pressures, the secondary electrons pass cathode sheath with no collisions, so hypothesis of [1, 2] in this case is not applicable. In [4] we suppose that the reason of non-monotonic region at low pressures is the effect of secondary electron capture by the cathode [5–7]. This leads to dependence of the number of ionizations produced by secondary electrons on radial coordinate of their emission on the cathode. This hypothesis is able to explain the main features of the observed $I$–$P$ dependencies. But it cannot properly explain the $I$–$P$ curves transformation with discharge voltage or the type of gas changes. This indicates that the reason of the non-monotonic region existence requires to be specified.

In magnetron discharge two regions can be distinguished especially. The first is the near cathode region, where magnetized electrons perform complex movement in the arc-shaped zones. In this region most ionizations occurs and the electron transfer takes place across the magnetic field. The second is the region near the axis of symmetry of the discharge. The main part of the electrons have low energy [8]. It extends from the end of the first region to the anode surface. In
Figure 1. The discharge gap cross-section: 1—the copper cathode; 2—the ring-shaped anode; 3—the movable anode; 4—the ring-shaped plasma glow; and thin black lines are magnetic field lines.

In this region the magnetic field is small and directed mostly vertically, along which the electrons move to anode. In the unbalanced magnetic system this area is sometimes can be seen as slightly luminous column. Transport of energetic electrons in the first region near the cathode across the magnetic field lines can be treated as diffusion process. In case of collisional transport its rate increases with pressure. The magnetic field in the second region, on the contrary, does not affect the movement of electrons, so their drift velocity in this region decreases with pressure. The total discharge current is inversely proportional to the total time of electron motion in both regions. Since the average electron speed in the near cathode region decreases with pressure, and increases in the region near the axis of symmetry, the local maximum appearance on $I$–$P$ curve can be expected if the position of this maximum on the curve is determined by the cold electron transport. In this case the position of the maximum should depend on the distance between anode and the cathode, defining the second region length, and allowing its experimental verification.

The aim of this work is to investigate the influence of cold electron transport on $I$–$P$ characteristics of dc magnetron discharge.

2. Experiment

The experiments were carried out in a cylindrical vacuum chamber. In the middle of the chamber the magnetron sputter with flat copper cathode was placed. The experimental design was similar to that described in [4]. In contrast to [4], the cathode system of smaller diameter was used, and movable grounded anode was placed in front of the cathode. The scheme of the discharge gap is shown in figure 1.

Around the cathode 1, slightly below of its surface the copper grounded flat ring-shaped shield 2 with internal diameter of 60 mm and the outer diameter of 120 mm was mounted. The movable grounded anode 3 with bottom part of 120 mm diameter was placed above the cathode. Under the cathode the type 2 [9] unbalanced axially symmetrical magnetic system was positioned.

The magnetic field lines above the cathode of 56.5 mm diameter are shown in figure 1. The maximum value of the horizontal component of the magnetic induction on the cathode surface was 77 mT. The walls of the vacuum chamber, the anode and the cathode were cooled by flowing water. The pressure was measured with a diaphragm transducer MKS Baratron 626B.
Figure 2. Current–pressure dependencies obtained at constant voltage of 500 V for various interelectrode distances $H$.

The discharge current, voltage and gas pressure values were recorded with 1000 Hz sampling rate with data acquisition module NI USB-6281. The radial distribution of ion glow intensity correlates with sputtering profile of the target [10, 11] making it possible to estimate the radial distribution of ion current density on the cathode surface. The spatial distribution of argon ion glow was registered with monochrome camera Flare 12M180MCX, that took side view images of the discharge. The interference filter Thorlabs FL488-1 (CWL (central wavelength) = 488 nm, FWHM (full width at half maximum) = 1 nm) was mounted in front of the camera lens that passed only the argon ion radiation. The inverse Abel transform [12,13] was applied to the images taken with the camera to obtain the ion distribution in $R$–$Z$ plane of cylindrical coordinates (where $R$ and $Z$ are the radial and vertical axes correspondingly).

The gas flow was being kept constant during the measurements and the pressure was changed by varying the pumping rate. The magnetron sputter power supply worked in the regime of constant voltage maintaining. Measurements were carried out at the voltage of 500 V, at which the $I$–$P$ dependences had a distinguished non-monotonic region. At the beginning of each measurement the desired electrode spacing was set and the discharge was started at high pressures. Next, the pumping rate was being increased and the current and pressure time dependencies were being recorded.

3. Results and discussion
The figure 2 shows the $I$–$P$ curves obtained for various anode-cathode distances. Reduction of the interelectrode distance from 80 to 20 mm results in an increase of the discharge current with no noticeable changes in the $I$–$P$ curve shape. Further shortening the distance leads to a decrease in current, the non-monotonomous part of the curve becomes less pronounced, while
the position of the local maximum is shifted to higher pressures. Let us introduce the following notation for the characteristic points on the $I$–$P$ curve:

- MAX is the point of the local maximum;
- MIN is the point of the local minimum;
- CURRENT is the point to the right of the local minimum, where the discharge current is the same as in MAX.

Figure 3 shows the ion glow distribution in $R$–$Z$ coordinates for these characteristic points. It can be seen that during interelectrode distance decrease down to 21 mm, the ion glow distribution remains almost unchanged. The further interelectrode distance shortening results in reducing the emission region in the vertical and radial directions, with the most dramatic changes in current distribution in MAX. Figure 4 shows the radial and vertical ion glow distributions for two interelectrode distances corresponding to the maximum and minimum of the discharge current. In case of the minimum current the glow distribution narrows in height and radius. The vertical size of the main region of ion emission at 1.5 mTorr pressure is about 1 cm.

The coordinates of the maximum on the radial and vertical emission distribution for MAX, MIN and CURRENT slightly change with the interelectrode distance (figure 5), accompanied by a noticeable change in the current. At the same time, the coordinates corresponding to the different points (MAX, MIN and CURRENT) quite differ among themselves. Thus, the current at point MAX at 81 mm distance is approximately equal to the current at point MIN at 21 mm, at the same time the corresponding coordinates of maximum of emission distributions are notably different.

Thus, significant changes in the shape of $I$–$P$ curves observed for interelectrode distance of 15 mm or less are due to the fact that in this case the interelectrode distance is comparable with vertical dimensions of the plasma structure in the near cathode region, where the most of ionizations occurs. If the interelectrode distance is greater than this value, then its change over a wide range (4 times) leads only to a change in the total discharge current due to the change in the time of cold electron transport from the ionization region to the anode, but not accompanied by a change in the shape of $I$–$P$ curves. The pressures corresponding to the local maximum (MAX) and minimum (MIN) of the current remain unchanged. This indicates that the non-monotonous part of the $I$–$P$ curve is determined by the processes in the near cathode region and does not depend significantly on the cold electron transport in the rest of the plasma.
Figure 4. Integral radial and vertical distributions of ion glow for interelectrode distances $H$ of 21 and 11 mm, corresponding to the maximum and minimum of the discharge current.

Figure 5. The dependence of vertical ($Z$) and radial ($R$) coordinates of the corresponding glow distribution maxima on interelectrode distance $H$ for characteristic points of $I$–$P$ curve: MAX, MIN and CURRENT (see notation in the text).
4. Conclusion
The current–pressure characteristics of dc magnetron discharge, obtained at a constant voltage for different interelectrode distances were studied. It has been established that the presence of non-monotonic region on the current–pressure characteristic is determined by the processes in the near cathode region and does not depend significantly on the electron transport in the rest of the discharge plasma.

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