Current–pressure dependencies of dc magnetron discharge in inert gases

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Abstract. The current–pressure (I–P) characteristics of dc magnetron discharge in inert gases (Ar, Kr and Xe) for various constant discharge voltages were measured. Under certain conditions on I–P characteristic, the nonmonotonic region of local maximum followed by a minimum is observed. It is found that increasing mass of the working gas ions results in a shift of the local maximum to lower pressures. The spatial distribution of ions in the plasma was studied by optical emission spectroscopy. Transformation of the discharge spatial structure with pressure was observed. A qualitative model of the observed trends is presented. It takes into account the pressure dependence of the discharge spatial structure, the capturing of secondary electrons by the cathode and charge exchange effects.

1. Introduction
For dc magnetron discharge over a flat cathode under certain conditions, the intersection of current-voltage characteristics of the discharge for different values of the working gas pressure can be observed. Most clearly this effect of equality both of the discharge current values and of the voltage ones at different pressures appears on the current–pressure (I–P) dependencies, obtained at constant discharge voltages. I–P dependencies for rectangular shape dc magnetron sputter were studied in [1, 2]. At some voltage values the discharge current increasing with pressure reaches a maximum in the region of 90 mTorr, followed by decreasing current with pressure increasing. With further increase in pressure the region of decreasing current can be followed by the region of increasing one. The authors of [1] relate the existence of the negative slope region to the fact that above some discharge pressure value the secondary electrons undergo inelastic non-ionizing collisions before they achieve the energy that is higher than the ionization potential, which decreases the number of ionization they produce and leads to the discharge current decrease. In our previous work [3], I–P dependencies for axial-symmetric magnetron discharge with flat cathode were obtained. The shape of the dependencies was similar to ones observed in [1,2], but the pressure corresponding to the local maximum of the discharge current was considerably smaller—about 2 mTorr. At these pressure values the electron collisionless path length is much greater than the cathode sheath thickness, so non-ionizing inelastic collisions of electrons in this case cannot be the cause of the observed effect.

The arc-shaped magnetic field configuration above the target of planar magnetron sputter leads to inhomogeneity of the spatial distribution of the parameters, both of the plasma and of
the plasma-surface interaction processes. The densest plasma is confined in the toroidal region where the magnetic field is parallel to the cathode. The ion bombardment of the cathode is most intensive just under this region. The secondary electron emitted due to ion bombardment can be captured again by the cathode. The probability of this process significantly affects the number of ionization. This probability is determined to a large extent by the magnetic field configuration in the region of the secondary electron emission [4–6].

In this paper, I–P dependencies in dc magnetron discharge with unbalanced magnetic system in Ar, Kr and Xe gases were studied. Radial distributions of ion emission were obtained for different region of I–P dependencies, which allows to estimate the radial distribution of the ion current density on the cathode surface. The nonmonotonicity of I–P dependence is qualitatively explained by the discharge spatial structure transformation in an arc-shaped magnetic field when the pressure increases and by the effects of capturing the secondary electrons by the cathode and resonant charge exchange of Ar$^+$ ions on Ar atoms.

2. Experiment

The experiments were carried out in the vacuum chamber shown in figure 1. In the middle of the chamber the magnetron sputter equipped with a flat circular copper or aluminum target of 10 cm in diameter and 10 or 8 mm in thickness was mounted. Axially symmetric type 2 [7] unbalanced magnetic system was placed under the target. The maximal value of the radial component of magnetic field on the sputtered surface was 500 G for the thick target and 650 G for the thin one. The magnetron body and the chamber wall were cooled by flowing water. The radial cross-section of the magnetic system and the discharge region are shown schematically in figure 2.

In the beginning of the experiment the discharge was turned on at the gas pressure of 5 mTorr, the power supply was switched to constant voltage mode, and the initial experimental gas pressure and the constant gas flow rate were established in the chamber. In the course of the experiment the pressure was varied by means of exhaust valve control from about 15 mTorr to the lowest possible values. The pressure change rate was about 10 mTorr/min. The pressure was measured by a diaphragm pressure transducer MKS Baratron 626B. The time dependencies of the discharge current, voltage and pressure were recorded continuously with 2.5 kHz sampling rate. The radial distribution of ion glow intensity correlates with radial sputtering profile of the
target \[8, 9\] making it possible to estimate the radial distribution of ion current density on the cathode surface. During the measurements the side view images of the discharge were taken through the Thorlabs FB470-10 bandpass filter (CWL = 470 nm, FWHM = 10 nm). In this case only the emission of ionized plasma species was transmitted through the filter in contrast to the one of neutral atoms. The photo camera sensor data were converted into the image files preserving linearity between pixel values and amount of light collected by corresponding elements of the sensor. Taking into account the axial symmetry of the discharge, the radial distributions of the plasma glow were reconstructed by applying inverse Abel transform to the images. It was done using a Fourier method, one of the benefits of which is the absence of recurrent calculation procedure leading to accumulation of significant errors in axial part of the reconstructed distribution \[10, 11\]. Nevertheless, as the plasma glow intensity in the central region of the discharge is weak, its contribution to the image taken by the camera is much smaller than contributions of the other regions, so the accuracy of reconstructed radial distributions in this region \((r < 0.5 \text{ cm})\) is low. The ion current radial distribution was obtained by integration over the height of the radial distribution of the ion glow.

3. Results

The I–P dependencies for discharges in argon, krypton and xenon over the copper target of 10 mm thickness are shown in figure 3.

At low discharge voltages, I–P dependence is monotonic. The increase in voltage leads to an increase in the discharge current and to the appearance of non-monotonic region. With further increase in discharge voltage the non-monotonic region becomes more pronounced: the ratio of local maximum discharge current to local minimum one increases. Changing the working gas to a heavier one leads to a shift of the local maximum and minimum to the lower pressures.

Figure 3. I–P dependencies for various constant discharge voltages of dc magnetron discharge over 10 mm thickness copper target in argon, krypton and xenon gases.
Figure 4. The I–P dependence for the discharge in argon over 8 mm thickness aluminum target (top left plot), and the radial distribution of ion current density (bottom left plot) corresponding to different regions of I–P curve: low-pressure region, local maximum and local minimum regions, high pressure region. The right side shows the corresponding ion emission radial distributions.

Ion current distributions over the target surface are distinctly different for the different regions of I–P dependence. I–P dependence for the aluminum target of 8 mm thickness and the corresponding radial distributions of ion current density are shown in figure 4. The distribution width decreases with pressure and the radial coordinate of the current density maximum shifts toward larger values. The essential difference of the ion current density distribution corresponding to the discharge current local minimum from the one corresponding to the local maximum is the significantly lower current density in the central region.

4. Discussion

The current growth observed on the I–P dependences is mainly due to increase of ionizing collision frequency with pressure. In some cases, there is a region on I–P curve where discharge current decreases with pressure. This is accompanied by a characteristic transformation of the discharge spacial structure (see figure 4 right).

4.1. Transformation of the discharge spacial structure

The scheme of the discharge structure at the low and high pressures is shown in figure 5. As the discharge current increases the thickness of the sheath decreases (in accordance with the Child–Langmuir law), the region of the maximum plasma density (plasma region) become closer to the cathode. At the same time the plasma region also shifts toward a larger radius. The
Figure 5. Scheme of the discharge special structure: (a) at low pressures (below 1.5 mTorr of argon); (b) at high pressure (more than 3.5 mTorr of argon). The area of the plasma is shown in blue color. The black lines show the magnetic field lines. The red dashed line shows the region where the magnetic field lines are parallel to the cathode surface. At the bottom the corresponding radial dependencies both of the flux density of the electrons emitted from the cathode (blue curves) and of the probability that the emitted electron will be recaptured by the cathode (red curves) are schematically shown.

latter is the consequence of the fact that, due to the magnetic system unbalance, the radial coordinate of the maximum plasma density region, where the magnetic field lines are parallel to the cathode surface, varies with the distance to the cathode surface: for small distance the plasma region radial coordinate is greater, than for the large one (compare figures 5a and 5b). That is the reason of the plasma region shifting toward the larger radii when is becoming closer to the cathode. In this case the volume occupied by the plasma is also reduced due to the fact that volume of the magnetic trap decreases with decreasing the distance. This makes it possible to maintain a high local current density at the cathode, even when the total discharge current decreases.

4.2. The mechanism of the discharge current decrease with pressure
The described discharge structure transformation result in the discharge current decrease in the following way (see also figure 5). At low pressures the plasma is confined closer to the discharge axis of symmetry than in case of high pressures. The ion current from the plasma on the cathode gives rise to the secondary electrons. The number of ionizations produced by secondary electrons in the magnetron discharge depends on the radial coordinate of the place on the cathode where they were emitted [4–6]. The configuration of the magnetic field over the target of planar magnetron sputter is such that the electrons generated on the area of the cathode where the magnetic field lines are parallel to the cathode surface with high probability will be recaptured by the cathode, producing no ionization [4–6]. On the contrary, the specific contribution to the ionization from electrons generated in the adjacent areas is much higher. The trajectories of electrons emitted from the cathode in this region have a greater length than the ones of the electrons emitted closer to the region where the magnetic field is parallel to the surface. Therefore, the recapture probability for them is lower. At low pressure, these electrons make the largest contribution to the ionization [4, 5]. It should be noted that the recapturing probability decreases with pressure [5].
At low pressures (the part of I–P curve before the local maximum) the ions traveling the shortest path from the plasma region to the cathode get to the area of the cathode located not so far from the axis of symmetry. This area emits electrons with low probability to be recaptured by the cathode. At higher pressures, after the transformation of the discharge structure, the situation is changed. The plasma is closer to the cathode and shifted toward the larger radii. The ions bombard the cathode surface near the area where the magnetic field is parallel to the cathode. The recapturing probability for the electrons emitted at this area is maximal. In this case, the secondary electrons produce less ionizations resulting in the total discharge current decrease.

4.3. I–P curves in various noble gases. Charge exchange effects

The ionization cross-section increases and ionization potential decreases in the transition from argon to krypton and xenon. This contributes to the fact that the local maximum in heavier gases are observed at lower pressures (figure 3). In addition to the mechanism of discharge current decrease described above the resonant charge exchange collisions can effect on the I–P characteristic. Ions born over the cathode during the movement to the cathode may undergo collisions, the probability of which increases with pressure. Collisions reduce flux and energy of ions bombarding the cathode, resulting in a decrease in the number of secondary electrons, and reduce a discharge current.

At low pressures, a significant part of ions is born at high distance over the cathode surface up to 0.5–1 cm, as confirmed by the observed ion emission distributions (figure 4) and by the calculation results [6]. The variable thickness of the cathode sheath (minimal over the area of maximum sputtering and maximal over the center of the cathode) results in the existence of the radial component of the electric field. The ions originated in these regions during their travel to the cathode may undergo substantial radial displacement toward the axis of symmetry. In this case the travel path to the cathode is increased as compared with a strictly vertical movement toward the cathode and can reach about 2 cm.

Let us estimate the pressure that is sufficient for collisional processes to become significant, particularly, resonant charge exchange of argon ions on argon atoms. The mean free path of argon ions of 2 cm at typical for our conditions cross-section values (see table 1) is achieved at pressures around 5 mTorr. This means that the charge exchange process will significantly reduce the flow of ions to the central region of the cathode at the pressure that is higher than 1–2 mTorr (figure 4). At lower pressures where the resonant charge exchange is insignificant there is a more rapid increase in current with pressure. For higher pressures (> 3.5 mTorr) the primary ionization region (glowing region in figure 4) becomes closer to the cathode. For ions, originated in this region (on a distance of about a millimeter from the cathode), the charge exchange collisions become unimportant.

The charge exchange collision cross sections increase when argon is replaced by a heavier gas (table 1). This factor leads to the shift of the discharge current local maximum to the lower pressures in heavy gases (figure 3), the corresponding pressures is inversely proportional to the charge exchange collision cross section. The lower value of the discharge current at the same voltage for the heavier gas comparing to the lighter one can be related with a decreasing of the drift velocity of electrons in the heavier gases, which leads to decrease of the equilibrium level of the discharge current. The decrease of discharge current can also be due to the consequent reduction of the secondary ion-electron emission coefficient in the transition from argon to krypton and xenon [12].
| Ion energy, eV | Ar<sup>+</sup> + Ar | Kr<sup>+</sup> + Kr | Xe<sup>+</sup> + Xe |
|--------------|-------------------|------------------|-------------------|
| 100          | 31.10             | 36.39            | 52.31             |
| 300          | 26.35             | 31.42            | 45.81             |
| 500          | 24.27             | 29.23            | 42.94             |

5. Conclusions
In the work, I–P dependencies of axially symmetric dc magnetron discharge over the flat cathode in argon, krypton and xenon were studied. If the discharge voltage is not too low, there is a region on I–P curve where discharge current decreases with pressure. These changes in discharge current correlate with the characteristic changes in the plasma ion distribution. Estimations show that the physical causes of the observed phenomenon are related to the transformation of the discharge structure in the arc-shaped magnetic field with increasing pressure and to the effects of resonant charge exchange collision of ions.

Acknowledgments
The work was supported by the Russian Foundation for Basic Research (grant No. 15-02-06873).

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Table 1. Resonance charge exchange cross sections in units 10<sup>−16</sup> cm<sup>2</sup> calculated according to [13].