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Current–pressure characteristics of dc magnetron discharge for high-rate sputtering

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Abstract. The current–pressure (I–P) characteristics of axially symmetric dc discharge of planar magnetron sputter were studied. The characteristics in argon and krypton gases for copper and aluminum cathodes and the spatial distributions of the plasma glow at different pressures are obtained. The sequence of local maximum and minimum is observed on current-pressure characteristics under defined conditions. The necessity of taking into account the gas heating by sputtered atoms for explaining the observed features of I–P characteristics is shown. Numerical simulation has allowed explaining the observed significant difference between the values of the discharge current density in argon and krypton.

1. Introduction

Magnetron sputtering is commonly used for coating. The magnetic field near the sputtered cathode-target increases the residence time of the secondary electrons near the cathode by hundreds of times, this effect leads to significant increase of ionization rate in this region and to increase of the sputtering ion current density. The physical picture of the magnetron discharge is quite complex due to the complex configuration of the magnetic field, making the problem non-one-dimensional.

In some cases, intersection of magnetron discharge current-voltage (I–V) characteristics obtained at different gas pressures is observed. Most clearly nonmonotonic dependence of the discharge parameters on gas pressure appears on the current-pressure (I–P) curves measured at a constant voltage. Until now, such characteristics were obtained experimentally in few studies [1, 2] where region of relatively low discharge currents and high gas pressures was investigated. Under certain conditions nonmonotonic I–P dependences are observed. This means in particular that the same current and voltage values can be achieved at two or three different pressure values and corresponding to these pressures I–V characteristics intersect at these values of current and voltage. The presence of mentioned nonmonotonicity depends on the type of the working gas, the discharge voltage, the magnetic field value in the discharge region and the geometric dimensions of the discharge gap. In [1, 2] the observed I–P curves are well approximated by obtained analytic curves, but the physical processes behind them are not entirely clear.

In this work we studied the I–P characteristics in the axially symmetric discharge of the planar magnetron sputter that is convenient for numerical simulations.

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2. Experiment

The experiments were performed in a vacuum chamber with a diameter of 40 cm and a height of 40 cm (figure 1). In the middle of the chamber, the magnetron sputter with a flat circular target of 10 cm diameter was mounted. The magnetic system under the target created axially symmetric magnetic field over the target surface. External pole of the magnetic system was stronger than the central one (magnetic system was of unbalanced type 2 [3]). The discharge was sustained between the target (cathode) and the grounded walls of the chamber. There was a grounded shield around the body of the magnetron, which prevents the occurrence of the discharge around the side surface of the magnetron. The walls both of the chamber and of the magnetron sputter were cooled by running water. Measurements of I–P characteristics were carried out at constant discharge voltages. During the obtaining each of I–P characteristics the discharge voltage was being kept constant by the power supply, the gas pressure was being varied continuously via the gas flow controller or the valve of the pump. The pressure was measured with the diaphragm sensor (Baratron 626A).

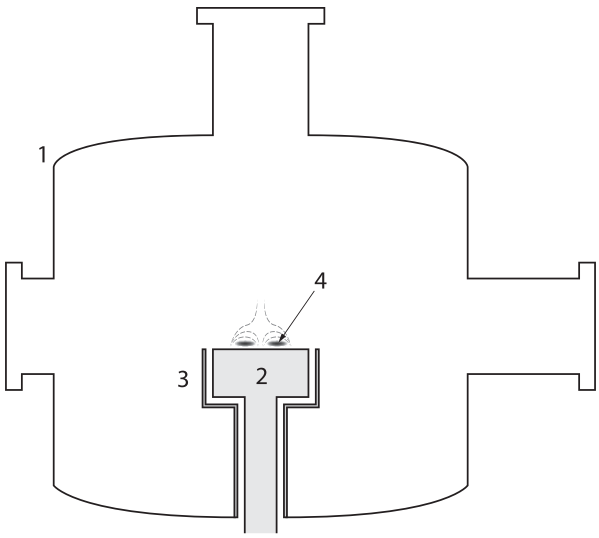

Figure 1. The experimental setup: 1 is the vacuum chamber, 2 is the magnetron sputter, 3 is the grounded shield, 4 is the plasma glow. Thin dashed lines show schematically magnetic field lines in the plasma region.

The magnetron plasma glow intensity distribution over the cathode surface, registered from the direction perpendicular to the cathode, repeats the distribution of the ion current density [4], therefore study of the plasma glow distributions provides important information about the discharge. Plasma glow pictures (top and side views) were recorded with the digital camera. Discharge parameters and the moments of taking photos were continuously recorded during the experiment using oscilloscope.

3. Simulations

Estimations of gas heating were carried out in hydrodynamic approximation, given the fact that the main contribution to the heating of the gas is the energy transfer in collisions of sputtered atoms with gas atoms [5]. It was assumed that the sputtered atoms leaving the cathode had the same energy that is equal to the average one (calculated according to [6]) and moved along a vertical axis, transferring energy to the gas in head-on collisions. The simulation geometry and temperature of the surfaces corresponded to ones inherent in the experiment. The linear dependence of the ion current on the pressure, approximately corresponding to the measurement data, was used.

A Monte Carlo (MC) model was developed for calculating the trajectories of electrons in crossed electric and magnetic fields (E×B) taking into account elastic and inelastic collisions of electrons with buffer gas atoms.

4. Results and discussions

Some typical I–P characteristics of the discharges in argon and krypton for copper and aluminum cathodes at constant discharge voltages are shown in figure 2.

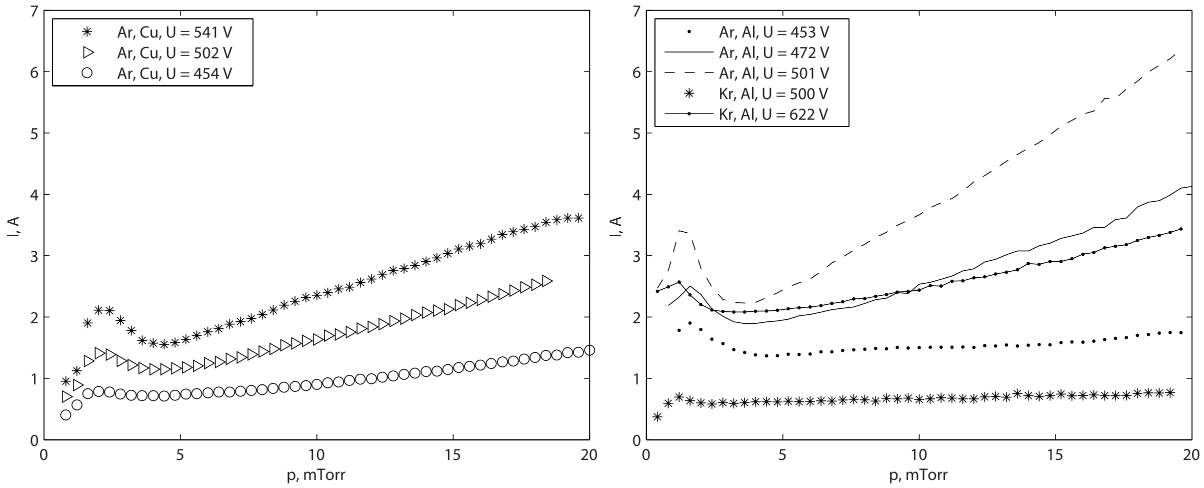

Figure 2. Current-pressure characteristics at constant voltage of magnetron discharge: in argon over the copper cathode of 10 mm thickness (left, maximal radial magnetic induction value B at cathode surface is 600 G), and in argon and krypton over the aluminum cathode of 8 mm thickness (right, B = 750 G).

The dependence of the current density on the gas pressure for the discharge over copper cathode in argon is shown in figure 3. Note that in this case the current density is higher by an order of magnitude than those of [1, 2]. Figure 4 shows the pressure dependence of the distance between the plasma glow maximum and the surface of the copper cathode in argon.

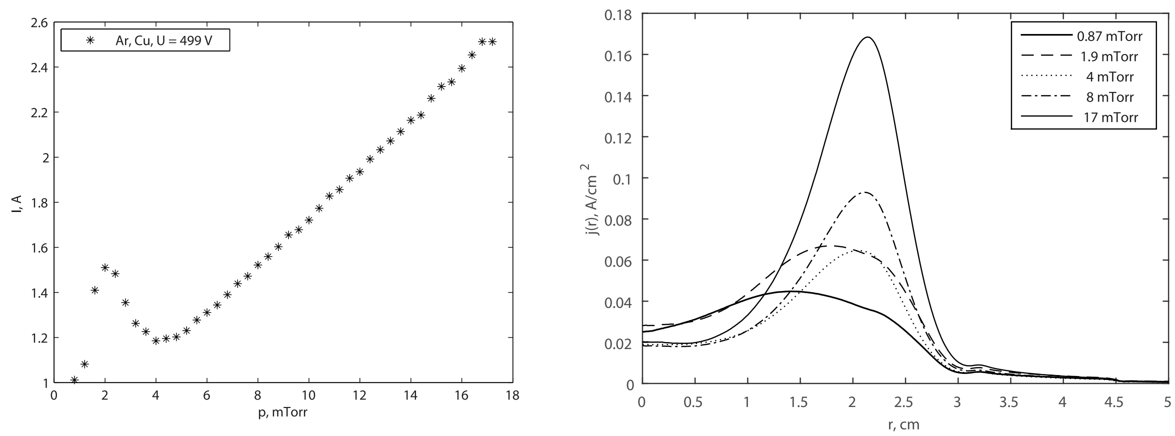

Figure 3. Current-pressure characteristic at a constant discharge voltage of 499 V over 10 mm copper cathode in argon (left) and corresponding radial distribution of the current density $j(r)$ at various pressures (right). Radial magnetic field maximum value is 600 G.

There are three typical stages of the current density distribution changes with a change in pressure (see figure 3): (1) in the range of 0.87–2 mTorr a rapid increase of the current density

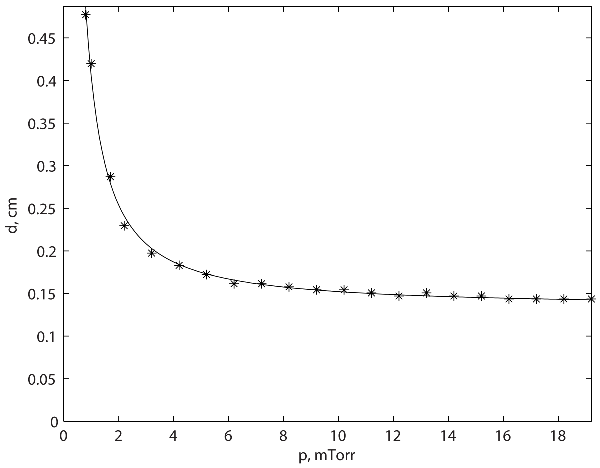

Figure 4. The experimental pressure dependence of the distance between the plasma glow maximum and the surface of the copper cathode in argon.

at the ring-shaped area of maximal sputtering rate is occurred, current density at the central part of the cathode remains unchanged, the local maximum of the I–P curve is achieved. (2) In the range of 2–4 mTorr both the current density at the central part of the discharge and one at the ring-shaped area of maximal sputtering rate decrease, which provides the local minimum of the I–P curve at pressure of 4 mTorr. (3) Above 4 mTorr there is a monotonic current density increase with pressure rise in the ring-shaped area of maximal sputtering rate. The radius of the ring-shaped area of maximal sputtering rate (and of the plasma glow) increases with increasing pressure. Simultaneously, the thickness of the cathode sheath decreases.

Growth of the gas density at the first stage leads to an increase in the number of ionization acts near the electrode and to the current growth observed in the experiment.

2D simulation of the gas heating by sputtered atoms shows a significant increase in gas temperature with increase of pressure and simultaneous shift of the gas temperature maximum to the electrode surface (figure 5, right). The gas heating leads to a slowdown in the growth of the gas concentration above the electrode with increase of pressure and leads to the appearance of the vertical component of the concentration gradient.

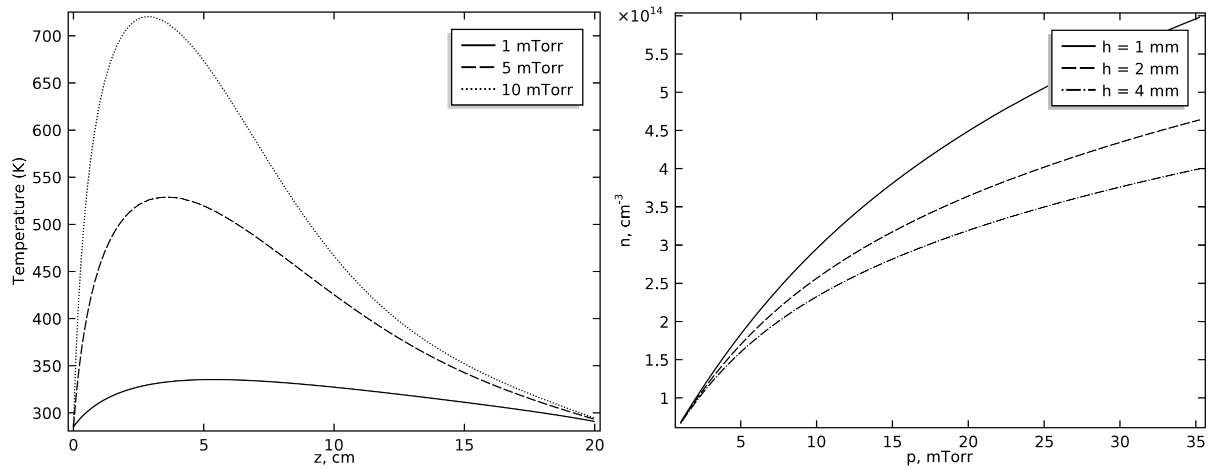

Figure 5. Calculated for various pressures the argon gas temperature distributions along the vertical axis z over the cathode area of maximum sputtering (left) and dependences of gas concentration on pressure at various height (right).

At pressure of 0.9 mTorr the mean free path of copper atoms is 7 cm which is comparable to the diameter of the magnetron sputter target (10 cm). For such low pressures the hydrodynamic approximation of the model lead to overestimated values of local temperature near the electrode. Hot gas atoms may be more uniformly distributed throughout the volume of the chamber at low pressures, than predicted by the model. In addition, the function of gas heating due to head-on collisions gives overestimated value of the energy transferred at low pressures (the first high-energy collisions of atoms create fast atoms that do not contribute to the heating of the gas [8]).

Therefore, it can be assumed that, at the low pressure, the gas heating is minor. When we adjusted intentionally in the calculation the gas heating function by equating it to zero at low pressures, the dependence of gas concentration on pressure near to the electrode surface shows local maxima and minima. The existence of such type dependence could explain the observed I–P characteristics. Test of this hypothesis requires a numerical simulation that correctly described the process of gas heating by sputtered atoms at low pressures.

Observed in the second stage change of the current density may be partially associated with the heating of the gas and the corresponding decrease of its concentration in the ionization region. The decrease of the ion current to the central part of the cathode leads to decrease of the amount of electrons emitted by this area. According to [7] the electrons emitted from the sputter track periphery contribute substantially to the ionization. So observed redistribution of the current may lead to the decrease of the total discharge current.

It can be seen from figure 2 that the same value of the discharge current is achieved in krypton at a significantly higher voltage U_{Kr} = 622 V than in argon U_{Ar} = 472 V. The reasons for this are not clear: the electron impact ionization cross section of argon atom in the energy range of 50–500 eV is 20–30 % lower than of krypton one. Calculations of the ionization coefficients were carried out in Monte Carlo model for these conditions.

Figure 6 shows the distribution of ionization coefficients and temperature of 'hot' electrons ejected from the cathode as a result of ion-electron emission and moving in crossed E×B fields on the cycloid with multiple acceleration-deceleration in the cathode sheath. As a result of collisions with atoms, electrons deviate from the cathode at a distance up to 6–7 mm forming a characteristic falling ionization profile. Similar dependences were obtained for the densities of excited atoms with a broad maximum in the range of the Larmor radius $r_L \sim 1$ mm (for electrons with an energy of 500 eV), which agrees with the magnetron plasma glow height over the cathode (figure 4).

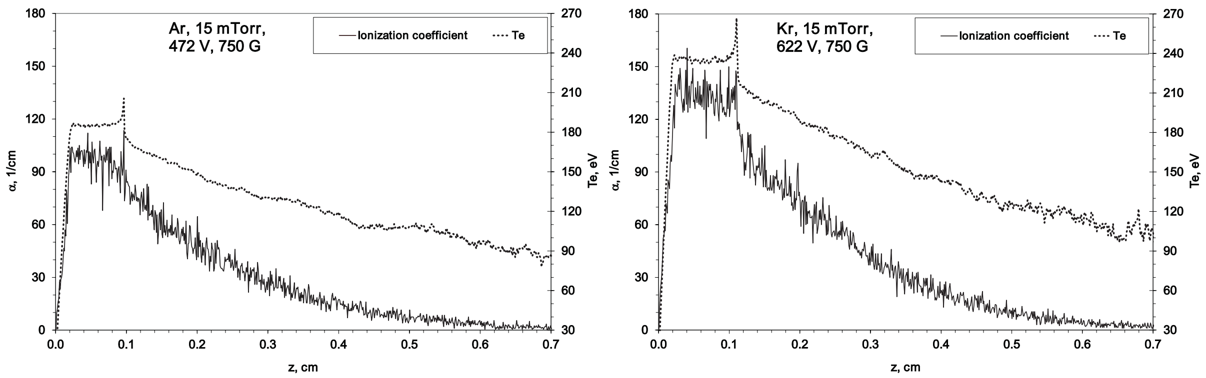

Figure 6. Results of Monte Carlo calculation of ionization coefficient profile and the temperature of 'hot' electrons inside and over the cathode sheath of the magnetron discharge in argon (left) and krypton (right), 15 mTorr pressure, magnetic field B = 750 G.

The total number of ionizations per emitted electron (without electron recapture at the cathode) was obtained $b_{Ar} \sim 29$ for argon and $b_{Kr} \sim 50$ for krypton from which a lower limit of the secondary emission coefficient can be estimated: $\gamma_{Ar} \sim 1/b_{Ar} = 0.034$ and $\gamma_{Kr} \sim 1/b_{Kr} = 0.02$. The theoretical estimations of these coefficients by the formula from [9]: $\gamma = 0.016\times(I_{ioniz} - 2\phi)$ gives $\gamma_{Ar} = 0.12$ and $\gamma_{Kr} = 0.09$ for aluminum cathode with work function of 4.08 eV and the ionization potentials $I_{ioniz}(\mathrm{Ar}) = 15.76$ eV and $I_{ioniz}(\mathrm{Kr}) = 14$ eV.

The calculated values of b_i (i = Ar, Kr) were obtained for magnetic field parallel to the flat cathode surface and with cycloid electrons trajectories attaching the cathode surface without any electrons recapture. In addition, we have probed various recapture probabilities $\gamma_{rec} > 0$ and revealed that any non-zero γ_{rec} (e.g. γ_{rec} = 0.1–0.5) leads to sharp dependence of b_i on gas pressure p ($b_i \sim$ p) and thus unreasonably high variability of SE coefficients $\gamma_i \sim 1/\mathrm{p}$. In real magnetron discharge conditions, magnetic field B is not ideally parallel to the cathode surface.

Under steady-state conditions in Ar and Kr gases for approximately the same losses and discharge currents $I = I_{Ar}(1+\gamma_{Ar}) \approx I_{Kr}(1+\gamma_{Kr})$ the relation must satisfy $\gamma_{Kr}(1+\gamma_{Ar})/(\gamma_{Ar}(1+\gamma_{Kr})) \approx b_{Ar}/b_{Kr} = 0.6$, which qualitatively does not contradict the ratio: $\gamma_{Kr}(1+\gamma_{Ar})/(\gamma_{Ar}(1+\gamma_{Kr})) = 0.77$ according to the above theoretical estimation $\gamma_{Ar} = 0.12$ and $\gamma_{Kr} = 0.09$. It is worth noting that the notable contribution (tens of percent) to the ion-electron emission will be made by doubly ionized atoms when their fraction is about 5 % with respect to singly ionized ones in these inert gases.

5. Conclusions

The I–P characteristics and current density distribution in a magnetron discharge in argon and krypton over aluminum and copper cathodes were obtained. The dependences show local maximum in the region of 1–2 mTorr followed by local minimum at 4 mTorr, that may be related with SE recapture and gas heating. It is shown that there is a significant gas heating in magnetron discharge under our experimental conditions. The maximal value of the gas temperature and its spatial distribution depend on the pressure in the chamber. The gas density decrease due to the heating and presence of secondary electrons recapture may qualitatively explain the features of the I–P characteristics. A self-consistent two-dimensional magnetron plasma model is required to understand better the causes of non-monotony of the I–P characteristics. The performed numerical MC simulations allow explaining the observed significant difference between the values of the discharge current density in argon and krypton.

Acknowledgments

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