Discharge parameters of a magnetron with a molybdenum target

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Abstract. In this work, we study the features of the discharge of a magnetron with a cold molybdenum target in an argon environment using a Langmuir probe. The novelty of this work is due to the placement of the probe near the anode. I-V characteristics of the probe were measured in the range of discharge current densities of 27–96 mA/cm² at argon pressures of 2–4 mTorr. The experimental I-V characteristics of the probe were used to calculate the electron temperature, ion and electron density. It was found that the density of charge carriers increases and the electron temperature decreases with an increase in the discharge current. In addition, it was found that the density of ions near the anode is almost an order of magnitude lower than the density of electrons, and the electron temperature weakly depends on the argon pressure.

The development of alternative energy has led to the emergence of new types of solar cells. Elements based on the Cu (In, Ga) Se2 compound are considered to be one of the most promising. A molybdenum (Mo) film is used as the back electrode in such devices based on a rigid or flexible substrate [1, 2]. It exhibits good chemical stability at high substrate temperatures during the process and low contact resistance. High adhesion and conductivity at the same time are usually difficult to achieve in a single Mo layer. Therefore, multilayer molybdenum coatings are usually made.

Like other refractory metals, Mo films are deposited by sputtering methods [3–5] such as RF magnetron sputtering, high-pulse magnetron sputtering, DC magnetron sputtering, etc.

Many authors have established a relationship between the properties of the deposited films and the discharge parameters (density of charge carriers, electron temperature, etc.) [6], which were measured using a single Langmuir probe [7, 8].

In this work, the task was to find out how the main parameters of a gas discharge during sputtering of a molybdenum target at a constant current depend on the pressure and density of the discharge current. The study of these dependences is required for the development of a method for the deposition of thin films of metals and their compounds. This problem was solved by other authors for regions near the target and in the positive column [9]. Therefore, in this work, attention was paid to the parameters of the discharge near the anode.

The experiments were carried out on a balanced magnetron with a diameter of 130 mm equipped with a 2 mm thick cold molybdenum target cooled by running water. The probe is made of tungsten wire with a diameter of 0.5 mm, placed in a set of ceramic cylinders. The probe height was 7 mm. The probe was located at a distance of 5 mm from the anode.

The study of the parameters of the gas discharge was carried out at a constant current in an argon atmosphere at a partial pressure of (2–4) mTorr. The discharge current density was varied in the range (27–96) mA/cm².
Figure 1, a shows the I-V characteristics of a gas discharge at pressures of (2–4) mTorr. As it can be seen from figure 1, a with an increase in argon pressure and a fixed value of the discharge current density the voltage across the discharge decreases. This is due to the fact that with increasing pressure the ionization cross-sectional area of Ar atoms, and hence the probability of collisions between particles, increases. With an increase in argon pressure and a fixed value of the current density, the voltage decreases by 10-12 V.

Figure 1. I-V characteristics of a gas discharge (a) at working gas pressures (mTorr): 1 – 2.0; 2 – 3.0; 3 – 4.0 and I-V characteristics of the probe (b) at a working gas pressure of 4.0 mTorr at a discharge current density of (mA/cm$^2$): 1 – 27.3; 2 – 54.7; 3 – 82.2; 4 – 95.9.

Figure 1, b shows the I-V characteristic of the probe at a fixed argon pressure of 4.0 mTorr and discharge currents (27–96) mA/cm$^2$. It can be seen from figure 1, b that at a fixed pressure and an increase in the discharge current the current supplied to the probe increases. An increase in the discharge current leads to an increase in the flux of particles from the ionized gaseous environment to the probe. All the required parameters were calculated for different parts of the I-V characteristic of the probe using the standard technique [10]. In figure 2, the electron density is an order of magnitude higher than the ion density.

Figure 2. Dependencies of the density of ions (a) and electrons (b) on the current density at pressure (mTorr): 1 – 2.0; 2 – 3.0; 3 – 4.0.

This is a quite expected result, which was observed in cathode tubes and was obtained when simulating a glow discharge [11]. In figure 2 as for all subsequent dependences, an approximation in the form of first-order polynomials was used. Such a simplified approach was applied only for the reason that it was necessary to show the main trend. The authors did not aim to model the observed features of the discharge.
Figure 3. Dependencies of the electron temperature on the current density (a) at a working gas pressure of 2.0 mTorr and on the working gas pressure (b) at a discharge current of 54.7 mA/cm$^2$.

Figure 3, a shows a characteristic change in the electron temperature depending on the current density. The effect of argon pressure on this discharge parameter is demonstrated in figure 3, b. The highest electron temperature recorded at an argon pressure of 2.0 mTorr was approximately 4.2 eV. This temperature is about twice the temperature of cold electrons usually observed. But it is about 30% less than the temperature of hot electrons [12, 13]. This effect can be attributed to the peculiarity of molybdenum. With an increase in the discharge current, the flux of the sputtered metal increases significantly. This can lead to a redistribution of the components of the ionic current in the discharge in favor of molybdenum ions. Taking into account the difference in the ionization potentials of molybdenum (7.1 eV) and argon (15.8 eV) atoms, it can be assumed that with an increase in the fraction of molybdenum in the environment, the total energy consumption for ionization decreases. Therefore, electrons in the region of intense ionization are not completely cooled and while remaining relatively hot drift toward the anode in a weak field of the positive column.

Figure 4. Change in the density of ions (a) and electrons (b) from the pressure of the working gas at a fixed value of the discharge current of 54.7 mA/cm$^2$.

Figure 3, b shows that with an increase in argon pressure the electron temperature decreases insignificantly. Observations by other authors in a wider pressure range showed a more significant decrease in the electron temperature [14]. The result is more than obvious. In the region of the anode, the features of the processes occurring in the region of the cathode appear. An increase in the density of particles in a gas leads to an increased energy consumption for ionization, which lowers the electron temperature. It has been shown in many works that the electron temperature decreases exponentially from about 6 to 1 eV in wider ranges of the discharge current and argon pressure [15–17]. This has been shown most convincingly for the sputtering of hot targets made of different metals [18].
Figure 4 demonstrates another effect that occurs when the argon pressure changes. It is associated with a change in the density of charged particles in a gaseous medium, which increases with increasing pressure. However, as in Figure 2 and in this case, the density of electrons and ions differ by an order of magnitude. As noted earlier, this is due to the fact that with increasing pressure the cross-sectional area of ionization of Ar atoms and hence the probability of ionization increase giving rise to a higher density of ions and electrons.

As a summary, we state that the main parameters of the discharge of a magnetron with a cold molybdenum target were studied using a Langmuir probe in this work. The probe was placed at a distance of 5 mm from the anode. It was found that the main feature of this discharge is the increased electron temperature. In addition, attention should be paid to the significant difference between the densities of electrons and ions, which is characteristic of the anode region.

References
[1] Zhou D, Zhu H, Liang X et al. 2016 Appl. Sur. Sci. 362 202–9
[2] Rashid H, Rahman K S, Hossain M I et al. 2019 Results in Phys. 14 102515
[3] Pustovalova A, Boytsova E, Aubakirova D et al. 2020 Appl. Sur. Sci. 534 147572
[4] Komlev A E, Shapovalov V I and Shutova N S 2012 Techn. Phys. 57 1030–3
[5] Shestakov D S, Shapovalov V I, Rudakov A V et al. 2021 J. Phys.: Confer. Ser. 1799 012031
[6] Salo S A, Abdallah B, Akel M et al. 2020 Optoelectr. Lett. 16 369–72
[7] Gudmundsson J T 2020 Plasma Sources Sci. Technol. 29 113001
[8] Ryan P J, Bradley J W and Bowden M D 2019 Phys. Plasmas 26 073515
[9] Haase F, Lundin D, Bornholdt S et al. 2015 Contrib. Plasma Phys. 55 701–13
[10] Singh A K, Kumari N and BarhaiIntern P K 2013 Intern. J. Engin. Res. Technol. 2 2284–93
[11] Saikia P, Kakati B and Saikia B K 2013 Plasmas Phys. 20 701–13
[12] Sigurjonsson P and Gudmundsson J T 2008 J. Phys.: Conf. Ser. 100 062018
[13] Dhawan R, Kumar M and Malik H K 2020 Phys. Plasmas. 27 063515
[14] Zhu X-M and Pu Y-K 2008 Plasma Sources Sci. Technol. 17 024002
[15] Saikia P and Kakati B 2008 J. Vac. Sci. Technol. A: Vac., Sur. Films 31 061307
[16] Sigurjonsson P and Gudmundsson J T 2008 J. Phys.: Confer. Ser. 100 062018
[17] Schmidt S, Hänninen T, Goyenola C et al. 2016 ACS Appl. Mater. Interfac. 8 20385–95
[18] Kaziev A V, Tumarkin A V, Leonova K A et al. 2018 Vacuum 156 48–54