Study of plasma dynamics in a pulsed hollow cathode magnetron

N P Poluektov, Yu P Tsar’gorodsev, I I Usatov, A G Evstigneev, E P Kozlovskaya and O O Amel’kin

Department of Higher Mathematics and Physics, Mytishchi branch of Bauman Moscow State Technical University (MB BMSTU), 141005, Moscow Region, Russia

E-mail: poluekt@mgul.ac.ru, tsargor@yandex.ru

Abstract. Study of the hollow cathode magnetron (HCM) discharge, which is supplied by a source of powerful current pulses, was carried out. By means of probe and spectral measurements, the dynamics of a pulsed discharge was studied. The results show that a high density plasma ($n_e > 10^{12} \text{ cm}^{-3}$) is generated at a distance of 20 cm from the HCM. Based on the data obtained, a mechanism for the formation and development of a discharge was proposed.

1. Introduction

Ionized physical vapor deposition (iPVD) is a class of PVD technique in which > 50 % of the deposition flux may be ionized. High impulse magnetron sputtering (HiPIMS) is a type of iPVD technique where shot high-peak-power (up to 5 kW/cm$^2$) pulses are applied to the magnetron target at low duty cycles (0.5–10 %). This results in plasma electron densities $n_e$ as high as $10^{13} \text{ cm}^{-3}$ above the planar target surface during the short high-power impulse [1–10]. These high electron densities near the target enhance ionization of sputtering materials. The increased ionization improves the film quality, such as density, adhesion, surface roughness, the possibility of conformal films deposition on relief surfaces.

In the physics department laboratory of the MB BMSTU was created the source of high-density plasma, based on the hollow cathode magnetron (HCM). The HCM is increasingly used to deposit diffusion barriers and copper seed layer materials onto high-aspect ratio vias and trenches for microelectronics fabrication [11–13]. In the HCM, due to cup-shaped target geometry, the electrons are as electrically and magnetically confined within the volume of the source and losses are minimized. As a result, the high density plasma ($> 10^{11} \text{ cm}^{-3}$) is created at a distance of 20 cm from the HCM, supplied by DC source with a power of 2.2 kW [14]. Ionization fraction of the copper flux was 25 % under these conditions [15]. The purpose of this work is to study plasma parameters, when the HCM is operating in high power impulse mode, to increase the ionization fraction.

2. Experimental apparatus

The experimental setup of the magnetron discharge with a hollow cathode is shown in figure 1 [14]. The cathode consists of a cup-shaped Cu target (diameter 0.14 m, length 0.11 m) made of copper and cooled with water. The HCM is powered with home-made a high power pulse supply capable of delivering 900 V and 150 A peak values. In this work, we used discharge with pulse duration of 150–300 µs and a repetition frequency of 100 Hz, the duty cycle was equal to 1.5–3 %. The pre-
ionization system with direct current 5–25 mA and voltage up to 2 kV was used to improve discharge repeatability. The chamber was pumped to base pressure 5·10⁻⁷ Torr using a turbomolecular pump. The copper target was sputtered using argon gas with pressure 1.3 Pa. Gas flow (25 sccm) is provided by a gas flow controller. The magnetic field is produced by eighteen columns of Nd-Fe-B magnets surrounded the target with ring iron flanges on the edges. An electromagnet is installed downstream of the HCM at a distance of several centimeters to expand the plasma flow and create a more uniform radial distribution. Its magnetic field is opposite in polarity to a magnetic field produced by permanent magnets. From the source, the plasma enters the reactor with a diameter of 30 cm and a length of 45 cm. The anode of discharge is a copper ring positioned in the reactor and insulated from it. In the experiments described below, a voltage U₀ of +30 V was applied to the ring anode from additional source. An insulated cylindrical insert with a diameter of 16 cm and a length of 11 cm was installed between the cathode and the grounded reactor.

Spectral measurements were carried out using an optical probe shown in figure 1. It is a ceramic tube with a length of 70 cm with internal and external diameters of 9 and 20 mm respectively. A quartz window was installed at the far end of the tube. The distance from the forward end of the tube was measured from the output section of the magnetron, i.e. at this point, Z = 0 cm (figure 1). The emission was collected by means fiber optic cable and imaged onto the entrance slit of a monochromator. The emission was also collected through a lateral quartz window at a distance of 18 cm from HCM.

A temporal evolution of plasma parameters was recorded using two-channel digital oscilloscopes Bordo B-421 and Bordo B-423.

We used a flat probe diameter of 2 mm and a cylindrical probe (r = 0.1 mm, l = 2 mm) to measure the spatial-temporal plasma parameters of the discharge. The I–V characteristics were recorded with the help home-made sampling-storage system and PCI card National Instruments NI PCI-6221. The processing of the experimental I-V characteristics involves smoothing the data with cubic splines or the Savitsky-Golay method, calculating the first (to determine plasma potential Vₐ) and the second (to determine the electron energy distribution function (EEDF) of the current derivatives by the technique proposed in [16]. The electron density was determined by integrating the EEDF.

3. Results and discussion

Figure 5 shows the typical current and voltage traces from the HIPIMS discharge with pulse duration of 300 μs. The current of the electromagnet Iₑ is equal to 3.5 A.

**Figure 1.** The experimental setup.

Figure 3(a) presents the time evolution of the ion saturation current Iₛ (Vp = –60 V) at various distances from the HCM. The plasma leaves the hollow cathode and propagates to the anode ring. The peak of the ion current increases as the distance from the cathode reaches. It is important to note that
the magnitude of the ion current increases by a factor of 9 at a distance of 0.5 cm < Z < 13 cm. In addition, at distances greater than 15 cm, the current of the probe has two peaks. The first peak is related with argon ions created in the initial stage of the discharge by secondary electrons that propagate from the cathode to the anode ring. The second maximum of the ion current is due to diffusion of ions from the hollow cathode. The time to reach the second peak increases with increasing distance from the cathode. Using these data, it is possible to estimate the diffusion rate, which is about 2200 m/s for distances < 12 cm and decreases to 700 m/s at distances > 19 cm. It can be seen that after the current pulse is turned off (t = 300 μs), plasma density decreases exponentially with a constant time of the order of 100 μs, then will remain until the next pulse (10 ms) due to the preionization system at a level of the order of 10^10 cm^-3.

![Figure 3](image_url)

**Figure 3.** Time evolution of: (a) – ion saturation current at various distances from the magnetron; (b) – optical emission intensity for Ar and Cu ions at a distance of Z = 18 cm. p = 1.3 Pa, I_m = 3.5 A, t_off = 300 μs.

Figure 3(b) shows the dynamics of emission of the spectral lines of argon and copper ions measured at a distance of 18 cm from the cathode. The intensity of the emission of the Ar^+ lines (480.6 nm) has two peaks. The first peak at = 50 μs corresponds to the breakdown between the cathode and the anode ring, and the second peak at 150 μs diffusion of ions from the cathode. The first peak at the emission of the Cu^+ lines (213.6 nm) is weak, due to the integration of the radiation along the radius, the second peak is reached with a delay of 20 μs with respect to the peak of the Ar^+ emission lines. The emission of Ar atom reaches a peak of 35 μs, then falls to a small value. The results of probe and spectral measurements, shown in figures 3 and 4, correlate well and provide information on the dynamics of ionization processes in a pulsed discharge. Discharge begins with a breakdown between the cathode and the anode ring. As the current increases, the densities of argon ions and sputtered copper atoms inside the hollow cathode grow. At the time t = 55 μs, the discharge current reaches a maximum, then begins to decrease. This behavior of the current and emission of Cu atoms is explained by rarefaction effect: flux of argon ions and sputtered metal atoms push out argon atoms from the cathode. The contribution of copper ions to the ejection process is insignificant, since the ionization of sputtered metal atoms near the cathode at a current density < 250 mA/cm^2 is small. As a result, the density of argon atoms decreases to 80% and the discharge current decreases.

Figure 4 shows time behavior of the emission for Cu^+ spectral lines, measured along the discharge axis at different distances from the magnetron using the optical probe. As the distance from the target increases, the maximum of the radiation lags with respect to the current maximum. This is clear since argon ions need time to travel the distance from the magnetron to the optical probe. In addition, the intensity of the radiation increases with increasing distance. Up to Z = 12 cm, the radiation increases rapidly, and then the growth slows down substantially.

Figure 5 presents the normalized intensities I(Z)/I(Z=0) of the peak emission of the lines of argon and copper ions as a function of the distance from the target, obtained from the data in figure 4. This quantity is the ratio of the integral radiation of the plasma column from the bottom of the magnetron to
the optical probe at a distance Z to the same value at Z = 0 cm, i.e. at Z = 0 cm this value is equal to 1. For comparison in figure 5 similar results for the lines of Cu atoms are presented. Here, the increase in the intensities with a distance is much less, only twofold. From figures 4 and 5 we can conclude that the main ionization of the sputtered metal atoms occurs not inside the hollow cathode, but at a distance of 5–12 cm from the magnetron.

**Figure 4.** Temporal evolution of discharge current I and optical emission J for Cu⁺ (213.6 nm) at various distances from HCM.

In Figure 6 is shown the emission spectrum, measured at 150 µs of discharge at a distance of 18 cm from the magnetron. Strong lines of copper ions are clearly visible in the spectrum. For comparison, we took the intensities of the lines Cu⁺ 213.6 and Cu 216.5 nm. Their excitation energies are close to (8.52 eV) and (5.72 eV), respectively. In the HiPIMS mode, the ratio of Cu⁺ 213.6 nm and Cu 216 nm is 2.7, while for the stationary regime this ratio is 0.46. It should be taken into account that the average power of a pulse discharge is 420 W, and the power of a stationary discharge is 2.2 kW.

**Figure 5.** Normalized intensities of Ar and Cu spectral lines as function a distance from HCM.

**Figure 6.** Emission spectrum measured at 150 µs of HiPIMS discharge. Z = 18 cm.

**Figure 7.** Axial distributions of the electron density nₑ and temperature Tₑ at 50 µs of discharge.

Figure 7 shows axial distributions of the electron density nₑ and temperature Tₑ, obtained from the current-voltage characteristics of the probe at 50 µs of discharge along its axis. The maximum values of the electron density (nₑ > 3.5·10¹² cm⁻³) and temperature (Tₑ > 3.5 eV) are found at distances of 4–10 cm from magnetron. At a distance of 18 cm they decrease to 1.3·10¹² cm⁻³ and 2.2 eV respectively. The electron density in the pulsed regime (420 W) is an order of magnitude larger than in the stationary mode (W = 2.2 kW), which increases the probability of ionization of metal atoms.

The results presented above show that in the HCM discharge operating in pulsed mode, there are regions with a high electron density and temperature. The main ionization of sputtered metal atoms
occurs outside the cathode. This is the essential difference between HCM and magnetron with planar cathode, where the region with the maximal density values is located near of the cathode surface.

It should be noted that the above results are valid for the current density at the target < 250 mA/cm². Such current density is insufficient for the appearance of self-sputtering.

4. Conclusions
The complex dynamics of the atoms and ions in plasma of a pulsed HCM discharge was studied. With the help of optical and probe measurements, the region of ionization of sputtered metal atoms was determined. These measurements showed that the main ionization occurs outside the cathode at a distance of 4–12 cm from the output cross section. It is established that the plasma density in this region at an average discharge power of 420 W reaches a value of 4·10¹² cm⁻³, and the electron temperature is of the order of 2 eV. The probability of ionization of sputtered metal atoms in plasma with such concentrations and volume is large.

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