Investigation of the influence of the parameters of a pulsed power source on the properties of a magnetron’s high-power gas discharge

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Abstract. The paper presents the results of an experimental study of the emission spectra of a gas discharge during high-power impulse magnetron sputtering. The influence of the repetition frequency and duration of current pulses on the intensity of the spectral lines of various particles is shown. The parameters of the gas-discharge plasma during HiPIMS and at a direct current were also compared.

1. Introduction
Nowadays, thin-film structures and coatings are widely used in science and technology, occupying a leading position in many areas of electronic industry: from conductive metal layers in the latest integrated circuits and microelectromechanical systems to sensitive elements of various sensors. There are many different manufacturing techniques for conductive film structures, but the most efficient way is the deposition of the sputtered in an inert gas material on the substrate. Modern science knows many methods of coating deposition based on physical sputtering. One of the methods that has high industrial potential is HiPIMS (High Power Impulse Magnetron Sputtering) method. The basis of the HiPIMS method is the use of a magnetron power source capable of generating current and voltage pulses with high amplitude and small with duty cycle of ~ 0.05 [1–2]. As a result, conditions are achieved under which the density of the gas-discharge plasma increases sharply. The concentration of charge carriers in it reaches $10^{12}–10^{13}$ cm$^{-3}$ [3–5]. At the same time, the metal atoms knocked out from the target also have the ability to ionize. Many studies show that the presence of high (compared to the classical magnetron sputtering at direct current (DCMS)) concentration of charged particles makes it possible to produce higher quality coatings, reducing the number of pores and increasing their adhesion to the substrate [6–7].

The HiPIMS method is a relatively new way of producing films and coatings, originating in the 90s of the last century. When using this sputtering mode, a number of problems arise associated with the optimal selection of technological parameters that affect the properties of the deposited coatings. For example, in comparison with classical deposition on a direct current the time of deposition of coatings is significantly increased during HiPIMS due to the low flow of the substance on the substrate. An increase in the number of sputtered metal ions leads to a significant decrease in the number of neutral atoms capable of participating in the film formation process. There are a number of technological solutions to reduce the deposition time, for example, heating the surface of the target. With an increase
in temperature, an additional flux of matter begins to appear on the substrate, associated with evaporation [8].

Despite the shortcomings, HiPIMS is a versatile method for the deposition of functional films and coatings, and a more detailed study of the physical features of this technology will allow to use it in the most efficient ways.

2. Description of the equipment

For the experiment, a modernized vacuum deposition unit with a diffusion pump was used. The purity of argon injected into the chamber was ~ 99.99%. The target material used was copper of high purity ~ 99.98%, 5 mm thick. The residual pressure in the chamber did not exceed 0.01 mTorr. The argon pressure was 3 mTorr. The target erosion zone is a ring with a sputtered area of ~ 31 cm². Spectrum measurements were performed using a spectrophotometric instrument. A comparative characteristic of the emission spectra of a gas discharge for different operating modes is presented for data obtained in one technological process.

3. Experimental results

As mentioned earlier, the HiPIMS sputtering method implies the use of high-power current pulses as a power source of a magnetron. The high power of the pulses applied to the magnetron makes it possible to achieve a state with an increased ion concentration of sputtered metal atoms in the discharge volume. Changing the pulse repetition rate and their duration, a proportional change in the discharge power density occurs. In figure 1(a), one can observe a change in the intensity of the spectral emission lines of copper ions (Cu I) at a wavelength of 506.8 nm. The emission of neutral particles of copper (Cu) corresponds to 324.8 and 518.4 nm. The dependence was measured with an average current of a high-power pulsed discharge of 2 A.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Dependence of the radiation intensity of atoms and copper ions on the repetition rate ($\tau = 50 \mu s$) (a) and on the duration ($f = 600$ Hz) (b) of pulses.

It can be seen that with the increase of repetition rate and pulse duration, an increase in the amplitude of spectral lines corresponding to the emission of both metal ions and neutral atoms occurs. In this case, the line corresponding to the emission of a charged copper ion particle has a much higher intensity.

Let us consider the influence of the pulse duration on the behavior of the radiation intensity. In figure 1(b), we can observe a change in the intensity of radiation of copper ions in the studied gas discharge, depending on the duration of the voltage pulses with an average discharge current of 2 A. It
can be seen that with an increase in the duration of the pulses, the radiation intensity also increases. Dependencies are increasing due to the increase in power supplied to the magnetron sputtering unit. Similar situation also occurs in the case of a change in the pulse repetition rate.

The increasing nature of the change in both dependencies can be understood using formula (1) for the average power of a high-power impulse gas discharge:

\[ P_{av} = P_{imp} \cdot D \]  

where \( P_{imp} \) is the pulse power (defined as the product of the pulse current and voltage), \( D \) is the duty cycle.

\( P_{av} \) in this case is defined as the product of the discharge current and voltage. The fill factor is determined by the formula (2):

\[ D = \frac{\tau}{T} = \tau \cdot f, \]  

where \( \tau \) – width, \( T \) – period, \( f \) – pulse repetition frequency.

Combining formulas (1) and (2), we obtain the final formula for the average power supplied to the magnetron:

\[ P_{av} = U_{imp} \cdot I_{imp} \cdot \tau \cdot f, \]  

where \( U_{imp} \) is the impulse voltage, \( I_{imp} \) is the impulse current of the gas discharge.

From the formula (3) it can be seen that the average supplied power increases with an increase in both the frequency and the pulse duration. Accordingly, at a constant average current of a high-power impulse gas discharge, the nonlinearity of the dependences can be associated with the behavior of the also changing voltage of the pulses. Figure 2 shows the dependence of the intensity of the spectral lines corresponding to the various copper particles depending on the average discharge current in the HiPIMS mode.

![Figure 2. The dependence of the intensity of spectral lines on the average discharge current.](image)

It is obvious that in the HiPIMS mode copper ions become the predominant particles in the discharge. The intensity of the spectral lines corresponding to the emission of copper ions is several times higher than the amplitude of the lines in the mode of classical magnetron sputtering at a constant current (at the same discharge current). For example for the Cu I 506.8 line in the mode of magnetron sputtering at a constant discharge current of 2 A, we have an emission intensity of ~ 32 a.u. The same line, corresponding to the emission of a copper ion, with the same average gas discharge current in HiPIMS mode with a pulse repetition rate of 600 Hz and a duration of 250 µs has an intensity of ~ 300 a.u., which is more than 9 times more than for the case of deposition on the constant current.
Figure 3 presents a general picture of the emission spectra of a gas discharge at a discharge current of 2 A in two different sputtering modes – DCMS and HiPIMS. The fundamental difference between the two states is obvious. In the case of magnetron sputtering at a direct current, the lines corresponding to the emission of neutral argon atoms have a maximum intensity. When switching to a high-power impulse mode, one can see a sharp increase in the intensity of the spectral lines corresponding to the emission of atoms and ions of copper. The presented spectra show such a mode in which the atoms of the sputtered target are largely ionized, but there is still a high concentration of neutral copper atoms in the gas discharge.

![Emission Spectra](image)

**Figure 3.** The emission spectra of the gas discharge in HiPIMS mode (a) and DCMS (b).

This mode of operation can give the opportunity to use the advantages of HiPIMS technology (the deposition of dense films with high adhesion to the substrate), while not significantly reducing the deposition rate of conductive film structures.

**4. Conclusion**

Relying on the obtained dependences, a conclusion can be made about the significance of the influence of the frequency and pulse duration on the properties of a gas discharge. When the frequency is increased by 2 times (from 100 Hz to 200 Hz), the intensities of the emission lines of copper particles increase by ~ 1.25 times. With an increase in the pulse duration by a factor of 2 (from 100 μs to 200 μs), the intensity is ~ 1.1 times higher. The main factor determining these changes at a constant average current is the amplitude of the voltage of the pulses.

In HiPIMS mode, the concentration of argon ions slightly increases (relative to DCMS), but the concentration of copper ions increases dramatically, which leads to the appearance of a process called as “self-sputtering”, which means the sputtering of the target by its already sputtered ionized atoms.

It was also shown that it is possible to select the parameters of a high-power impulse supply unit (pulse duration and frequency, pulse current), which provide a high amount of ionized target material in the gas discharge gap, don’t significantly reduce the deposition rate of the coatings.

**Acknowledgments**
The work was supported by the Russian Foundation for Basic Research (grant 18-32-01063).

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