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Plasma parameters of a pulsed high-current low-voltage non-sputtering magnetron discharge in light gases

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Abstract. In this study, the operation of millisecond-scale non-sputtering discharge in hydrogen and helium has been examined. The pulse duration was around 1 ms, and the maximum pulse power was around 80 kW. The plasma parameters were monitored with an electric probe. The optical emission spectra from plasma were recorded synchronously with each pulse by AvaSpec ULS2048 spectrometer. The use of the pulsed non-sputtering modes in hydrogen and helium enables achieving non-constricted plasmas with high density and no traces of optical emission lines corresponding to the species of cathode or anode materials.
Keywords: non-sputtering magnetron discharge, HiPIMS, hydrogen, helium, metal-free plasma

1. Introduction

Nowadays, a lot of practical applications – such as material etching; electric propulsion (plasma thrusters); material testing under high thermal and plasma loads – demand having efficient sources of highly ionized metal-free plasma. It could be convenient to utilize commercially available high-power impulse magnetron sputtering (HiPIMS [1]) technique for this purpose. However, originally HiPIMS is being used for coating deposition and thus in its conventional form is not suitable for generating plasma free of metal species. The usage of light working gas (hydrogen or helium) can significantly reduce the sputtering effects and turn this type of discharge into highly efficient generator of metal-free plasmas.

Depending on operating conditions (including pulse duration), it is possible to transform long HiPIMS regime (L-HiPIMS) into the non-sputtering low-voltage mode at the same power level. This mode is known as non-sputtering magnetron discharge (NSMD) [2–4]. Introducing hydrogen or helium into NSMD might result in high density plasma generation with extremely low cathode material erosion rate.

In this study, the operation of millisecond-scale non-sputtering discharge in hydrogen and helium has been examined in the pressure range 1–2 Torr.

2. Experimental setup

The experiments were carried out in a special discharge device that is a cusped magnetic trap with a pair of electrodes whose shape replicates the magnetic field lines curvature (see [2] for details). The experimental setup scheme is shown in Fig.1.

The power supply was a custom pulse forming network capable of storing energy of 9 kJ. It was charged to the required voltage in the range from 600 to 2500 V, which was controlled by a Pintek DP-50 differential voltage probe, which was connected to a Fluke 177 multimeter. After that, the voltage was applied between the cathode and the chamber. The power supply was switched on synchronously with the control clock pulse (TTL 5 V) from the Stanford Research Systems DG645 delayed pulse generator. The latter was also used to synchronize the recording of waveforms and optical emission spectra. The duration of the discharge was more than 1 ms. The discharge voltage during the pulse was measured using a Pintek DP-50 differential probe. The discharge current was measured with a Pintek PA-622 current probe (designed for a maximum current of 200 A) and a Rogowski coil RFSY-70-50 with a rated sensitivity of 50 mV/kA (calculated for a standard main 50 Hz signal).

The conversion factor α for determining the discharge current $I_d(t)$ based on the Rogowski coil signal $U_{Rog}(t)$ ($U_{Rog}(t)$ ($I_d(t) = \alpha\int^t_0 U_{Rog}(t)dt$) was $\alpha = 2\pi\cdot(50\ \text{Hz})\cdot2\cdot10^4(\text{A/V}) = \pi\cdot10^6\ \text{A/(V}\times\text{s)}$. In most of the experiments, the Pintek PA-622 current sensor was outside its stated measurement limits; however, it enabled quick evaluation of the discharge behavior without the need to recalculate the current from the Rogowski coil signal. The signals from the sensors were recorded by an AKIP-4126/3A-X digital four-channel oscilloscope.

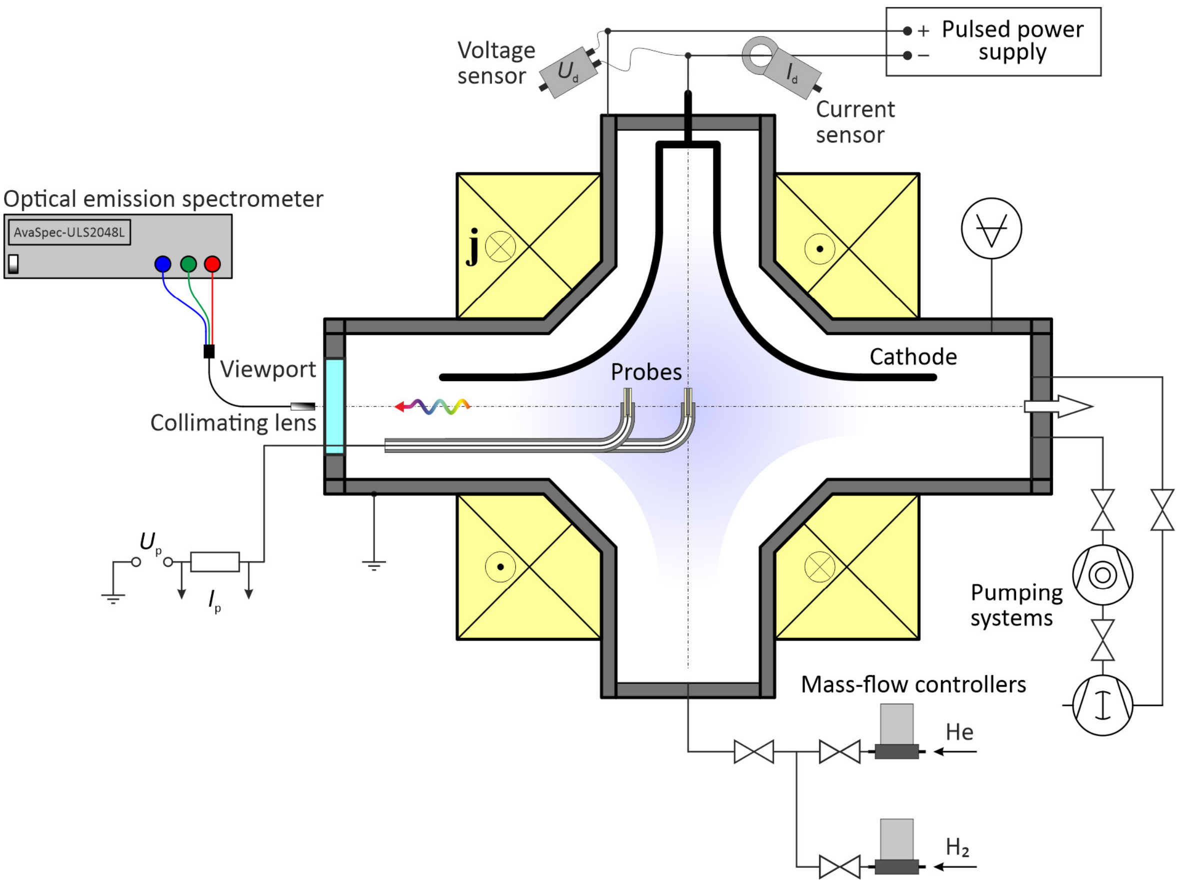

Fig.1. Experimental setup.

The presence of impurities was detected using an Avantes AvaSpec ULS2048L three-channel fiber optic spectrometer with spectral ranges of 200–365 nm (resolution 0.12 nm), 364–603 nm (resolution 0.18 nm) and 600–810 nm (resolution 0.15 nm). The plasma emission spectra were measured through an acrylic window with a bandwidth of ~370–2000 nm. When detecting the elements, the visible region of the spectrum was used as a rule. The presence of an element in plasma was determined by the appearance of stable lines according to the NIST Atomic Spectra Database. The optical radiation of the plasma was collected by an Avantes COL-UV/VIS collimating lens and transmitted via an optical fiber to the channels of the spectrometer. The exposure time was fixed at the minimum value available for the device and was 1.050 ms. The recording of the spectrum was synchronized with the leading edge of the voltage pulse.

Plasma concentration was determined with an electrostatic probe in the ion saturation mode. The probe connection diagram is shown in the installation diagram (see Fig.1). A measuring resistor with a nominal value of 10 ohms was used. A GW Instek GPR-730H10D power supply with a maximum voltage of 300 V and a maximum current of 1 A was used as a voltage source.

3. Results and discussion

3.1. Discharge in hydrogen

The typical stable NSMD discharge and voltage waveforms are shown in Fig.2 together with the ion current signal from the probe (note the $\times 10^3$ scaling factor).

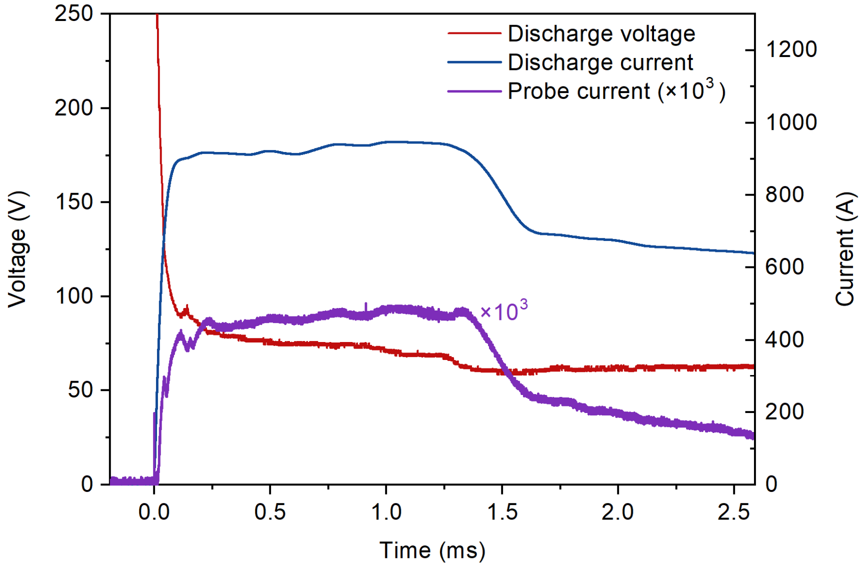

Fig.2. Discharge current and voltage traces together with probe current waveform (H_2, 2 Torr).

Eventually, each NSMD pulse is characterized by transition into an arc mode. Because of high pulsed power (around tens of kW), such arcs inflicted visible damage to the cathode surface, and the OES spectra in arc mode contained strong metal lines. Typical optical emission spectrum recorded for NSMD discharge (corresponding to the waveforms shown in Fig.2) is demonstrated in Fig.3.

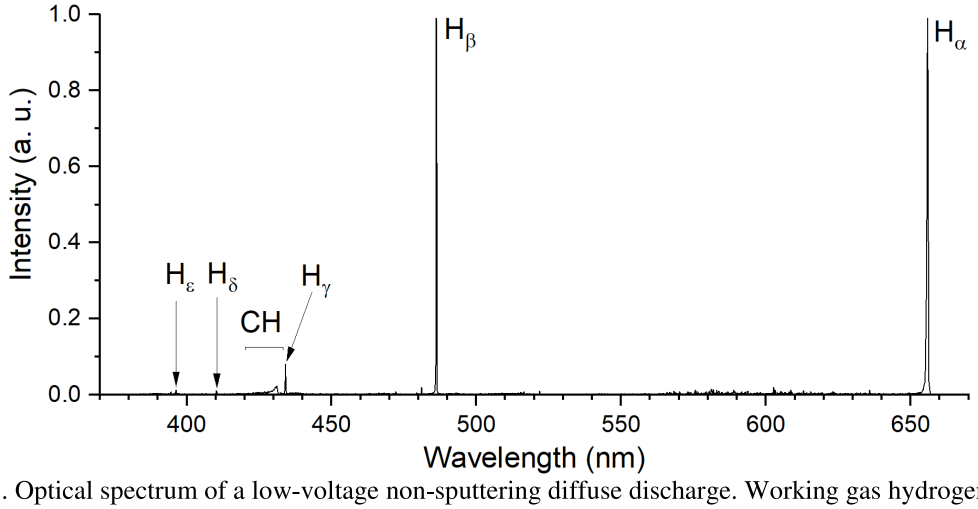

Fig.3. Optical spectrum of a low-voltage non-sputtering diffuse discharge. Working gas hydrogen H_2.

Unlike the spectrum of an arc, this one only contains lines that correspond to hydrogen working gas (except traces of CH, which are probably due to decomposition of uncooled polymer insulator materials). The maximum measured plasma density of a high-current pulsed magnetron discharge in hydrogen was $1.8 \cdot 10^{20}$ cm^{-3} at an average discharge current of 1200 A. The current per probe was 0.9 A. The degree of ionization in this case was about 20%.

3.2. Discharge in helium

In helium, the discharge current is generally lower provided all other parameters are fixed. A sample optical emission spectrum is shown in Fig.4.

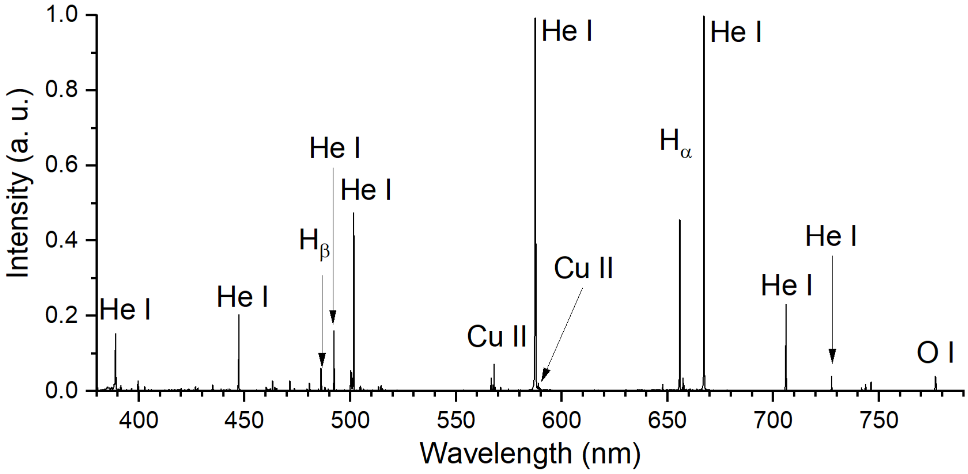

Fig.4. Optical spectrum of a low-voltage non-sputtering diffuse discharge. He working gas.

Despite the fact that the maximum values of the current to the probe turn out to be lower in the case of helium than in the case of hydrogen plasma, the stability of the discharge with respect to contraction and transition to an undesirable arc mode for a discharge in helium is higher. This can be regarded as a positive factor for potential applications. The maximum measured plasma density of a high-current pulsed magnetron discharge in helium was $2.0\cdot10^{20}$ cm^{-3} at an average discharge current of 1050 A. The current per probe was 0.5 A. As in the case of hydrogen, the degree of ionization in this case was of the order 20%.

4. Conclusion

The plasma concentration and degree of ionization of a high-current non-sputtering magnetron discharge were determined. For hydrogen, the maximum measured plasma density was $1.8\cdot10^{20}$ cm^{-3}, for helium it was $2.0\cdot10^{20}$ cm^{-3}. In both cases, the degree of ionization is on the order of 20%. All of these modes are characterized by suppressed electrode erosion. A high-current non-sputtering magnetron discharge in helium is practically not subject to the contraction effect, which is a favorable factor for practical applications of such regime. The use of the pulsed non-sputtering modes in hydrogen and helium enables achieving non-constricted plasmas with high density and no traces of optical emission lines corresponding to the species of cathode or anode materials.

Acknowledgements

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5. References

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