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Features of plasma structure observed in high-current quasi-stationary magnetron discharge

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ABSTRACT

The plasma structures in a high-current impulse magnetron discharge (HCIMD) were studied by means of a fast gated camera facing the cathode target, made from Cu, Ti, and Mo. The current–voltage characteristics of HCIMD were obtained for the range of transverse magnetic field on the cathode surface $B_s = 40$–65 mT and working gas (Ar) pressures $p_{Ar} = 0.5$–2 Pa. Fast camera images were recorded throughout the pulses for all experimental regimes, and the regions of plasma non-uniformity were found. The *I-V* curves studied in detail revealed from three to five distinct discharge regimes with quite different plasma appearance and behaviour, depending on the target material. Our observations of the initial stage of HCIMD indicate that in a certain discharge current range there is a characteristic time (~tens μs) needed for the azimuthally symmetric structure of spokes to build up, even while the discharge current remains constant. During a quasi-stationary stage of HCIMD a well-defined spoke structure may rotate or remain stable depending on the discharge power.

1. Introduction

Over the past five years several research groups have been observing and investigating a peculiar phenomenon in high-power impulse magnetron sputtering (HiPIMS) discharges, namely, zones of enhanced visible emission intensity in the near-cathode region, or so-called spokes (reported for the first time in [1–3]). The term "spoke" originates from the literature dealing with the Hall thrusters where the effects of plasma fluctuations of different types are present. The spokes observed in sputtering magnetrons appear to influence the deposition parameters such as the deposition rate and the ion energy distribution [4–6]. Considerable effort is being made to determine the mechanisms of patterns appearing in the cathode region of high-power pulsed magnetron plasmas, and to find a way to control their formation. The experiments show that the spokes appear only in well-defined regions of the current–voltage characteristics [7,8], and their dynamics depend on the discharge current density [9]. A few theoretical models have been proposed to describe the phenomenon [10–13]. Our present contribution deals with the investigation of the high-current impulse magnetron discharge (HCIMD) where similar effects take place under a certain range of conditions. HCIMD was developed in the beginning of the 1990s [14,15] as a high-voltage (up to 1.5 kV), high-current (up to 20 A/cm^2) sputtering regime with a quasi-stationary stage duration up to tens of ms [16] that distinguishes it from typical discharges used in HiPIMS technique, which emerged later in the 2000s [17].

We present the results of HCIMD time-resolved plasma diagnostics using fast gated camera imaging as well as the optical emission spectroscopy data and discuss their correlation with the electrical parameters of the discharge (voltage and current density).

2. Setup and diagnostic methods

The experiments were carried out in a planar magnetron device with a 90-mm diameter disc cathode target. The scheme of the experimental setup is shown in Fig. 1 (not to scale). Vacuum chamber 45 × 45 × 30 cm in size was evacuated to a base pressure of 1×10^{-3} Pa by means of a turbo-molecular pump in series with a roughing pump. The working gas was Ar.

HCIMD was initiated by applying a high voltage pulse across the discharge region, pre-ionized with a direct current (DC) magnetron discharge (U_{DC} ~300 V, I_{DC} ~100 mA). The "background" plasma (n_b ~10^9 cm^{-3}) is essential to minimize the time of transition to a high-current mode [15]. The pulsed power supply consists of a pulse forming network and a high power switch. The maximum stored energy is 9 kJ, and the pulse duration τ_{pulse} can be remotely set up to tens of ms using custom software. In the described experiments we used $\tau_{pulse} =$ 8 ms. The discharge voltage U_d was measured with a 1:1000 voltage divider probe, and the discharge current I_d was registered using a closed loop linear current sensor Honeywell CSNR 161-002 with 0.5% accuracy. The electrical signals (U_d, I_d) were recorded by Tektronix TPS 2024

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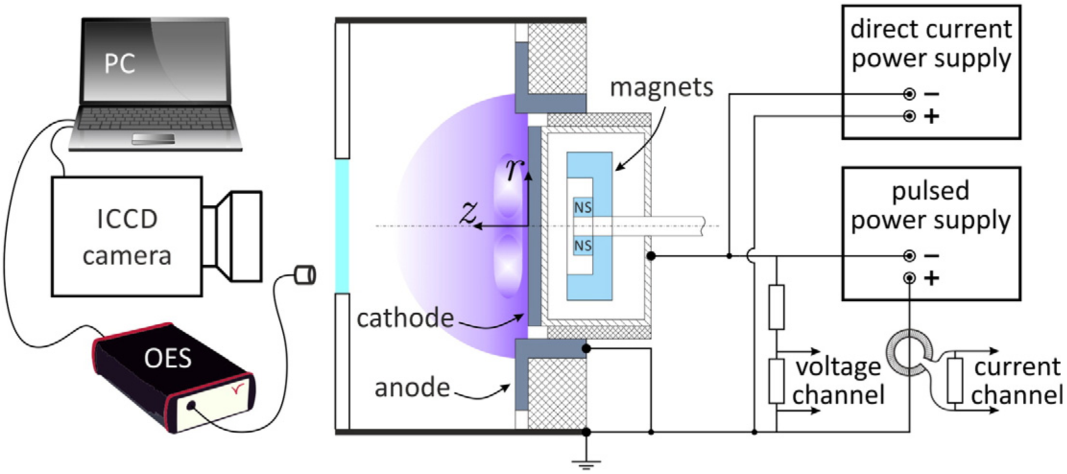

Fig. 1. Scheme of the experimental setup.

digital storage oscilloscope synchronized with the discharge triggering circuit by a delay generator.

Cu, Mo and Ti targets were used in these experiments. The physical properties of these materials, such as sputter yield, thermal conductivity, secondary electron emission coefficient, etc. are quite different, which ensures observing a wide range of the possible plasma structures.

The magnetic configuration was unbalanced, with the inner SmCo ring magnet and outer iron magnetic circuit.

The HCIMD plasma was investigated using the fast gated camera (BIFO K011) and fiber optic spectrometer (Avantes AvaSpec-2048x14) both oriented end-on with respect to the cathode and synchronized with the discharge triggering. The fast ICCD camera allows for taking nine consecutive images with frame acquisition times and frame delays that can be set in the range 100 ns–100 μs each. A built-in initial triggering delay option can be used to shift the start of the recording up to 1300 μs. Spatial resolution of the parts of the matrix for each frame is 340 × 340 pixels. Spectral sensitivity range is 400–800 nm. The camera was equipped with a Zenitar-M 50 mm lens.

The current–voltage characteristics were obtained for the range of transverse magnetic field above the target surface in the racetrack center $B_s = 40$–65 mT. Working gas (Ar) pressure was varied in the range $p_{Ar} = 0.5$–2 Pa. Fast camera images were recorded throughout the pulses for all experimental regimes, and the regions of non-uniform plasma patterns formation were found. The fast camera images were analyzed together with the electrical parameters of the discharge. We compare the features of the observed plasma structures and their behaviour to the case of HiPIMS studies.

3. Results and discussion

3.1. Current–voltage curves of HCIMD

In order to establish the range of discharge parameters corresponding to stable HCIMD operation and formation of spokes, the current–voltage curves were acquired for Cu, Mo and Ti targets for a range of Ar pressure $p_{Ar} = 0.5$–2 Pa and the surface magnetic field values $B_s = 40$–65 mT. At a fixed B_s both the trends of *I-V* curves and the fast images of the discharge were found to be insignificantly affected by changing the Ar pressure within the abovementioned range. However, varying the magnetic field at a constant Ar pressure had much stronger impact on the discharge parameters and appearance. The *I-V* curves for HCIMD at $p_{Ar} = 1$ Pa and $B_s = 40$–65 mT on Cu, Mo, and Ti targets are presented in Figs. 2–4, respectively, accompanied by the images of the discharge plasma recorded in the quasi-stationary phase. To guide the eye the plots of the constant discharge power P_d are also shown.

The behaviour of *I-V* curves obtained is quite expected. The magnetic field influence on the *I-V* characteristics of sputtering magnetron discharges has been extensively studied in literature [18–22]. Low *B* values result in electrons' gyration radii exceeding the discharge gap dimensions due to inefficient magnetic confinement of high-energy electrons

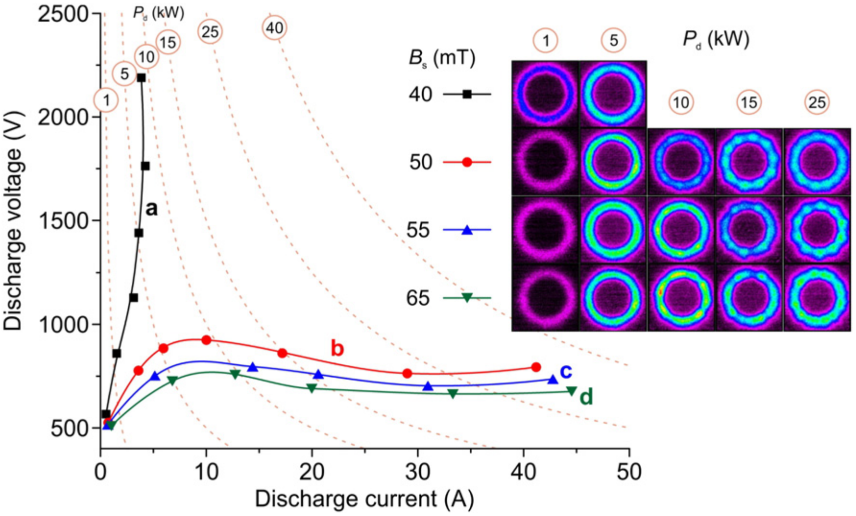

Fig. 2. Current–voltage characteristics of HCIMD operated on Cu target at $p_{Ar} = 1$ Pa and different B_s. The corresponding fast images were acquired with 200 ns exposure time.