Spokes and cathode voltage and discharge current oscillations in HiPIMS

J. Hnilica[1],P. Klein[1], Z. Hubička[2], M. Čada[2], P. Vašina[1]

[1]*Department of Physical Electronics, Faculty of Science, Masaryk University, Kotlářská 2, CZ-61137, Brno, Czech Republic*
[2]*Institute of Physics v. v. i., Academy of Science of the Czech Republic, Na Slovance 2, CZ-18221, Prague, Czech Republic*

Oscillations were observed on cathode voltage and discharge current temporal evolution of HiPIMS pulse. The frequency of the oscillations depends only on the actual value of the discharge current for given pressure. Rotation of the spokes over the target surface and the frequency of the oscillations on cathode voltage and discharge current show different trends. The oscillations are observed at conditions where at least certain critical amount of spokes emerges.

1. Introduction

Recent investigations of the non-reactive High Power Impulse Magnetron Sputtering (HiPIMS) discharge using high speed imaging, current probes and optical spectroscopy measurements revealed that plasma is not homogenously distributed over the target surface, but it is concentrated in regions of ionization zones called spokes and drifting above the erosion racetrack in ExB direction [1, 2, 3]. Spokes emerge only for certain discharge current and in certain pressure range [4]. The spoke rotation velocity was evaluated around ~10 km/s [2]. Similar spoke rotation velocity was obtained from oscillations of both the floating potential of the probe and collimated optical signal [3]. Further observations differentiated ionization zone shapes into triangular or diffusive shape depending on the second ionization potential of the target material with respect to the first ionization potential of Ar [5].

Besides the previously mentioned inhomogeneity, several observations of oscillations on both cathode voltage and discharge current were reported during the high current phase of HiPIMS pulse [6, 7]. Usually these oscillations were attributed and neglected as generator effect. Recently it was reported that such oscillations indicate the spoke formation [8].

The aim of this study was to find out direct connection between oscillations on cathode voltage and discharge current and spoke presence.

2. Experimental set-up

Alcatel SCM 650 magnetron sputtering system was used. Titanium target 20 cm in diameter with purity 99.95% in balanced magnetic field was used as a sputter source. Argon supply with purity 99.999% was directed to the substrate area in the range 1-100 sccm. Pressure was measured by Baratron gauge as well as Pfeiffer Vacuum full range gauge. Background pressure was < 1.10^{-3} Pa and working pressure was from 0.18 Pa to 2.5 Pa. Dual-channel Melec SIPP 2000 HiPIMS generator capable of pulse peak up to 500 A and up to 1000 V supplied the discharge with power. The generator is arc protected by coil. Voltages and currents were measured directly at the output of the Melec power supply. The pulse length was set to 200 μs with 20 Hz repetition frequency. The optical imaging was made by ICCD camera PI-MAX 3 working in dual image mode which enabled us to capture two snapshots in series with 3 μs between them. The exposure time was 100 ns. The pictures were later converted from greyscale by MATLAB Jet (72) scale to colours.

3. Results

3.1. Cathode voltage and discharge current measurements

Fig. 1 shows cathode voltage and discharge current waveforms measured for several voltages for working pressure of 1 Pa. The oscillations on both the cathode voltage and discharge current were clearly visible when applied voltage was 560 V and higher. Two different types of oscillations were identified. The first type of oscillation was present at the beginning of the pulse and they were dampened shortly after the beginning of the pulse. The second type of oscillation was present during the high current pulse phase. Amplitude of the cathode voltage of the second type of oscillation was up to 500 V and amplitude of the discharge current of the second type of oscillation was around 50 A.

Temporal evolution of the cathode voltage and discharge current was analysed by Fast Fourier Transformation (FFT). The oscillations at the beginning of the pulse had frequency of 500 kHz

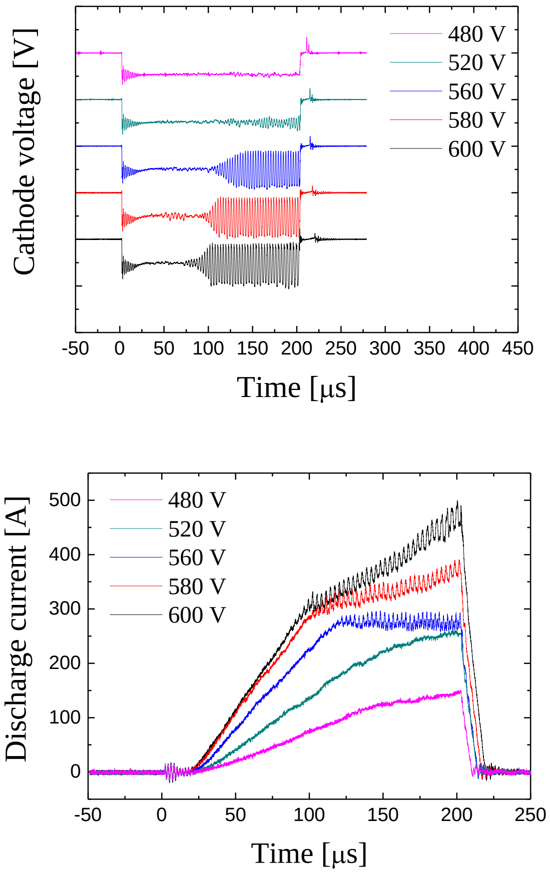

Fig. 1: The upper graph shows cathode voltage evolution for several voltages set and the lower graph shows corresponding discharge current evolution. The pulse length was 200 μs, repetition frequency 20 Hz and pressure 1 Pa.

and the oscillations during high current phase had the beginning of the pulse were present for all experimental conditions. The oscillations at the beginning of the pulse were still present, even when generator was connected only to 1 Ω resistor (to simulate load of the discharge) and the plasma was absent. This shows that the oscillations at the beginning of the pulse are caused by the generator setup.

When the generator was loaded by 1 Ω resistor and the plasma was absent, no oscillations of the second type were observed during the high current phase even for currents reaching 400 A. It leads to the conclusion that generator is not the source of this oscillation. They are observed only in the presence of plasma.

Periodic oscillations during high current phase were observed only for strict experimental conditions: pressure ranged from 0.3 to 2.0 Pa and discharge current higher than 225 A. For lower pressures only aperiodic oscillations were detected with much lower magnitude. No oscillations were observed for the pressure overreaching 2 Pa.

Temporal evolutions of discharge current were recorded at argon pressure of 1 Pa for different sets of voltages. The frequency of the oscillations decreased as the discharge current evolved in time. Fig. 2 showed main frequency of oscillations as a function of actual discharge current, where data from probe measurements performed for different voltages were merged together. The frequencies were in the range from 325 kHz for to 385 kHz. For a given pressure the frequency of oscillations depends on the actual discharge current and is independent on the applied voltage. The increase of the discharge current led to a decrease of the oscillations frequency.

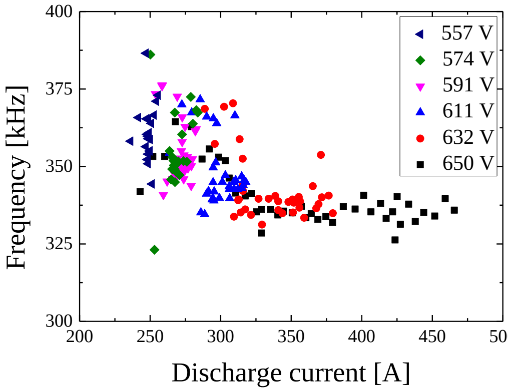

Fig. 2: Frequency of oscillations as function of actual discharge current for different applied voltages and 1 Pa argon pressure.

Pressure dependency of the oscillation frequency as a function of the actual discharge current is shown in Fig. 3. The measurements with different set voltages were merged and averaged together.

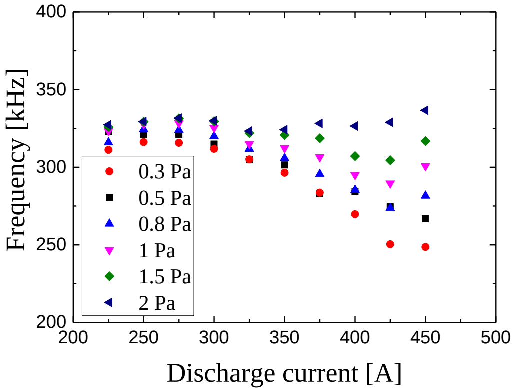

Fig. 3: Frequency of oscillations as function actual discharge current for different argon pressures.

The decrease of the oscillation frequency with increase of the discharge current was proved in the whole studied pressure range. The oscillations frequency increased with increasing of the pressure. The oscillations frequencies changed only slightly for 2 Pa. The maximum observed oscillations frequency reached 330 kHz for 275 A at 2 Pa.

3.2. High-speed camera measurements

The spoke presence and their behaviour were studied by high-speed imaging. Fig. 4 showed typical image of the spokes for different pressures attained at the same actual discharge current (400 A). The spoke appearance was strongly dependent on the pressure. At very low pressure (0.18 Pa), the triangular spoke shape was well recognized (see Fig. 4a). The shape became diffusive with increasing pressure (see Fig. 4b-c), overreaching 2 Pa there were no recognizable spokes (see Fig. 4d).

The spokes were imaged for different pressures and different actual discharge currents. Two successive images were taken from the same pulse with time delay of 3 μs and exposure time 100 ns. Spoke rotation velocity and frequency was derived from the spoke image shift. The parameters in Table 1 (number of spokes, rotation velocity and spoke characteristic frequency) were determined as average values from series of twenty captured dual-images.

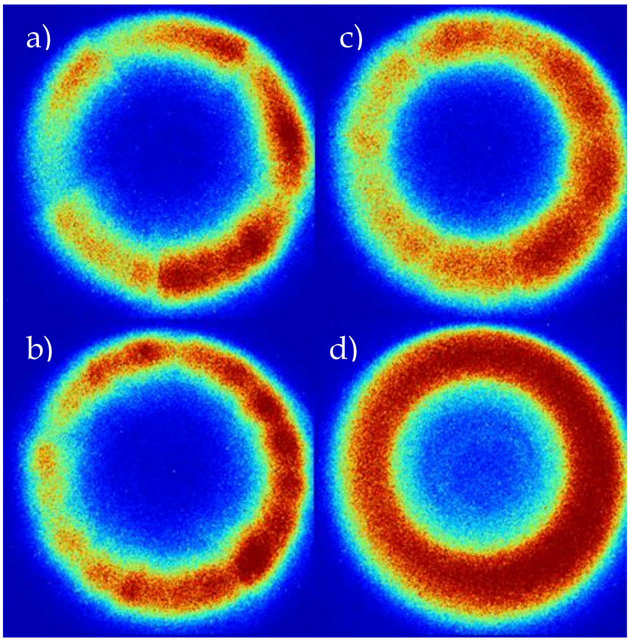

Fig. 4: Target image for the same actual discharge current of 400 A at different working pressures a) 0.18 Pa, b) 1 Pa, c) 1.5 Pa and d) 2.5 Pa. Light intensity is represented in the false colour.

The spoke characteristic frequency was determined as multiplication of number of spokes with rotation frequency. The rotation frequency was simply determined from rotation velocity and racetrack diameter (13 cm).

The number of spokes rose significantly with both the increasing actual current and increasing pressure. For the lowest pressure (0.08 Pa) the number of spokes was constant for all actual currents set.

The rotation velocity significantly decreased with increasing pressure, but it rose only slightly with increasing actual current. The rotation speed was in the range of 5-10 km/s.

The spoke characteristic frequency was almost constant for the argon pressure of 0.08 Pa. For all the higher pressures it rose with increasing current. The spoke characteristic frequency is in the same order of magnitude as observed oscillations on cathode voltage and discharge current, nevertheless they are not identical. Spoke characteristic frequency is 3-4 times lower than the frequency of the oscillations.

Trends of the evolution of the quantities describing spokes are in agreement with other observations. Ehiasarian et al. [7] also observed lowering rotation velocity with increasing the pressure. Decrease of the rotation velocity was explained by more frequent collisions with residual gas at higher pressures. Increase of rotation frequency with actual discharge current growth was also observed by Winter et al. [9].

4. Discussion

For pressures higher than 2.0 Pa neither the spokes nor the oscillations on cathode voltage and discharge current were detected for the discharge currents in the studied range from 0 to 500 A. At the pressure range from 0.3 to 2.0 Pa, both the periodic oscillations and spokes were detected simultaneously for discharge current higher than 225 A. At lower currents, only spokes showed up. For lower pressures, only spokes are observed, but there are no periodical oscillations detected on cathode voltage and discharge current. Despite a broad range of experimental conditions scanned, no particular conditions to detect cathode voltage and discharge current oscillations at spoke absence were found out. Wherever the periodic oscillations on cathode voltage and discharge current were detected, they always accompanied spokes. However, the oscillations on cathode voltage and discharge current are not a marker of the spoke presence as there exists a wide range of conditions (particularly low pressures and low currents) where spokes were clearly identified at absence of the oscillations.

Table 1: Influence of argon pressure and actual current on average number of spokes, average rotation velocity and characteristic spoke frequency.

Pressure [Pa]	Actual current [A]	Number of spokes	Rotation velocity [m/s]	Spoke characteristic frequency [kHz]
0.08	262	5.2	8300	106
0.08	343	5.8	8300	118
0.08	491	5.5	9900	113
0.38	213	6.6	6600	106
0.38	338	7.2	6500	115
0.38	382	10.0	6800	167
0.50	274	6.1	5100	77
0.50	353	8.3	5700	118
0.50	441	12.1	6000	178

The oscillations on cathode voltage and discharge current are observed at conditions where at least 8 spokes emerge. We propose that oscillations on cathode voltage and discharge current could be the result of spoke to spoke interaction. For the small number of spokes present (less than 8) the spokes are spatially separated and each spoke has enough space for propagation without significant interaction with neighbouring spokes. For 8 and more spokes, the limited space over the magnetron cathode forces the spokes to interact with each other. We propose that this spoke to spoke interaction acts at a source of oscillations with certain characteristic oscillation spectrum. The certain oscillation frequency of this spectrum is then amplified by the resonance LC circuit, where coil protecting the generator is an inductance part and the chamber and plasma is a capacity part.

5. Conclusion

The periodic oscillations on cathode voltage and discharge current were observed for different experimental conditions during high current phase. The generator as the source of these oscillations was ruled out. Increasing the pressure, the oscillations frequencies increased. Increasing actual discharge current the oscillations frequencies decreased.

High-speed camera imaging revealed the spokes present. The number of spokes increased with increasing pressure and discharge current. The rotation velocity increased with increasing discharge current but decreased with increasing pressure. The oscillation frequency and spoke characteristic frequency were in the range of a few hundreds of kHz, but they showed different trends.

Spoke to spoke interaction taking place at experimental conditions where the amount of the spokes exceed certain limit is proposed to explain our observations

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