Spoke induced cathode voltage and discharge current oscillations in HiPIMS

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

Keywords: HiPIMS, spokes, magnetron sputtering, plasma instabilities

1. Introduction

High Power Impulse Magnetron Sputtering (HiPIMS) is relatively new technique for depositing thin films [1]. It leads to the formation of dense plasmas with high fraction of ionized species and consequently higher ion flux towards substrate which enables to tailor specific properties of the deposited film [2]. In HiPIMS discharge the power is focused into short high energetic pulse followed by long off time. Recent observations using high speed imaging revealed that plasma is not homogenously distributed over the target surface, but it is concentrated in regions of ionization zones called spokes [3, 4]. Spokes are drifting in ExB direction [4]. Further observations differentiated ionization zone shapes into triangular or diffusive shape based on the target material [5]. Spokes emerge only for certain discharge current and certain pressure range [6]. The spoke rotation speed was evaluated around ~10 km/s [4]. Similar spoke rotation speed was obtained from oscillations on both floating potential of the probe and collimated optical signal [7]. A spoke model was developed too [8].

Apart from previously mentioned inhomogeneity, several observations of oscillations on both discharge current and cathode voltage were reported during the high current phase of HiPIMS pulse [9, 10]. Usually these oscillations were attributed as peculiar generator effect. Recently it was reported that such oscillations indicate the spoke formation [11]. Aim of this paper was to find out direct relation between spoke presence and oscillations on cathode voltage and discharge current.

2. Experimental setup

Alcatel SCM 650 magnetron sputtering system was used. 20 cm in diameter titanium target 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 10^{-3} Pa and working pressure was from 0.18 Pa to 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. Voltages and currents were measured directly at the output of the Melec power supply. For advanced high frequency measurements calibrated current and voltage probe connected directly to the target was employed. Optical screening was made by the ICCD camera PI-MAX 3 working in dual image mode which enables us to capture two snapshots in row with 3 µs between them. Exposure time was 100 ns. The pictures were later converted from greyscale by MATLAB Jet(72) scale colours.

3. Results

3.1. Cathode voltage and discharge current measurements

Fig. 1 showed typical example of cathode voltage and discharge current waveforms measured for 200 µs pulse length, 20 Hz repetition frequency and 1 Pa working pressure. Oscillations on both cathode voltage and discharge current were clearly visible and two different types of oscillations were identified. The first type of oscillation was at the beginning of the pulse and the second type of oscillation was present during high current pulse phase. First type of oscillation was dampened shortly after the beginning of the pulse. Amplitude of the cathode voltage of second type of oscillation was up to 500 V and amplitude of the discharge current of second type of oscillation was around 50 A.

Obtained signal from the probe was analysed by Fast Fourier transformation (FFT). Oscillations at the beginning of the pulse had frequency 500 kHz and oscillations during high current phase had frequency around 300 kHz. The oscillations at the beginning of the pulse were present for any experimental conditions. Even when generator was connected only to the 1 Ω resistor (to simulate load of the discharge) and the plasma was absent, the oscillations at the beginning of the pulse were still present. It excludes direct plasma action and indicates direct generator effect. When the generator was loaded by 1 Ω resistor no oscillations of the second type were observed during the high current phase even for currents reaching 400 A. It rules out generation of the oscillations by generator itself, they are observed only in the presence of plasma.

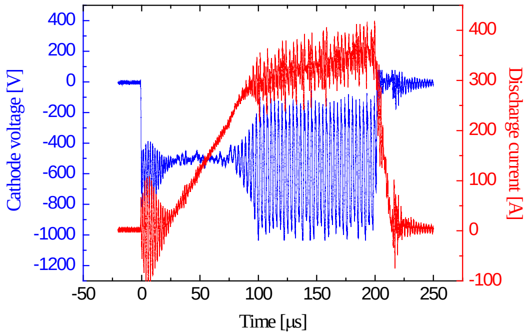

Fig. 1. Cathode voltage and discharge current oscillations. Pulse length 200 µs, repetition frequency 20 Hz, pressure 1 Pa.

The coil protecting the generator is an inductance part and the chamber and plasma is a capacity part of resonant LC circuit. Adding additional coil in series between the generator and the magnetron, the oscillations frequency changed only slightly however oscillations amplitude decreased significantly. The LC circuit is not a source of the oscillations, it is rather amplifier for oscillations originating in the 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 present for the pressure overreaching 2 Pa.

Temporal evolutions of discharge current were recorded at argon pressure 1 Pa for different set 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. Data from measurements performed for different voltages were merged together. The frequency ranged from 280 kHz for to 375 kHz. For given pressure the frequency of oscillations depends on actual discharge current independently on the applied voltage. The increase of the discharge current led to decrease of the oscillations frequency.

Pressure dependency of the oscillation frequency as a function of the actual discharge current is shown in Fig. 3. Again measurements with different set voltages were merged together. The decrease of the oscillation frequency with increase of the discharge current was proved in all studied pressure range. Increasing the pressure the oscillations frequency increased. For 2 Pa the oscillations frequencies changed only slightly. The maximum observed oscillations frequency reached 400 kHz for the 250 A at 2 Pa.

3.2. High-speed camera measurements

The spokes presence and their behaviour were studied by high-speed imaging. Fig. 4 showed typical snapshot of

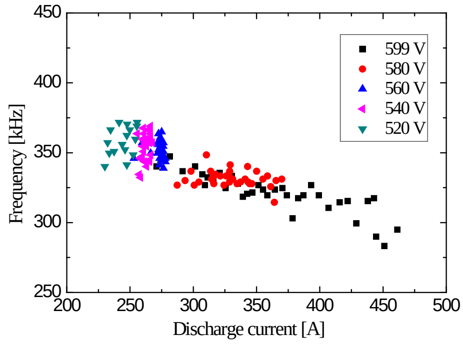

Fig. 2. Frequency of oscillations as function of actual discharge current for different applied voltages and 1 Pa argon pressure.

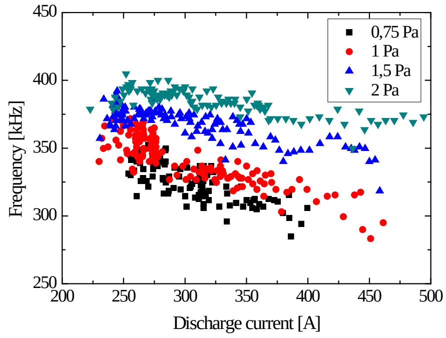

Fig. 3. Frequency of oscillations as function actual discharge current for different Ar pressures.

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 spokes recognizable (Fig. 4d).

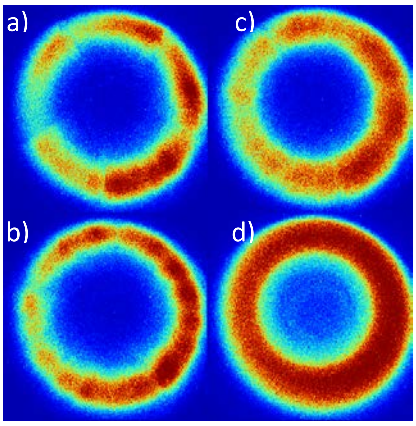

Fig. 4. Target image for the same actual discharge current of 400 A at different working pressures a) 0.18 Pa, b) 1 Pa, c) 1.5 Pa, and d) 2.5 Pa. Light intensity is represented in the false colour.

The 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. 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.

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	1.0	6800	167
0.50	274	6.1	5100	77
0.50	353	8.3	5700	118
0.50	441	12.1	6000	178

The spoke characteristic frequency was arbitrary 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 increasing actual current and increasing pressure. For the lowest pressure (0.08 Pa) the number of spokes was constant for all actual current sets (Fig. 5). The statistical error of spoke number was 1.

Rotation velocity significantly decreased with increasing pressure. The rotation velocity rose only slightly with increasing of the actual current. The rotation speed was in the range of 5 - 10 km/s. The statistical error of rotation velocity was around 500 km/s.

Spoke characteristic frequency was almost constant except the highest current and highest pressure cases. 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 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. [12].

4. Discussion

For pressures higher than 2.0 Pa neither the spokes nor the oscillations on cathode voltage and discharge current are 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 for discharge currents in the studied range from 0 to 500 A. 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 wide range of conditions (particularly low pressures and low currents) where spokes were clearly identified at absence of the oscillations.

The oscillation frequency is determined in the range from 280 kHz to 400 kHz for the pressure between 0.75 Pa and 2 Pa. Spoke characteristic frequency ranges from 77 kHz to 178 kHz for the pressure from 0.18 Pa to 0.5 Pa. The spokes are well distinguished for chosen pressures. The oscillation frequency and the spoke characteristic frequency are in the same order of magnitude. Nevertheless, the oscillation frequency decreases with increasing discharge current but the spoke characteristic frequency rises. With increasing pressure both the oscillation frequency and the spoke characteristic frequency have rising trends. Dependency of the cathode voltage and discharge current oscillation frequency and spoke characteristic frequency on the discharge current shows opposite trends. The opposite behavior of the spoke characteristic frequency reflecting the spoke amount and motion and cathode voltage and discharge current oscillation frequency point out to no direct correlation between rotational motion of the spokes over magnetron cathode and the emergence of oscillations on cathode voltage and discharge current. This conclusion is in agreement with the observation of rotating spokes at the absence of oscillations on the cathode voltage and discharge current.

Fig. 5 shows the average number of detected spokes as a function of actual discharge current for different working pressures. The region of the experimental conditions to detect oscillations on cathode voltage and discharge current is depicted, too. 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 neighboring 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 and detected on the oscilloscope. At low pressures and low discharge currents, the amount of the spokes is below the limit value and the oscillations on cathode voltage and discharge current are not detected. At pressures higher than 2.0 Pa the spokes disappeared and consequently the oscillations on cathode voltage and discharge current are no more detected.

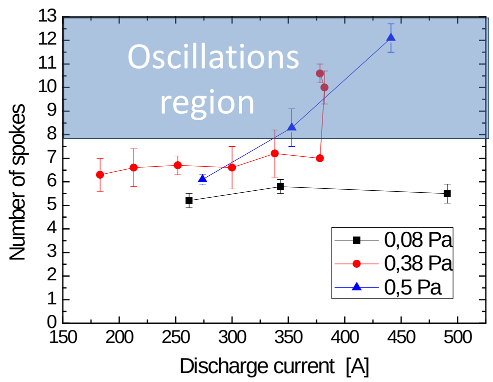

Fig. 5. Average number of spokes as function of actual discharge current for different working pressures.

5. Conclusion

The periodic oscillations on cathode voltage and discharge current were observed for different experimental conditions. The generator as an oscillations source 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 100 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.

6. Acknowledgements

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