High Power Impulse Magnetron Sputtering –
Extreme Plasmas for Extreme Materials

A. von Keudell, J. Held, W. Breilmann, V. Schulz-von der Gathen, A. Hecimovic, C. Maszl
Chair for Experimental Physics II, Reactive Plasmas, Ruhr University Bochum, Germany

Abstract: The dynamic of high power impulse magnetron plasmas (HiPIMS) is analysed using various diagnostics ranging from optical emission spectroscopy, probe diagnostics to mass spectrometry. It shown that structure formation in these plasmas is driven by drift wave instabilities leading to the appearance of rotating spokes along the racetrack of the magnetrons. It is shown that the energy distribution of the ions reaching the substrate are directly connected to the appearance of these spokes. The underlying mechanisms are discussed to explain the good performance of HiPIMS plasmas for material synthesis

Keywords: High Power Impulse Magnetron Sputtering (HIPIMS)

1. Introduction

High power impulse magnetron sputtering (HiPIMS) plasmas use conventional magnetron targets, but applying the power as short pulses with power densities at the target of several kWcm^{-2} and pulse lengths of 10 to 200 µs and duty cycles of a few percent only. HiPIMS plasmas are characterized by a high degree of ionization and a very energetic metal growth flux leading to superior material properties.

Many studies focus on unraveling the dynamic of these HiPIMS plasmas. The intense sputter wind in a HiPIMS pulse causes gas rarefaction after a time span of 10...30µs after the onset of the plasma pulse. At target power densities above 1 kW cm^{-2}, localized ionization zones, so-called spokes, are observed which rotate along the plasma torus in ExB direction (or in the opposite direction) with a typical velocity of 10 km s^{-1} (see Fig. 1). It is assumed that the localized ionization zones correspond to regions of high electrical potential, and are, therefore, the source of an energetic group of ions of typically few tens of eV in the growth flux on the substrate. The spoke pattern depends on target material, plasma gas, power density and pressure. By adding a reactive gas such as oxygen or nitrogen to a HiPIMS plasma specific oxides and nitrides can be deposited on the substrate.

Our group worked intensively over the last years assessing this phenomenon [1..8] using probe diagnostics to follow the plasma evolution, ion energy mass spectrometry and retarding field analysers to characterize the growth flux and active and passive optical diagnostics to evaluate the plasma parameters of the HiPIMS plasma itself.

2. Spokes in HiPIMS

The analysis of the plasma parameters of these dynamic plasma pulses is very demanding because two time scales need to be taken into account: the first is the pulsing of the discharge with a duty cycle of a percent of less, the second is the dynamic of the plasma evolution during each pulse

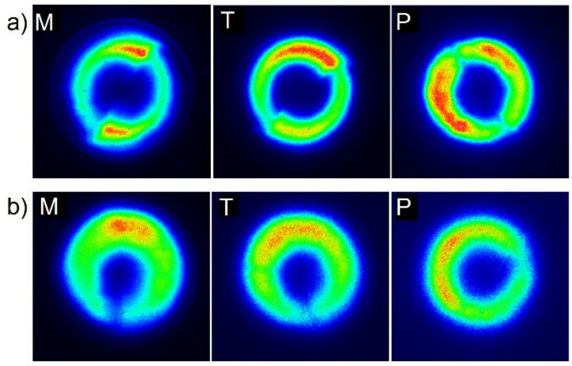

Fig. 1. Shape of the spoke in metallic mode M, transition mode T, and poisoned mode P. a) Al target in Ar/O2 gas mixture. b) Ti target in Ar/N2 gas mixture adopted from [2].

itself, where the current is rising from zero to over 100 A for a 2” target and the spokes form dynamically.

The rotation direction exhibits a strong dependence on power density and pressure. The exact values of power and pressure where the rotation direction changes depend on the geometry of the magnetron, with the shape and magnitude of the magnetic field having the most significant influence.

At very low power densities below 0.1 W/cm^2, it has been observed that the spoke rotation direction alternates on time scales of about 1 ms. In the power density range from 0.1 to 10 W/cm^2, the spoke rotation direction is opposite to the expected electron E x B drift (retrograde E x B rotation). At power densities between 10 W/cm^2 and 250 W/cm^2, the plasma starts to oscillate, which has been compared to breathing mode observed in Hall thrusters. Further increasing the power, the breathing plasma behaviour turns into disordered oscillations which are characterised by a stochastic behaviour. At power density of about 250 W/cm^2 the plasma spokes reappear with a spoke rotation in ExB direction. The threshold of the power density at which the transition takes place depends on target material, pressure, and magnetic field configuration. At power density above 2 kW/cm^2 and for certain combinations of target/background gas (in Ar: Cr, Au, Cu, Al, Ta, Mo, in Kr: Al, and in gasless environment: Cu) the spokes disappear and the plasma becomes completely homogeneous. In the homogeneous mode the system exhibits high impedance, as the plasma is dominated by self-sputtering. In this mode, substantially higher ion fluxes have been measured at the substrate. In reactive HiPIMS, the transition to a homogeneous plasma has not been observed for any target/gas combination. The transition to a homogeneous plasma at very high powers depends also on the target element/background gas combination, and the pressure.

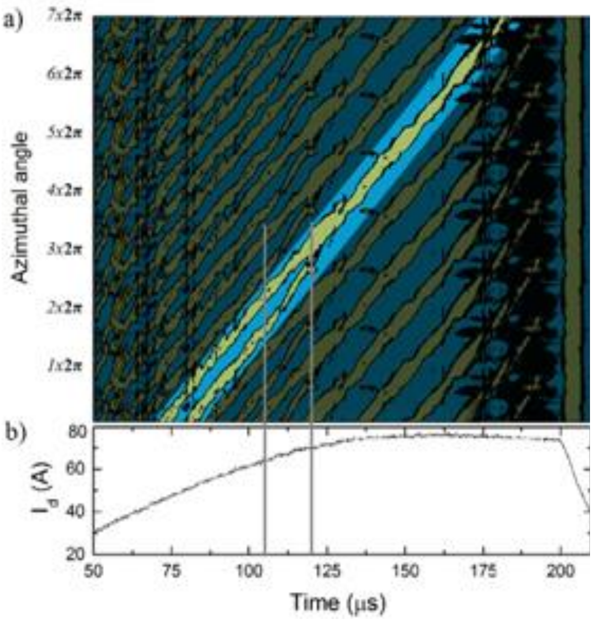

Fig. 2 (a) Floating potential oscillations recorded using the 12-probe setup. HiPIMS discharge with Cr target at 0.5 Pa. The light area emphasizes the transition between spoke mode 2 and spoke mode 1. (b) discharge current waveform, adopted from [8].

The dynamic of the spoke mode transitions can be directly observed by monitoring the plasma using probe arrays in real time [8]. Figure 2 shows a measurement obtained by stacking the floating potential measurement of twelve azimuthally distributed at probes on two of each other to show 7 revolutions of a spoke pattern on a 2" target. Two spokes are observed for discharge current from about 65 µs (discharge current I_d = 50 A) to 105 µs (I_d = 70 A). After 105 µs the discharge current increases beyond 70 A and two spokes merge with the trailing spoke reducing in size and accelerating until it merges with the other leading spoke. After 120 µs (I_d = 80 A) only one spoke remains, rotating along the racetrack. This merging of two spokes is explained by a competition between local Ar rarefaction at the location of a spoke and the replenishment of Ar behind the spoke along the racetrack: a spoke merger may occur with increasing target current when the larger local current through a leading spoke results in an enhanced local Ar rarefaction. In the wake of this larger spoke the Ar replenishment rate is reduced and the trailing spoke behind encounters a reduced neutral density. Consequently, the trailing spoke becomes smaller since fewer Ar neutrals are available to ionise and the E x B drift velocity becomes larger due to less friction with the neutral gas. The trailing spoke, therefore, catches up to the leading spoke and both merge.

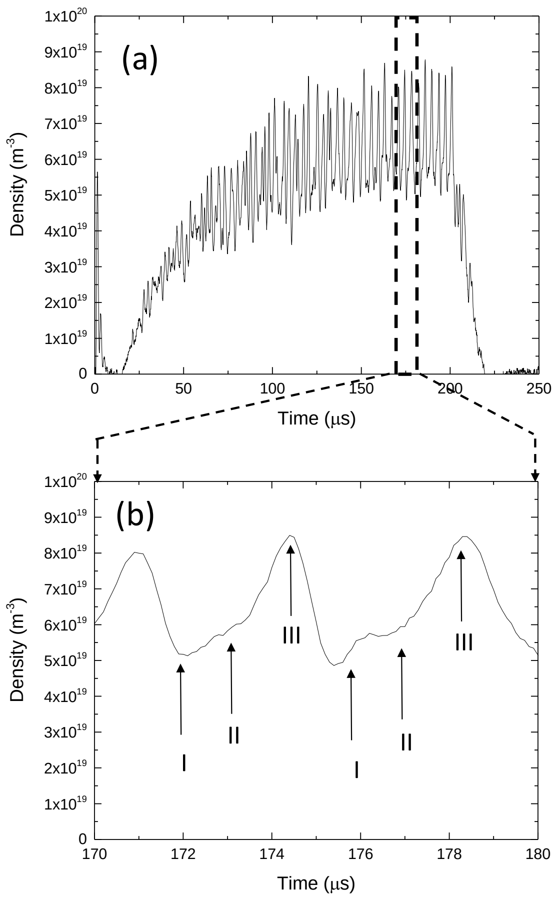

Fig. 3 (a) plasma density variation during the pulse, as deduced from the Child-Langmuir law; (b) plasma density variation between 170 µs and 180 µs. From [10]

3. Electron Densities in HiPIMS

The most important plasma parameter, however, is the electron density in the ionization zones, which is very difficult to measure directly, because any probe may not survive the intense plasma load and any optical method has to be triggered to the spoke movement. As a first indication, the local plasma density has been measured using probes inserted into the magnetron target. The custom made magnetron was designed to include 4 pins in the target, placed azimuthally at the racetrack, to measure the local current. The pins are biased to the same potential as the target, with main electrical connections separating to 5 lines (4 pins and the rest of the target surface) at the back of the magnetron stem tube. At the target the pins are placed flush with the target surface, but isolated with the Kapton tape, to allow independent measurement of the current flowing through the pin. The diameter of the pin was 4.9 mm, and the opening in the target was 5 mm. The small gap between the pin and the target was necessary to avoid any penetration of the plasma in the gap, which would result in a hollow cathode effect, and uncontrolled electron avalanche effect.

The evolution of the discharge current, and the current measured on one pin during a HiPIMS pulse is shown in figure 3. The peak of the current measured at the pin at 0 µs is an artefact due to capacitive pick-up by the current probe of the voltage switching. The discharge current exhibits an usual delay of about 20 µs, increase after the breakdown, and saturation after about 150 µs to the peak value of 50 A, with the discharge current waveform being relatively smooth. The current measured at the pin exhibits the same delay, but already during the current rise the current exhibits oscillations. After 150 µs the measured oscillations become steady, indicating steady spoke mode. The average value of the current at the pin is about 1 A, with current oscillating between 0.7 A and 1.2 A.

Assuming homogeneous plasma above the pin and collisionless sheath, we use the Child-Langmuir law to calculate the density at the sheath edge The calculated density at the sheath of 1.4×10^{20} m^{-3} is comparable to the Ar density of 1.2×10^{20} m^{-3} at 0.5 Pa and at room temperature, indicating highly ionised plasma. The density higher than the Ar density can be explained by understanding that the material sputtered from the target contributes to the density of species in the target vicinity.

4. Triggering the diagnostics to the spokes

A more detailed analysis of the spoke phenomenon requires elaborate triggering schemes to synchronize the data acquisition with the pulsing nature of the plasma itself, but also with the formation of the spokes during the evolution of each pulse. The latter process exhibits a stochastic nature, so that the data accumulation is not straightforward, but each pulse has to be treated independently. Several acquisition schemes had been developed, which allow now the accumulation of the information of a single ionization zone.

5. Conclusion

HiPIMS plasmas are very challenging and dynamic high performance discharges. The analysis of these plasmas is very challenging from an experimental point of view but also for modelling due to their inherent 3d nature. Nevertheless, the key control parameters and the fundamental aspects of the ongoing physics are now understood and the transfer of the knowledge from small scale research magnetrons to large scale industrial devices is on its way.

6. References

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