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SPECTROSCOPIC ANALYSIS OF A PULSED MAGNETRON DISCHARGE

P. Vašina[a,c*], M. Meško[a,c], J. C. Imbert[a], L. de Poucques[a], L. Teule-Gay[a], C. Boisse-Laporte[a], J. Bretagne[a] D. Pagnon[a], M. Touzeau[a], M. Ganciu[a,b]

[a]Laboratoire de Physique des Gaz et Plasmas, Université Paris-Sud, 91405 ORSAY Cedex France
[b]National Institute of Laser, Plasma and Radiation Physics, MG 36, Magurele, Bucharest, Romania
[c]Department of Physical Electronic, Masaryk University, Brno, CZ-61137, Czech Republic

To investigate the generation and transport of ions during and after a high power current pulse applied on magnetron cathode, we performed spectroscopic measurements with time and space resolution. The microwave antennas placed between target and substrate ensure proper conditions of current pulse development, ion transport and, by re-exciting sputtered species, allows spectroscopic emission measurements of species transported towards the substrate. Measured data are presented and discussed.

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1. Introduction

To improve the film quality as well as the deposition on complex surfaces (vias and trenches for highly integrated microelectronics, tools, connectors…) needed in industrial applications [1] works were developed on Ionised Physical Vapour Deposition (IPVD). In these reactors, the sputtered species of classical magnetron devices are ionised in the region between the target and the substrate by an additional source such as RF [2] or microwave discharges [3].

More recently, an alternative technique was explored which using magnetron discharges working in high power pulsed regimes [4]. Typical pulsed current density values in the order of 1 A/cm^2 are achieved (two orders of magnitude higher than in continuous DC magnetrons). This high current density ensures a high ionisation ratio of the sputtered vapour. In this work, the ionisation process and the transport of sputtered ionised vapour from the magnetron driven by high power pulses towards the substrate are studied by emission spectroscopy.

2. Experimental

The schema of our experimental set-up is presented in the Fig. 1. The reactor, described in details in [3] is 50 cm diameter and 45 cm cylinder height. It contains a planar rectangular titanium magnetron cathode and two coaxial-type microwave antennas located perpendicularly to the substrate-magnetron axis on both sides of the sputtered vapor flow. The magnetron cathode is driven by a high power adapted pulsed generator [5,6]. Microwave antennas are used for monitoring the sputtered species transport by particles re-excitation. They are located perpendicularly to the magnetron-substrate axis, 4.5 cm from magnetron, 8 cm from the axis. They are supplied by two 2.45 GHz 800 W generators and covered by metallic protection to avoid titanium deposition on the

* Corresponding author: petr.vasina@pgp.u-psud.fr, vasina@physics.muni.cz

quartz tube from the magnetron side. This protection induces a maximum electron density at the distance of 10 cm from the magnetron [3]. The quartz rectangular window at the top of the reactor allows spatially resolved measurements in the magnetron-substrate holder axis (z-axis). Spatially resolved optical emission spectroscopy is carried out using 13 collimators placed equidistantly with 1 cm step, the first was located at the distance of 0.2 cm from magnetron, the last 0.2 cm from substrate holder. The light emitted by the plasma is then collected into 13 optical fibers connected to an entrance slit of a imaging spectrometer ARC 500i equipped by an intensified CCD camera. This experimental configuration allows spatial resolution ~ 2 mm. The time resolution in the case of the active discharge is 1μs, whereas in the afterglow, time window is increased up to 10 μs to collect sufficient signal. Experiment was performed at the pressure of 4 Pa.

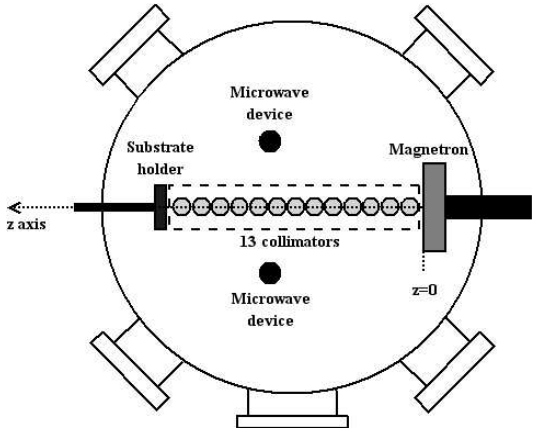

Fig. 1. Experimental set-up.

3. Results

Typical pulse shapes of the target voltage and current are presented in Fig. 2 together with the time evolution of the Ti I (363.5 nm), Ti II (398.5 nm), Ar I (750.4 nm) and Ar II (434.8 nm) line intensities taken from the second collimator placed at the distance 1.2 cm from the magnetron cathode. The magnetron current ~ 100 A is reached very quickly (~ 10 μs) when 1 kV of voltage is applied. At the early beginning of the pulse only Ar and Ar^+ lines are detected and after this initial phase, the intensities of these lines progressively decrease. Ti lines appear after certain time needed to transport first sputtered Ti in magnetised region. Ti^+ lines follow as the result of a strong ionisation.

In the Fig. 3, we report the time and space evolution of Ti and Ti^+ line intensities near in the magnetized region during the pulse. We observe that line intensities decrease rapidly for cathode distances higher than 2 cm which well correspond to the measured magnetic field distribution. As we go away from the magnetron cathode, tangential component of the magnetic field changes from 100 Gauss at the distance of 1 cm to 20 Gauss at the distance of 4 cm.

Species are re-excited in the magnetron-substrate holder area by the electrons produced by two microwave antennas (which run continuously) even after the magnetron pulse. So intensity variation in this region should follow the evolution of the species density and by time and spatially resolved optical emission spectroscopy we can monitor the transport of sputtered particles from the magnetron towards the substrate. Because microwaves run continuously, we could suppose that when the packet of sputtered particles reaches the region covered by certain collimator, the intensity of these species will be maximum for this collimator. Time and space evolution of Ti and Ti^+ line intensities and consequently Ti and Ti^+ densities at the magnetron-substrate holder area is presented in Fig. 4. Very strong Ti and Ti^+ lines intensities are observed during the magnetron pulse mainly by the first four collimator but some signal was detected even by the last one due to the reflection of the light by metallic vessel. After the pulse, there is a time (~200 μs) during which the emission is very low. After that, depending on the distance from the cathode we detect a maximum of emission

(~225 μs at 3 cm and ~275 at 10 cm for Ti) which seems to propagate with apparent velocity in the order of 1 km/s. Note that the maximum of both species intensities at the distance of 10 cm well corresponds to the area, where the density of electrons created by the microwave is maximal. We have still to keep in mind that our signal results from the product of time varying sputtered particle densities with almost time constant electron density.

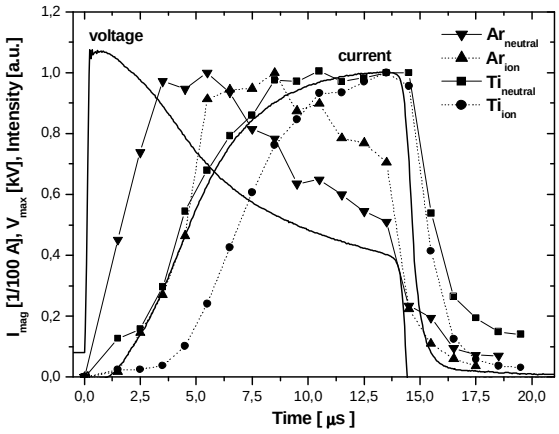

Fig. 2. Time dependences of the magnetron current, voltage and lines intensities taken from the magnetron area at distance 1.2 cm from target.

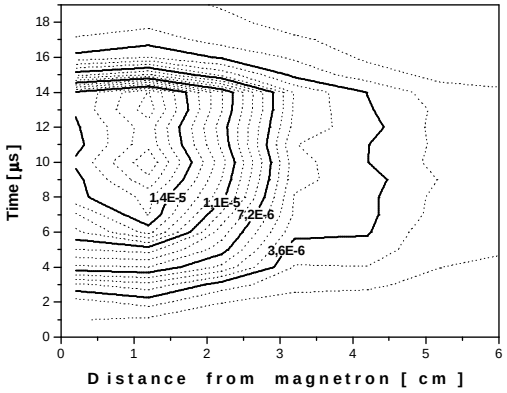

Fig. 3a. Time and space distribution of Ti line intensity near the target during the pulse.

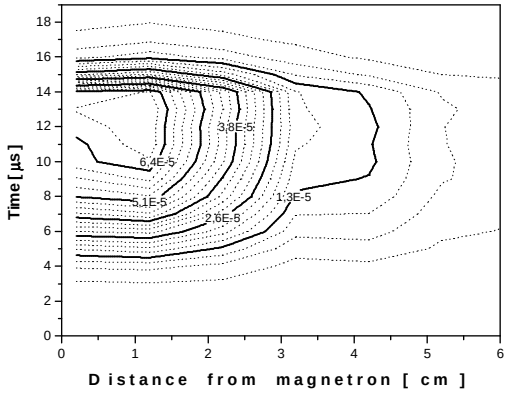

Fig. 3b. Time and space distribution of Ti^+ line intensity near the target during the pulse.

4. Discussion and conclusion

We observe from Fig. 2 that at the beginning of the pulse, the plasma is dominated by Ar ions and, as the time elapses, metallic ions are detected and become dominant. This transition was previously observed in [7,8] where similar shapes of the time resolved Ar and Ti lines were measured. However, in our case, the time needed to reach gas-metal plasma transition is about 5 times lower.

We can suppose that the fast and proper conditions for the current pulse development may be ensured by the well chosen preionization voltage (in our case ~ 100 V) and/or by the presence of electrons from continuously running additional plasma in the magnetized region.

From Fig. 4, we observed re-emission of Ti and Ti^+ at times depending on the distance from the cathode due to transport of these species. This is consistent with a ballistic transport of sputtered particles parallely with z-axis followed by simultaneous thermalization and scattering of sputtered particles by buffer gas to all directions. Sputtered particles emitted near the racetrack are transported towards the centre of the vessel where they are excited by electrons generated by the microwave plasma and observed through collimators. A delay of at least 200 μs is needed for the diffusion of low energy sputtered particles to the centre of the vessel.

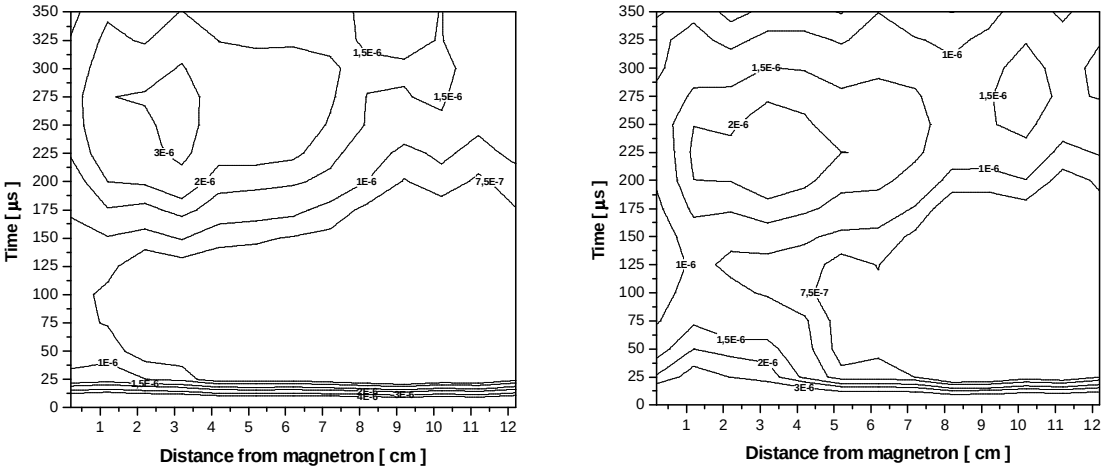

Fig. 4. Time and spatial evolution of Ti (left) and Ti^+ (right) intensities in magnetron-substrate holder area. At the distance of 10 cm, the density of electrons created by the microwaves is maximal.

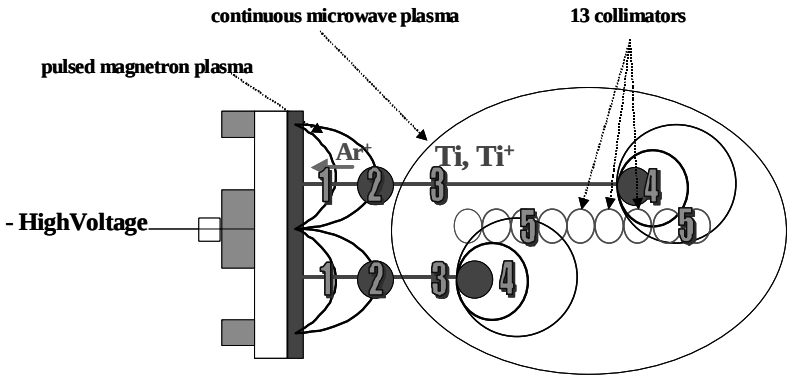

Fig. 5. Schematic representation of the relevant processes concerning the creation and transport of the species in the pulsed magnetron discharges.

This complicated process can be split into five elementary processes, one coming after another. This is schematically shown in Fig. 5. First, huge amount of Ti atom is sputtered by a pulse (1) and a part of them is ionised. After, they leave the magnetized plasma (2) and then, they follow the ballistic transport with velocity associated to the ejection velocity (3). After first collision with buffer gas atom, which changes the preferred particle momentum, thermalization and diffusion start (4). At the end, particles arrive and are re-excited in the observation axis region and light is detected in the certain collimator (5). A delay of ~ 200 μs is needed for diffusion of thermalized particles toward the central axis.

Now, it is clear that the apparent velocity, which was observed long time after the end of the pulse (~ 200 μs), is associated with the velocity of the particles sputtered during the pulse.

The difference in arrival times of Ti I and Ti II peaks are not completely explained; we can invoke various processes such as the different channels for the excitation of Ti* and Ti^+* emitting states and the cooling of plasma electrons by the metal vapour as well as different transport pathways for neutrals and ions.

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