Optical emission spectroscopy of a HiPIMS plasma with high spectral and time resolution

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Application Note

Introduction

In the recent years, high power impulse magnetron sputtering (HiPIMS) has established itself as the new standard in the deposition of high-quality hard coatings. Compared to traditional direct current magnetron sputtering, under which a low continuous voltage is applied, a HiPIMS discharge is driven with short high voltage pulses, leading to a higher ionization degree and thus better coatings. The pulsed nature of the discharge makes research of the physical processes involved particularly challenging, since all measurements have to be performed in a time-resolved manner. Of particular concern for application is the investigation of velocity distributions of sputtered species during the discharge pulses.
This application note describes the measurement of optical emission lines with high temporal and spectral resolution using an ICCD camera (iStar DH320T-25U-A3 from Andor Technology) as shift and shape of selected lines can yield the required insight.

Time-resolved intensities of emission lines

To perform the measurements, we used an old spectrograph (Zeiss PGS 2) with a high focal length of two meters and a grating of 1300 lines/mm. The spectrograph, originally designed for photo plates, was retrofitted with a stepper motor to change the wavelength in a motorized way and an iStar 320 ICCD camera to enable measurements with high time resolution. The iStar ICCD has 1024 x 256 x 26 µm pixels, resulting in a spectral resolution of about 8 pm (pixel-to-pixel) in the first diffraction order and up to 1.5 pm in the third.

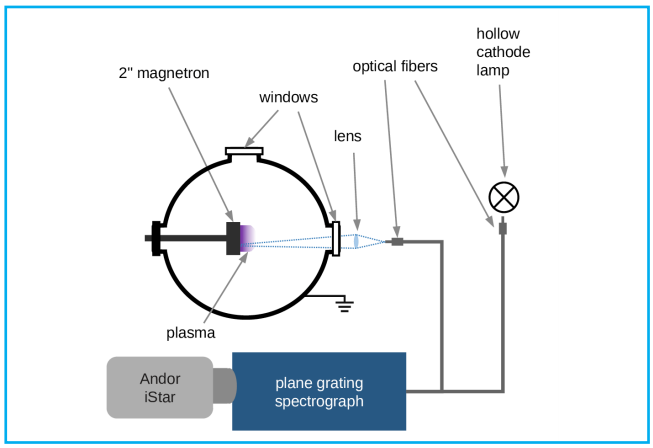

Figure 1: Experimental setup, adapted from [1]. The magnetron is covered by a Titanium target and operated as cathode.

Figure 1 shows the experimental setup. The plasma emission is coupled into an optical fiber using a lens and is transferred in front of the spectrograph's entrance slit. In this way the plasma emission can be observed. The camera is operated at full vertical binning and synchronized to the discharge pulse. Using the cameras digital delay generator, different points in time during the discharge pulse can be observed by varying the gate delay. In order to capture enough light, for each point in time the measurement is accumulated over a couple of 100 pulses. Using the "Kinetic series option of the camera, this complete time sequence can be automated. As an example, figure 2 shows the intensity evolution of spectral lines of neutrals and single or double charged ions of both argon and titanium. Here, the HiPIMS discharge was operated at 570 V using argon as base gas on a titanium target operated as discharge cathode. The voltage pulse length was set to 200 µs. Additionally, the discharge current is shown in gray on the right axis of figure 2.

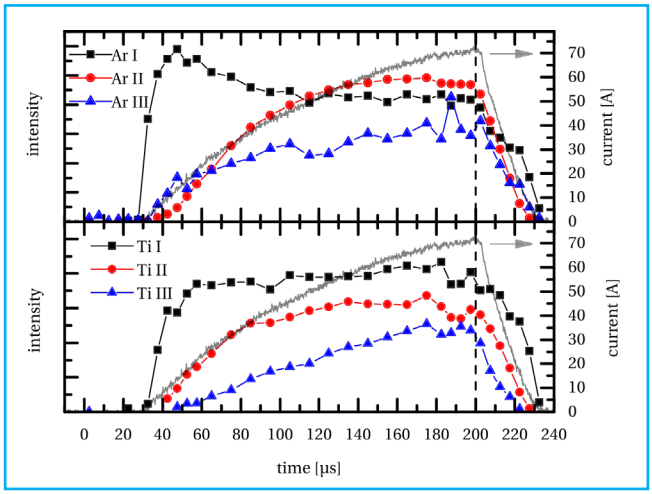

Figure 2: Evolution of multiple spectral line intensities of the course of the 200 µs long HiPIMS pulse. The discharge current evolution is additionally shown in gray on the right scale.

Initially, the discharge is ignited in argon, marked by strong emission from argon neutrals (Ar I) as the current begins to rise about 30 µs after the voltage is applied. Subsequently, a small part of the argon gets ionized and accelerated towards the cathode where the titanium gets sputtered. This is accompanied by a rise in titanium neutral emission (Ti I).

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As the current rises, the ionization degree gets higher and emission of single (Ar II, Ti II) and double (Ar III, Ti III) charged ions becomes observable [2].
This example illustrates the great insight that can be gained from time resolved measurements.

Time-resolved shift and broadening of emission lines
While the intensity evolution gives insight into the time evolution of the discharge, we were particularly interested in the movement of particles leaving the cathode surface. Because of the Doppler effect, particle movement causes broadening and shift of optical emission lines. With sufficient spectral resolution, it should be possible to determine the movement of particles as a line shift.

However, for this purpose it is necessary to have a precise reference showing the unshifted emission line. Therefore, the setup shown in figure 1 includes a hollow cathode lamp (HCL) as a reference for the unshifted emission line. In order to measure plasma and HCL emission at the same time, a special optical fibre was designed to simultaneously illuminate different parts of the spectrograph's entrance slit with the emission of the respective source.

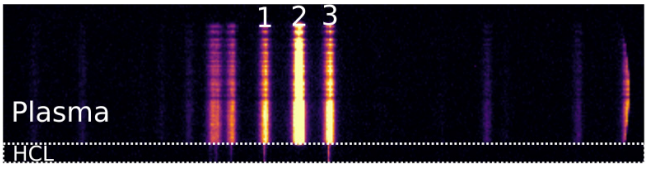

Figure 3: False color image of the spectrograph's camera. The entrance slit is illuminated by the plasma (upper part) and the hollow cathode lamp (HCL) simultaneously. The plasma emission is visibly broadened. Three lines are marked in the figure: 1) Ti I 453.478 nm, 2) Ti II 453.396 nm and 3) Ti I 453.324 nm.

Figure 3 shows a false color image of the spectrograph's camera with both the plasma emission and the HCL emission visible. The plasma emission illuminates the upper part of the entrance slit. Only a small part of the lower part of the entrance slit is illuminated by the HCL emission. The plasma emission lines are clearly broadened as compared to the HCL lines. Additionally, a small shift can be observed, especially on the third of the lines marked in the picture. This line is the titanium neutral line at 453.324 nm and the shift is caused by the particle movement away from the cathode surface. Using the cameras multi-track feature, each part of the image is binned separately and figure 4 can be obtained.

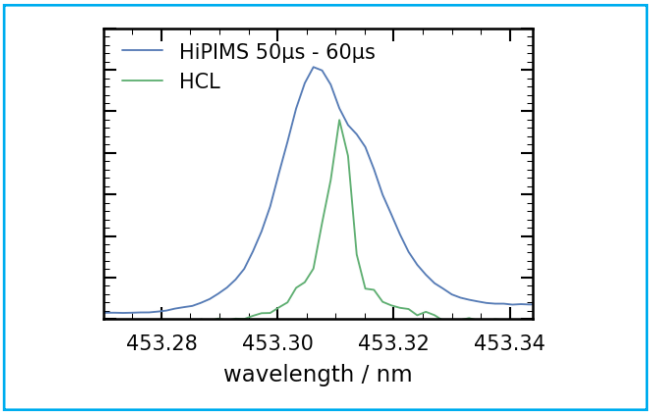

Figure 4: Titanium neutral emission line at 453.324 nm from the plasma and the hollow cathode lamp, taken simultaneously 40 µs to 50 µs after voltage switch on using the cameras multi-track feature.

In this way, we could follow the time evolution of the velocity distribution function of sputtered particles in HiPIMS. A physical model was fitted to the emission line, to show, that the velocity distribution of sputtered titanium neutrals can be described by the sum of a Thompson and Maxwell velocity distribution function. As they travel from the target towards the substrate, most of the particles seem to experience multiple collisions already in the first 5 mm distance to the target surface.

References

The results have been presented in detail in [1].
[1] J Held et al 2018 Plasma Sources Sci. Technol. 27 105012.
[2] A Hecimovic et al 2012 Plasma Sources Sci. Technol. 21 035017

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