*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-1.070 (2009)*

ENERGY INFLUX MEASUREMENTS IN HiPIMS PLASMAS

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Introduction

The energy per incoming particle and the particle flux are essentials in plasma processing of solid surfaces, particularly in the case of thin film growth. The product of these two quantities constitutes the energy flux, which is a key parameter when investigating the energetic conditions at the surface of a growing film [1,2].

At present, high power impulse magnetron sputtering (HiPIMS) is one of the most promising techniques for improving common magnetron sputtering used in many industrial processes for thin film deposition [3]. The HiPIMS plasma generates large quantities of highly energetic ions with, in some cases, a directed flux of charged species. The transport of these energetic particles is not fully understood, but it is clear that they have a dramatic effect on thin film growth, such as densification and improved adhesion [2,4].

In this study, the spatial distribution of the total energy flux in a HiPIMS plasma has been investigated using thermal probes [5]. The average power was varied and the results were compared to conventional direct current magnetron sputtering (DCMS) discharges.

Experimental

A standard planar circular magnetron with a diameter of 15 cm, equipped with a Ti target mounted in a cylindrical vacuum chamber (height 70 cm, diameter 44 cm) was used in the present experiments. The chamber was pumped by a turbo-molecular pump to a pressure of about 1.5×10^{-4} Pa, after which 0.53 Pa of Ar was let into the chamber. High-voltage pulses were applied between the cathode (target) and the chamber walls using a HiPIMS power supply, 100 µs pulses were used at a repetition frequency of 100 Hz. The applied voltage was varied between 720 – 800 V resulting in a peak current of about 270 – 500 A and an average power of approximately 500 – 615 W. For DCMS reference measurements the same power supply was used to deliver constant voltage (~ 330 V) and current (~ 1.5 A) to match the average power in the HiPIMS discharge. The energy flux from the plasma was measured using thermal probes [5]. The probes were mounted on a movable rod for scans taken at different axial as well as radial positions as seen in Figure 1. Furthermore, the probe and rod could be rotated in order to measure directional fluxes. The principle for measuring the energy flux is based on the rate of change in temperature of the substrate (probe), dT_S/dt, which implies measuring the temperature characteristic during the heating process during plasma-on, and the cooling after the plasma has been switched off [5,6].

If the incoming power, P_{in}, is constant during the heating process and the heat loss, P_{out}, is only a function of T_S, then for each temperature, $\tilde{T}$, measured during the heating and the following cooling processes the incoming power can be calculated by

$$P_{in}(\tilde{T}) = C_S \left[\left(\frac{dT_S}{dt} \right)_{heat} - \left(\frac{dT_S}{dt} \right)_{cool} \right]_{\tilde{T}}$$

If the slopes of dT_S/dt are determined under the condition that the measurement starts and ends at equilibrium temperature together with the exact knowledge of the heat capacity, then P_{in} can easily be determined. The heat capacity, C_S, is measured by applying a known power to the substrate surface e.g. by using a laser or electron beam. In the present work C_S was in this way estimated to an average of 0.3 J/K for all probes used.

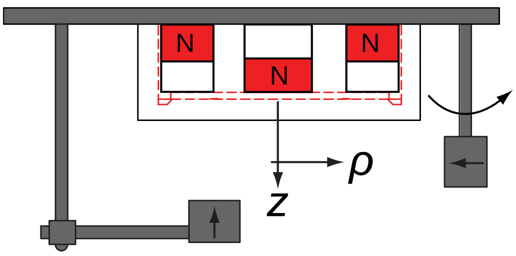

Figure 1: Schematic of the top-mounted magnetron and the probes measuring axial and radial (ρ) energy flux.

The energy flux consists of different contributions, such as radiation from the environment (plasma and chamber walls) as well as kinetic and potential energy from energetic particles in the flux. These different constituents are not easily separated in any measurement, but by a combination of several experiments it is possible to map out the energy transfer in more detail [6].

Results and Discussion

The radial (ρ) as well as axial (z) distribution of the energy flux in a HiPIMS plasma of approximately 500 W power (average) is presented in Figure 2. The thermal probe is facing the magnetron, and is thus picking up the same axial heat flux as a substrate would for the same position. The shape of the energy flux profile indicates that the total heat flux increases towards the surface of the magnetron, and peaks in a region between the race track (ρ ~ 4.5 cm) and the rim of the magnetron. Directly in front of the cathode (z ~ 4 cm) the energy flux is twice as large at ρ ~ 8 cm compared to the center at ρ ~ 0 cm. As we move away from the cathode surface the energy flux gets more homogeneously distributed, and at z > 10 cm the radial variation of the energy flux is rather small. Outside the magnetron (ρ > 8 cm) the flux decreases rapidly.

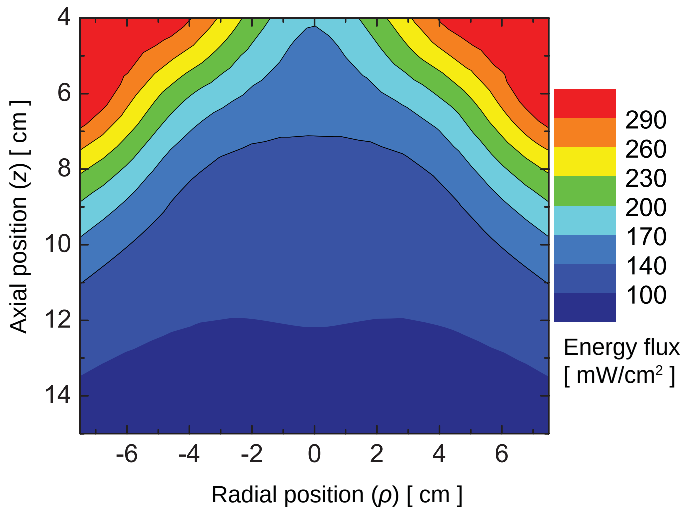

Figure 2: Energy flux using HiPIMS at 500 W measured with the thermal probe facing the magnetron surface.

A comparison of the energy flux between HiPIMS and DCMS at approximately the same average power is presented in Figure 3 for different axial positions. The probe was placed above the race track of the circular magnetron ($\rho = 4.5\,\mathrm{cm}$) facing the magnetron surface. In all cases the measured values for HiPIMS are lower than those of the DCMS discharge. The fraction J_{HiPIMS}/J_{DCMS} can be estimated to 32-48 % depending on the axial distance. Previous measurements using the same setup show that the deposition rate ratio for Ti between DCMS and HiPIMS is about $rate_{HiPIMS}/rate_{DCMS} = 0.2$. Taking this into account one can conclude that 90 % more energy per particle is deposited on the substrate in the HiPIMS case. This is not surprising when considering that there is a much larger proportion of highly energetic ions in the HiPIMS discharge [5].

Furthermore, the same data was used to estimate the fraction of the total applied discharge power used for substrate heating in HiPIMS and DCMS. A discharge power of about 500 W results in a power density of 2.83 W/cm^2 on the target (15 cm in diameter).

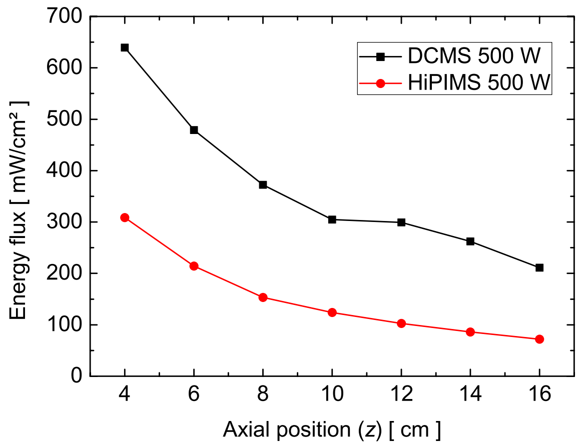

Figure 3: Comparison between HiPIMS and DCMS at approximately the same average power.

From Figure 2 the position $z = 10\,\text{cm}, \rho = 4.5\,\text{cm}$ was chosen, since it is a commonly used target-to-substrate distance for this deposition system and located at the same radial position as the race track. For the HiPIMS case the average energy flux is about 120 mW/cm^2, resulting in 4 % of the average discharge power is converted into heating the substrate. The corresponding value for the DCMS case is 300 mW/cm^2, i.e. about 10 % of the discharge power is converted into substrate heating.

Conclusion

Thermal probes were successfully used to measure the energy flux at different positions in a HiPIMS discharge. It was found that the substrate heating is severely reduced in the HiPIMS process compared to conventional DCMS at the same average power. The maximum temperature reached at the substrate position was found to be very low for the HiPIMS discharge making it suitable for coating thermally sensitive substrates.

References

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