IOP Conf. Series: Journal of Physics: Conf. Series **1115** (2018) 032020 doi:10.1088/1742-6596/1115/3/032020

# Operation parameters of magnetron diode for high-rate deposition of aluminum films

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**Abstract**. This article reports on the results of the detailed study of erosion of Al target in magnetron discharge plasma. It was demonstrated that the combination of middle-frequency (MF) and high impulse power (HiPIMS) power supply results in the significant increase of deposition rates of Al films by changing of sputtering yield. The MF pulse assists HiPIMS discharge to transit in a high power mode.

## 1. Introduction

High-current pulsed magnetron sputtering (HiPIMS) is an perspective and effective tool for thin-film deposition [1, 2]. The main feature of HiPIMS technology is a formation of high power density (by 1-2 orders of magnitude higher than for DC sputtering) in a pulse. It results in higher ion flux (ions of gas and target material) to the substrate. To prevent target overheating, this type power supply usually generates low-frequency pulses (0.1-10 kHz) with duty cycle lower 10%.

However, the technology of HiPIMS is characterized by the significant decrease of deposition rates of coatings (~30...70% [1]), which is caused by several factors. It is the effect of electrical discharge parameters, the influence of sputtering mode (by gas ions or target ions), the decrease of atom flux to the substrate due to their ionization and etc. [2]. All of them have already been sufficiently well studied. So, the main research direction in the HiPIMS technology is the search for methods of increasing deposition rates.

Thus, the paper is devoted to search operation parameters of magnetron diode with HiPIMS power supply to increase deposition rate. Special to this, the power supply with low- and high-current pulses were used to increase the deposition rate of Al coatings.

The choice of Al as a target material is due to its high thermal conductivity (236 W/m·K), which is important in view of high thermal load on the cathode. Moreover, Al films have a lot of applications in nanoscale industry. Such films are used as reflective layers in optics [3].

## 2. Experimental part

This work was carried out by using the ion-plasma installation (figure 1) equipped by an ion source, a magnetron sputtering system, a rotating substrate holder (2 rpm) and an optical two-channel spectrometer AvaSpec ULS-2048L2. The base pressure was $5\cdot10^{-3}$ Pa. The distance from sputtering target to substrate was 100 mm.

The unbalanced magnetron sputtering system with disk (90 mm in dia) Al target was used. The purity of Al was 99.99%. To control electrical output parameters of the magnetron, the digital oscilloscope Tektronix TDS 2022B was used.

For the experiment, a combined (MF + HiPIMS) power supply was developed based on standard power supplies APEL-M-5PDC and APEL-M-5HiPIMS.

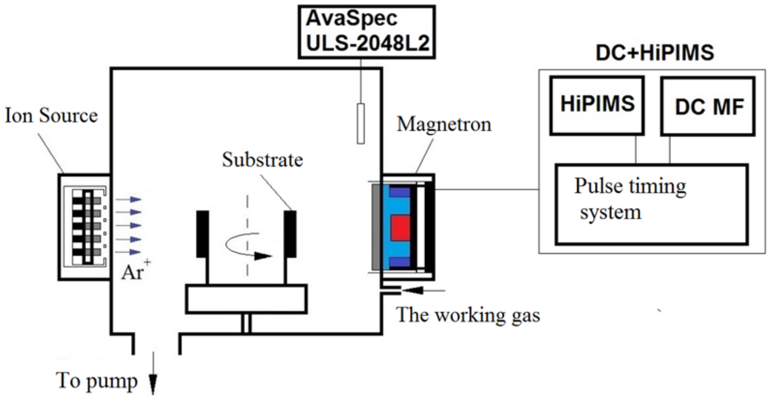


**Figure 1.** The scheme of ion-plasma installation.

The synchronization system provides consecutive low- and high-current pulses with a fixed pause (10...100 μs) after a high-current mode. The voltage and current of the combined power supply is shown in figure 2.

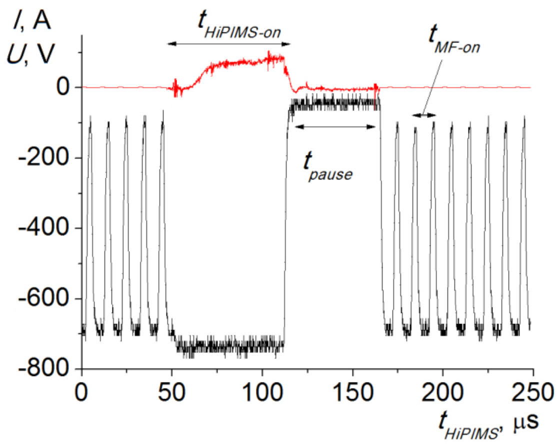


**Figure 2.** The voltage and current of the combined power source: $t_{HiPIMS\text{-}on}$ – HiPIMS pulse, $t_{MF\text{-}on}$ – low-current pulse, $t_{pause}$ – fixed pause.

## 3. Results and discussion

Figure 3a shows the voltage-current characteristics of the magnetron discharge generated by high-current power source (HiPIMS) and combined power supply (MF + HiPIMS). It is shown that the pre-sputtering of Al target by MF power in front of a high-current pulse leads to a decrease operation voltage and an increase in the average discharge current. In this case, preliminary ionization by MF power supply can promote a faster output of the magnetron diode to the high-power mode [4]. This is obvious in the behavior of voltage-current characteristic with increase of pulse durability.

Similar results were obtained by changing the operation pressure (figure 3b). Moreover, the high-current mode can be more stable at lower operation pressure, when the combined power supply is used. In this case, the residual concentration of charge carriers after the low-current pulse makes it possible to form a plasma discharge even at lower pressure. Al target sputtering in HiPIMS mode at extremely low operating pressure (<0.1 Pa) was unstable. In view of the pause between high-current pulses, the formation of plasma discharge was difficult, plasma can diffuse to walls of vacuum chamber and dissociate. The using of combination of low- and high-current pulse makes the sputtering process more predictable.

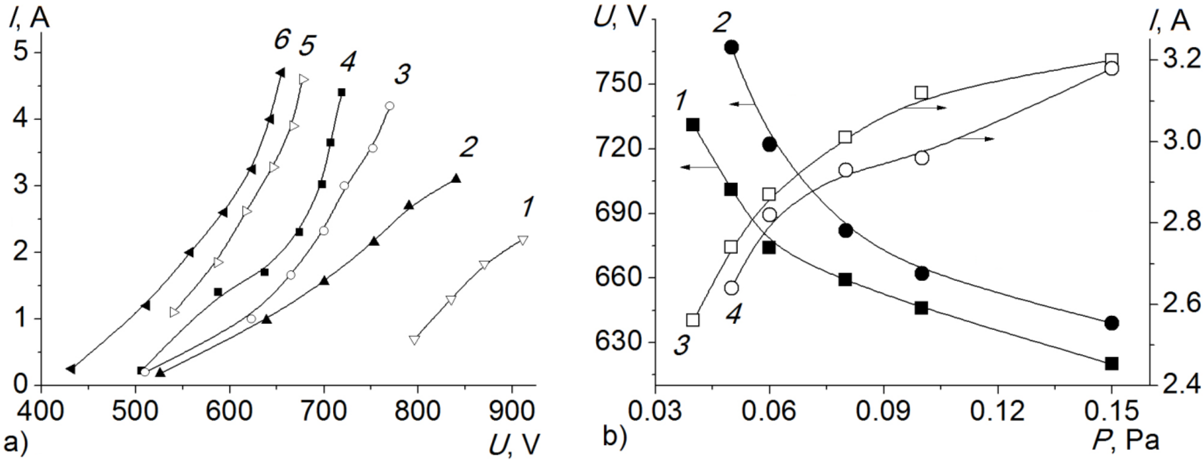


**Figure 3.** (a) Voltage-current characteristic of magnetron diode with HiPIMS (1 – 30 μs, 3 – 60 μs, 5 – 90 μs) and combined power supply (2 – 30 μs, 4 – 60 μs, 6 – 90 μs). (b) Evolution of voltage and current for power stabilization mode: 1, 3 – MF (0.6 kW) + HiPIMS (2 kW); 2, 4 – HiPIMS (2 kW).

Figure 4 shows the evolution of optical signals from neutral and ion components of the plasma discharge with variation of HiPIMS pulse duration. For the combined power supply, higher intensity of signals is determined. It can be caused by enhanced emission process from Al target and higher quantity of ions in discharge due to the pre-ionization stage (by MF power supply) before high-power mode.

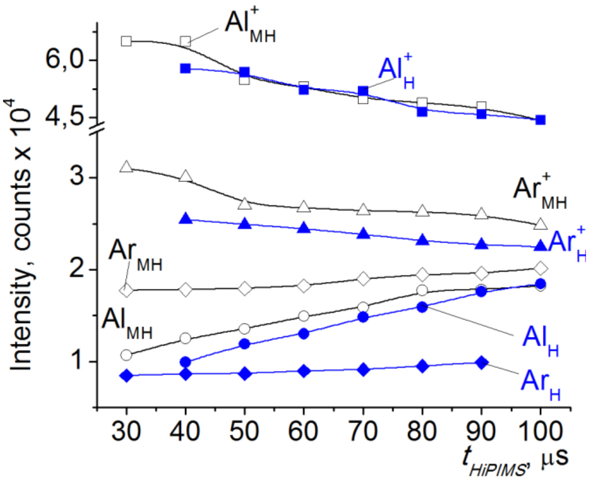


**Figure 4.** The intensity of optical signal from plasma component for Al target sputtering by using HiPIMS ($Al^+_H$, $Ar^+_H$, $Al_H$, $Ar_H$) and combined power supply ($Al^+_{MH}$, $Ar^+_{MH}$, $Al_{MH}$, $Ar_{MH}$).

Figure 5a shows the deposition rates of Al films using different power supplies. There is a significant increase, when the combined power supply was used. Sputtering yield (*Y*) has a strong dependence from energy of the incident ions. Special to this, TRIM calculation were performed to evaluate sputtering rate in the cases of using HiPIMS and combined power supplies.

Figure 5b presents the dependence of the sputtering yield of Al target, bombarded by Ar ions. This data were determined by calculation in the TRIM-2008 program [4]. According to the data, the change of sputtering yield under variation electrical discharge parameters for HiPIMS and combined power supply leads to 8...13% increase of the deposition rate of Al films. In addition, the growth of Ar ions, which is observed to combined power supply, reduces the possibility and intensity of self-sputtering mode. This process has a significant influence of deposition rates (decrease) due to sputtered particles of Al target can be ionized in plasma discharge and, then, accelerated to the target. Thus, sputtered particle flux to the substrate is lower in comparison with direct current or MF sputtering.

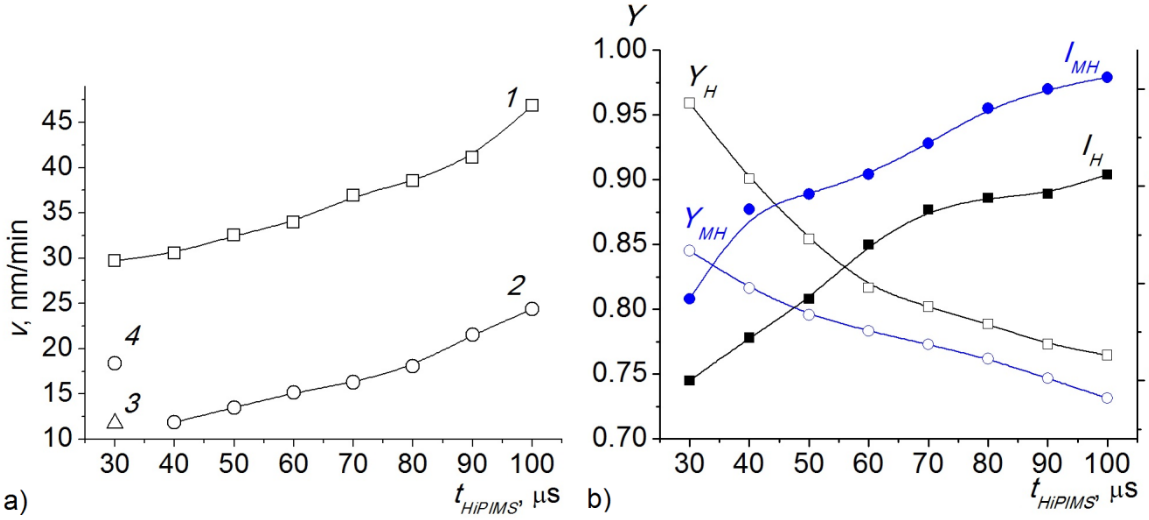


**Figure 5.** (a) Deposition rate of Al film on the rotating substrate by using: 1 – combined power supply (MF – 0.6 kW and HiPIMS – 2 kW), 2 – HiPIMS power supply (2 kW), 3 – MF power supply (0.6 kW), 4 – HiPIMS power supply (2.6 kW). (b) The dependence of sputtering yield of Al target and average discharge current for combined ($Y_{MH}$, $I_{MH}$) and HiPIMS ($Y_H$, $I_H$) power supply.

## 4. Conclusion
The article shows that deposition rate of Al films by magnetron sputtering can be enhanced, when the combination of low- and high-current pulses are applied. In this case, lower voltage and higher average discharge current are observed. It results in the increase of sputtering rate of target and lower possibility to the self-sputtering mode.

## Acknowledgments
This work was supported by the Russian Foundation for Basic Research (project no. 18-38-00676 mol_a).

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