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Power supply for mid-frequency magnetron sputtering with a wide-range control of pulses parameters

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Abstract. The paper presents a description of a pulsed power supply of a magnetron sputtering system with a power of 10 kW, which has a wide range of output parameters, such as the amplitude, the frequency, and duration of voltage pulses. High values of the pulse current (up to 100 A) and voltage (up to 1800 V) provide the ability to work at low duty cycle, which in turn allows to increase the value of the ion current on the substrate. It has been experimentally found, that changing the frequency and duration of the pulses can increase the ion current density to the substrate while maintaining the average discharge power.

1. Introduction

Medium-frequency magnetron sputtering (MFMS) is a well-known high-quality coating method that has been used on an industrial scale for many years [1, 2]. The advantages of this method are clearly presented in the reactive modes (in the O_2 or N_2 environment) of the dielectric coatings deposition. Pauses between negative voltage pulses allow removing the charge accumulated by the dielectric film on the surface of the target and leading to the formation of arcs [3]. This ensures high process stability and prevents the formation of defects in the coating in the form of microdrops [4]. It is known that the parameters of the pulsed power supply have a significant effect on the parameters of the magnetron discharge, as well as on the structure and properties of the coating. For example, during transient processes at the beginning and end of the discharge current pulses, the plasma potential changes and high-energy electrons are generated [5].This leads to a change in the ionic effect on the growing coating, which causes a change in its structure and properties. The amplitude, frequency and duration of the pulses, along with the average values of voltage, current, and discharge power, are parameters that can be used to control the coating deposition process. The probability of finding the optimal deposition mode depends on the range of variation of these parameters. To ensure a wide range of adjustment of the frequency and duration of pulses, the power supply should have elements with a high switching speed, and be able to change the values of the output voltage and current over a wide range.

This paper describes the developed power supply (APEL-M-10PDC/DU-200k Applied Electronics LLC, hereinafter APEL-M), which has more capabilities than conventional power supplies designed for MFMS.

2. Experimental part

Typically, MFMS uses current pulse generators with a frequency of 5–350 kHz and an output voltage of up to 1000 V (Table 1). The maximum pulse value of the output current is not much higher than the average value of the current, and the duty cycle *D* (percentage of the ratio of the pulse duration to the total period) does not fall below 50 %. The APEL-M power supply has an expanded range of variation of the output voltage to 1800 V and the maximum value of the pulse current to 100 A, which allow to significantly increase the pulse output power. In addition, the power supply is able to work with various types of magnetron sputtering systems (MSS), both with single targets and with dual.

Table 1. The parameters of MFMS power supplies

Parameters	APEL-M-10PDC-200k (Applied Electronics LLC)		AE Pinnacle Plus+ (Advanced Energy)	TruPlasma Bipolar 4010(G2) (Trumpf)	SPIK2000A-10 (Melec GmbH)
	LV	HV			
Maximum voltage	900 V	1800 V	800 V	1000V	1000
Average current	22 A	11 A	30.8	25 A	10 A
Average power	10 kW		10 kW	10 kW	10 kW
Max. pulse current	100 A	50 A	30.8	25 A	200 A
Duty cycle, pulse and pause duration	10 – 100 %, pause 2 – 950 μs		≥ 55% (pause 0.4÷10 μs)	Pause 1 – 10 μs	Pulse ≥ 5 μs
Frequency	1 ÷ 200 kHz		5-350 kHz	20-80 kHz	≥ 50 kHz

Figure 1 shows the APEL-M power supply block diagram. The device is powered by a three-phase network. At the input, there are a network rectifier and an inverter, which converts the rectified direct voltage into alternating one. The inverter generates sinusoidal current pulses, which are fed to the primary winding of the step-up transformer VT. The transformer has two secondary windings connected to high-frequency rectifiers. Storage capacitors are charged through rectifiers to voltage U_c. Capacities smooth out the output voltage ripple and provide a high pulse output current. Between the storage capacitance and the output of the source are pulse formers (PF1 and PF2) having a bridge circuit. The bridge circuit allows the formation of unipolar (UP) and bipolar (BP) pulses, which provides the ability to work with single and dual MSS. In this paper, UP mode is considered for working with a single-target MSS. In this case, two of the four power transistors operate in each pulse former PF. At the output of the pulse former there is a small inductance, limiting the rate of growth of the output current.

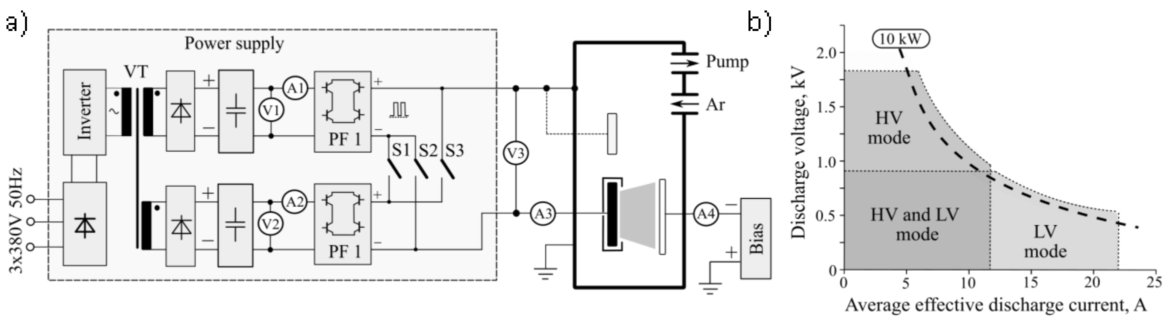

Figure 1. Scheme of APEL-M power supply, vacuum coater (a) and range of output voltage and current in the LV and HV modes (b).

The load distribution between several power modules allows for high output characteristics of the source, avoiding the use of powerful and expensive elements. Earlier, we already used the modular principle of power supply system's building, which allowed us to provide an output power of 80 kW [6]. In the present case, the modules are PF1 and PF2, between which the output voltage or current is distributed, depending on the way they are connected. The use of two pulse formers allows reducing static power losses in each of them. Due to this, it is possible to increase the maximum frequency of pulse formation to 200 kHz and the amplitude of the output current pulses to 100 A, which entails an increase in dynamic power losses. Table 1 presents the main parameters of the power supply. For comparison, the table also shows the parameters of several well-known brands of power supplies for MFMS with the same average output power (10 kW).

On the output of APEL-M power supply, there is a commutator that changes the connection configuration of pulse formers and, accordingly, the operating mode of the power supply. In the case when the keys S2, S3 are closed and S1 is in the open state, PF1 and PF2 are connected together in parallel, and the power source operates in low voltage (LV) mode. The output current of the formers is summed at the output. When S1 is closed and S2 and S3 are open, PF1 and PF2 are connected in series. In this case, the power source operates in high voltage (HV) mode, and the voltage of the formers is summed at the output. Figure 1 schematically shows the available range of output current and voltage in LV and HV modes. In LV mode the nominal output power of 10 kW is provided in the voltage range of 500–900 V. In HV mode the same power can be maintained in the voltage range of 900–1800 V. The transition to the HV mode allows the MSS to operate at a reduced working pressure in the vacuum chamber, to sputter high resistivity targets, and also to maintain magnetron discharge at a low duty cycle.

The experiments using the APEL-M power supply were carried out at the installation, a diagram of which is shown in Figure 1. An extended MSS with a 400×100×10 mm^3 rectangular aluminum target was located in the vacuum chamber. At a distance of 10 cm from the target surface, a flat substrate 400 × 200 cm^2 in size was located. It was used to measure the ion current to the substrate. The shape of the pulses of the discharge current and voltage was recorded by sensors of current (A3) and voltage (V3) connected to the outputs of APEL-M power supply. When studying the influence of the frequency and duty cycle on the electric parameters of the discharge, the average values of the voltage across the storage capacitors (sensors V1 and V2) and the average values of the current flowing from the storage capacitors to PF1 and PF2 (current sensors A1 and A2) were recorded.

The current flowing in the output circuit of the power source includes a reactive component. Part of the energy stored in the output inductance is returned back to the power supply and does not enter the load. As the pulse formation frequency increases, the fraction of reactive energy may increase, making it more difficult to control the active output power [7]. In the APEL-M power supply, current measurement is performed at the PF1 and PF2 inputs. During recuperation, the current flows in the opposite direction, which eliminates the reactive component. The average output current we call the effective current I_{eff}. If I_{eff} is multiplied by the voltage of the storage capacitance, we get the active power entering the load without taking into account the power losses in PF1 and PF2. When changing the operating mode (LV or HV), the methodology for calculating the effective current and voltage changes.

During the experiments, a negative bias potential of 50 V from an additional source was applied to the flat probe (15 mm diameter) with guard ring. The A4 current sensor recorded the average ion current on the substrate. The vacuum chamber was pumped to the base pressure of 4×10^{-4} Pa, the working pressure of argon gas was 0.67 Pa. In all experiments, the constant average discharge power was 4 kW and limited by the capabilities of the magnetron cooling system.

3. Results and Discussion

Figure 2 shows the waveforms of the pulses of the discharge current and voltage obtained at a pulse frequency of 5, 10 and 80 kHz. The APEL-M power supply is a voltage source. Therefore, voltage pulses in all three cases have a rectangular shape. An increase in frequency at a constant average power leads to an increase in the amplitude of voltage pulses, a decrease in amplitude, and a change in the shape of current pulses. The dashed lines on the figure show the voltage across the storage capacitance U_c and the effective current I_{eff}. The amplitude of the voltage pulses is almost equal to U_c, and the value of the current pulse in all three cases is more than twice as large as I_{eff}.

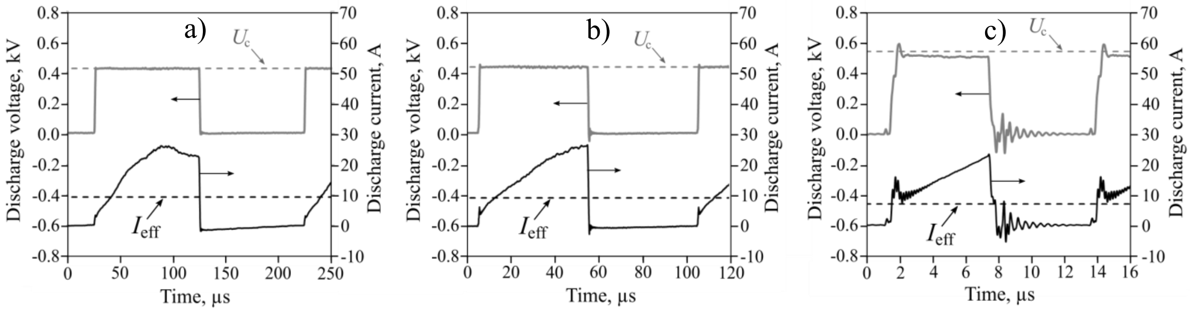

Figure 2. Oscillograms of pulses of discharge current and voltage at different pulse formation frequencies: (a) 5 kHz, (b) 10 kHz and (c) 80 kHz (P = 4 kW, D = 50%).

Figure 3a, b, c shows the dependences of discharge voltage, peak discharge current and substrate current density on pulse frequency. The density of ion current to the substrate was averaged over one pulse period. Figure 3a shows that an increase in the pulse frequency leads to a smooth increase in discharge voltage. Since the power supply stabilizes the average output power, which equals to

$$P = U_c \cdot I_{eff},$$

an increase in voltage is accompanied by a decrease in the average effective current. The peak discharge current increases in the range of 1–20 kHz. At frequencies greater than 20 kHz, it decreases. The density of the ion current on the substrate changes in a similar way. Its sharp increase in the low-frequency region is replaced by a smooth decrease with a further increase in the pulse frequency. The similar character of the dependences in Figures 3b and 3c indicates that the ion current density to the substrate strongly depends on the amplitude of the pulses of the discharge current. The minimum ion current density of 150 mA/cm^2 is observed at a frequency of 200 kHz, and the maximum (250 mA/cm^2) at frequencies of 20–30 kHz. Thus, a change in the frequency of pulse formation at fixed values of the duty cycle and average discharge power allows us to adjust the density of the ion current on the substrate, and therefore the amount of energy transferred to the coating as a result of ion bombardment.

Also, a change in the ion current density can be achieved by changing the pulse duty cycle. Figure 3d, e, f shows the dependences of the discharge parameters on the duty cycle obtained at a frequency of 10 and 80 kHz. A decrease in the duty cycle in both cases leads to an increase in the discharge voltage and a decrease in the effective current. The amplitude of the current pulses increases together with the voltage. This leads to a significant increase in the pulse power of the discharge. At a frequency of 80 kHz and a duty cycle of 20%, the amplitude of the current pulses reaches 30 A at I_{eff} = 4.4 A. The pulse discharge power in this case is 24 kW, and the power density on the magnetron target is 30 W/cm^2. At a frequency of 10 kHz and a duty cycle of 16%, the amplitude of the current pulses reaches 80 A (at I_{eff} = 6.5 A), which allows providing a pulse discharge power of 48 kW and a power density of 60 W/cm^2. Thus, the pulsed values of the power density on the target surface are several times higher than the average value (5 W/cm^2). An increase in the amplitude of current pulses and pulsed power density leads to an increase in the ion current density on the substrate. A decrease in the duty cycle makes it possible to increase the ion current density from 0.16 mA/cm^2 to 0.26 mA/cm^2 at a pulse frequency of 80 kHz, and from 0.2 mA/cm^2 to 0.36 mA/cm^2 at a frequency of 10 kHz. The experimental results confirm that, along with the frequency of pulse formation, the ion current density on the substrate can be controlled by changing the duty cycle.

The pulsed discharge parameters at low values of the duty cycle observed in this work approach the values characteristic of high-power impulse magnetron sputtering (HIPIMS) processes. HIPIMS is a pulsed magnetron sputtering technology based on the application of low-frequency pulses with a low duty cycle. As a rule, the pulse repetition rate does not exceed 5 kHz, and the duty cycle is below 10%.

The low duty cycle of pulses allows to manifold increase the pulse power of the discharge relative to the average power, which leads to a high plasma concentration, the high degree of ionization of the atomized material and a high ratio of ion/atoms flows arriving at the substrate [8]. Such conditions favor the formation of high-quality films, however, due to the effect of the ionized material returning to the target [9], HIPIMS has a lower coating deposition rate compared to MFMS and is still of limited use.

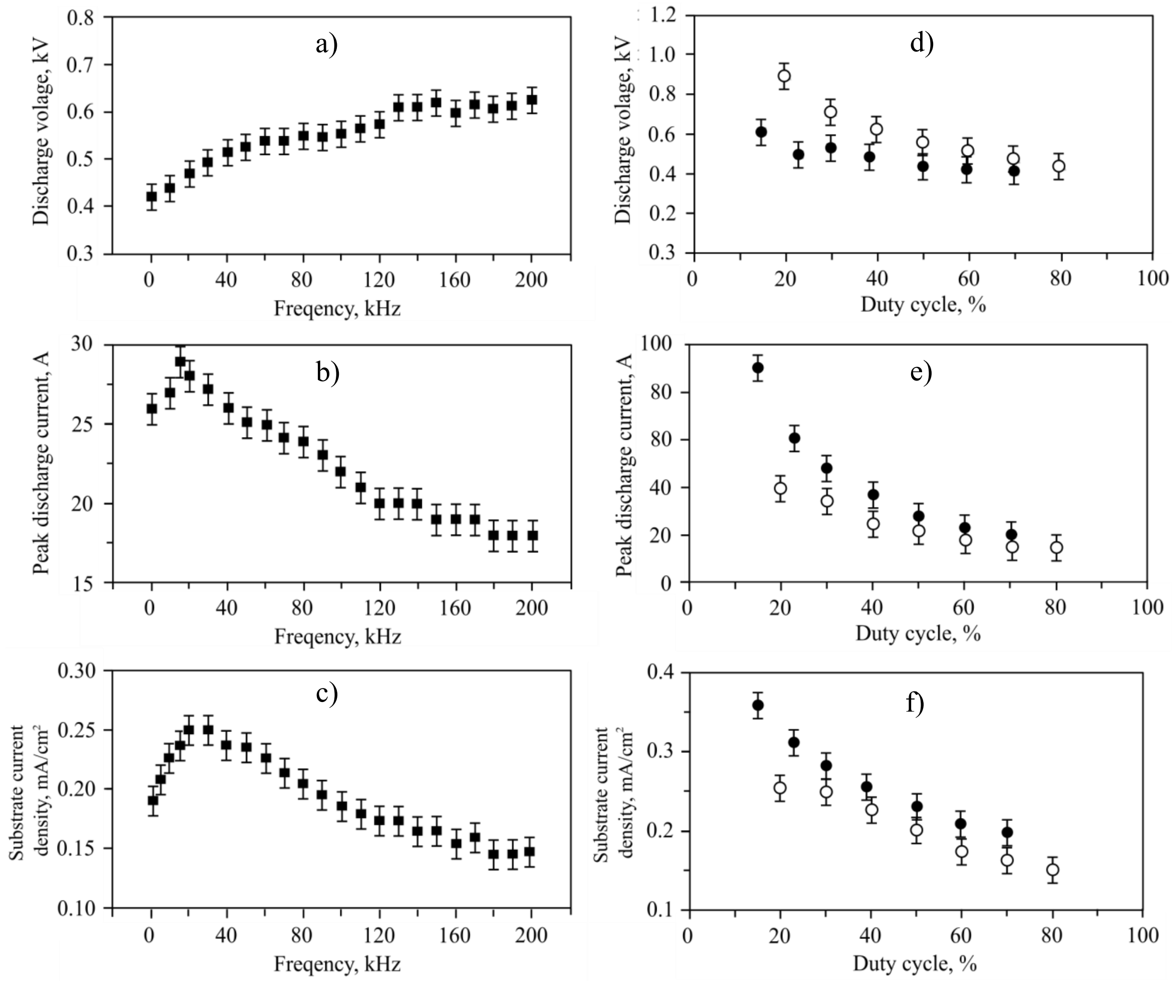

Figure 3. Dependences of the discharge voltage (a), the amplitude of the current pulses (b) and the ion current density to the substrate (c) on the pulse formation frequency; dependence of the discharge voltage (d), the amplitude of the current pulses (e) and the ion current density on the substrate (f) on the duty cycle at a pulse frequency of 80 kHz (○) and 10 kHz (●).

Despite the higher values of the duty cycle and pulse formation frequency, compared with HIPIMS, a significant increase in the substrate ion current density is also observed in the modes considered in this work. In some cases, this can be used to improve the characteristics of the deposited coatings. There are examples where the use of mid-frequency pulses with a low duty cycle has improved the characteristics of ITO [10], VO_x [11], and ZrN films [12]. However, in these works, measurements of the parameters of the ion effect on the substrate were not made. The change in the ion current density that was observed in this work may be one of the reasons for the change in the properties of the coatings mentioned above.

4. Conclusions

The paper describes a new power supply for medium-frequency magnetron sputtering that provides a wide range of regulation of output voltage (up to 1800 V), current (up to 100 A), pulse frequency (1–200 kHz), and duty cycle (10–100 %). It has been demonstrated that by changing the frequency of the discharge current pulses and the duty cycle, it is possible to control the density of the ion current on the substrate at a constant discharge power. There is an optimal frequency range (20–30 kHz) at which the ion current density to the substrate is maximum during aluminum target sputtering. The dependence of the substrate ion current on the frequency and duty cycle coincides with a similar dependence of the maximum pulse discharge current. Due to the high amplitude of the pulses of the discharge current, the power source is capable of providing a pulsed discharge power in the mid-frequency mode, many times higher than the average discharge power.

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