Unipolar and bipolar mode of deep oscillation magnetron sputtering

V O Oskirko, A N Zakharov, A P Pavlov, A S Grenadyorov and V A Semenov
Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia

E-mail: oskirkovo@gmail.com

Abstract. The paper presents the results of a study of the modes of dual deep oscillation magnetron sputtering. The use of packet pulse discharge power supply allowed to provide a high power density on the surface of the Al target 60–500 W/cm² and the ion current density on the substrate 4–20 mA/cm² during the duration of the macro pulse – 1 ms. In addition to the parameters of a pulsed power supply, the way of connecting the power source to the dual magnetron sputtering system and the vacuum chamber changed during the experiments. Targets of the magnetron sputtering system were isolated from the chamber or alternately connected to it. A change in the connection method led to a change in the anode area and such discharge parameters as: discharge current, plasma concentration, bias voltage, and ion current density on the substrate. It is shown that in the mode with a small area of the anode, the substrate is exposed to a higher energy impact in comparison with the regime when the anode had a large area.

1. Introduction
High-power impulse magnetron sputtering (HIPIMS) is one of the technologies of highly ionized physical vapor deposition. The use of high duty cycle pulses to power the discharge in HIPIMS processes makes it possible to ensure high instantaneous power values, high plasma concentration and density of the ion flux on the substrate [1–3]. This has a positive effect on the quality of sputtered coatings [4–6]. The pulse duration in HIPIMS usually does not exceed 200 µs, which is due to the problem of electric arcs formation and the complexity of stabilizing the output current. These limitations are overcome by the use of packet pulsed power supply of magnetron sputtering system (MSS). Packets (or macro-pulses) consist of a sequence of tightly packed micro-pulses whose duration is only a few microseconds. Short pauses between the micro pulses prevent the formation of electric arcs. This technology is known as deep oscillation magnetron sputtering (DOMS) [7–9]. The duration of macro pulses in DOMS is 1–3 ms, and the repetition frequency does not exceed 500 Hz.

Initially, DOMS processes were implemented on the basis of a single MSS using unipolar high-power pulse packets [7–9]. In [10] we demonstrated that the DOMS process can be implemented on a dual magnetron sputtering system (DMSS) using bipolar pulse packets. The use of bipolar pulses allows preventing the formation of arcs, and the dual configuration of the MSS to solve the “disappearing anode” problem in the reactive magnetron sputtering. In addition, the use of the dual system increases the energy impact of ions on the deposited coating, which significantly affects its properties [11, 12].
In this work, two DOMS modes were investigated, which differed in the way of connecting the power source to the magnetrons and the vacuum chamber. In the first mode, which we called bipolar, the magnetrons were electrically isolated from the walls of the vacuum chamber, and their targets alternately served as an anode and cathode (figure 1a). The discharge current flowed between the magnetrons and bipolar voltage pulses were formed on their targets. In this mode, the discharge anode had a small area equal to the target area. In the second mode, which we called unipolar, the power supply terminals, in addition to the magnetron targets, were connected to the walls of the vacuum chamber, acting as an anode in the discharge system. In this case, unipolar pulses of negative polarity voltage were formed on the targets, and the anodes had a large area equal to the sum of the areas of the walls of the vacuum chamber and the magnetron target.

The paper presents a brief description of the power source that provides operation in both modes, the results of measurements of plasma parameters, the deposition rate of coatings and the degree of ion impact on the substrate.

2. Methodology and Materials

Let us consider in more detail the unipolar and bipolar modes of operation of DMSS and their main differences. Figure 1 shows the diagrams and voltage plots explaining the principle of operation of the DMMS in both modes. In bipolar mode, the voltage source is isolated from the grounded vacuum chamber and connected only to the DMMS targets, as shown in figure 1a. All discharge current flows through the target. During the first half cycle, the M1 target acts as a cathode and the M2 target acts as an anode. During the second half-period, the polarity of the voltage changes and the targets change roles. The result is alternate sputtering of targets. In the bipolar mode, the anode has a smaller area, compared to a conventional MSS, in which the walls of the vacuum chamber are usually the anode. In the case of a small-area anode, in order for the electron current to remain equal to the discharge current, an increased anode voltage drop is required. An increase in the anode voltage drop leads to an increase in the target potential relative to the ground. As a result, a small positive (with respect to the ground) voltage appears on the target acting as an anode during the pause between negative pulses.

In unipolar mode, the voltage source is connected to the vacuum chamber via diodes D1 and D2, as shown in figure 1b. When a positive (relative to the ground) voltage is applied to the M2 target, the D2 diode opens and the discharge current is distributed between the M2 target and the chamber walls. Since a negative voltage is applied to M1, the diode D1 remains closed. During the second half-period, the situation changes and the diode D1 opens and connects the target M1 with the vacuum chamber. Since in this mode the anode has a large area, the anode voltage drop does not increase. The amplitude of the positive voltage pulses is only a few volts, which corresponds to the voltage drop across the diode. Therefore, we called this mode unipolar.

For DOMS, a power source (PS) was used, the scheme of which is shown in figure 2. Its main parameters are listed in table 1.

![Figure 1. Bipolar (a) and unipolar (b) DOMS modes.](image_url)
The formation of high-power pulses in the PS is carried out using four transistors \((T_1 – T_4)\), which commute the storage capacitors \(C_1\) and \(C_2\) with targets of DMSS. Capacitors have a total capacity of 3 mF, which allow obtaining the duration of the packets (macro pulses) in the range of 1–3 ms. The transistor \(T_1\) is turned on simultaneously with \(T_4\) and a negative voltage is applied to the target \(M_1\). When \(T_2\) and \(T_3\) are turned on, negative voltage is applied to target \(M_2\). The amplitude of the voltage pulses is regulated by changing the charging voltage. Separate capacitor charging channels make it possible to independently adjust the amplitude of the voltage pulses on each target.

### Table 1. The parameters of DOMS power source.

| Parameters                      | Values                                      |
|---------------------------------|---------------------------------------------|
| Output voltage                  | 100–1500 V                                 |
| Average output current          | up to 12 A                                 |
| Average output power            | up to 10 kW                                 |
| Maximum pulse current           | 200 A                                       |
| Maximum pulse power             | 300 kW                                      |
| Macro pulse frequency           | 1–1000 Hz                                   |
| Duration of macro pulses        | 100–3000 \(\mu\) s                        |
| Micro pulse frequency           | 10–50 kHz                                   |
| Duration of micro pulses        | 3–50 \(\mu\) s                             |
| Stabilization modes             | voltage/current/power                       |
| Modes of operation              | direct current magnetron sputtering (DCMS), |
|                                 | dual mid frequency pulsed magnetron sputtering (DUMS), |
|                                 | dual deep oscillation magnetron sputtering (DU DOMS) |

At the output of the PS is a switching unit (SU), designed to switch modes of dual magnetron sputtering. The SU includes two switches \(S_1\) and \(S_2\), diodes \(D_1\) and \(D_2\), and also resistors \(R_1\) and \(R_2\). SU is connected to the outlets of PS and to the vacuum chamber. In bipolar mode \(S_1\) and \(S_2\) are open and the targets are disconnected from the chamber. Resistors \(R_1\) and \(R_2\), connected in parallel to the switches, have a high resistance \((1\ \text{k}\Omega)\) and are used to initiate a discharge in bipolar mode. In the unipolar mode, \(S_1\) and \(S_2\) are closed, and the PS outlets are connected to the camera via diodes \(D_1\) and \(D_2\).

In addition to PS and DMSS, the experimental setup includes a vacuum chamber, a triple probe, current sensors \((A_1, A_2)\), voltage sensors \((V_1, V_2)\), measuring circuit and a digital oscilloscope (figure 2). The volume of the vacuum chamber is 215 liters. For vacuum pumping, a turbomolecular pump was used, providing a base pressure of \(6 \times 10^{-3}\) Pa. DMSS with flat round aluminum cathodes with a diameter of 76 mm and a thickness of 5 mm was placed on the side wall of the chamber. The cathodes were direct water cooling. The magnetic system of magnetrons formed by the inner cylindrical and outer ring NdFeB magnets is weakly unbalanced with a geometric unbalance factor \(K_g = 1.2\). The magnitude of the magnetic field on the surface of the target in racetrack area is 730 Gs. DMSS has a
closed configuration of the magnetic field. The angle formed by the surfaces of the magnetron targets is 160°.

To measure the discharge current and voltage, current sensors A₁, A₂ (Rogowski coils) and voltage dividers V₁, V₂ were used. The signals from the sensors were recorded using a digital four-channel oscilloscope (GW INSTEK GOS-72074E).

To measure the parameters of the plasma, a triple Langmuir probe [13] was used, which was located at a distance of 12 cm from the target surface. One of the three electrodes of the probe was under a floating potential, between the other two electrodes were a 500 Ohm resistor and a battery, which was used to maintain a bias voltage of 40 V. The signals from electrodes were recorded with an oscilloscope, and then the data were processed on a computer.

The experiments were carried out in argon at a working pressure of 0.25 Pa. PS worked in symmetric mode, i.e. the amplitudes of the positive and negative voltage and current pulses at the outputs of the PS were equal. The duration of the macro impulses was 1000 μs, the frequency was regulated in the range of 40–300 Hz. The average discharge power of 1 kW was constant. The repetition frequency of micro pulses and their duration were 33 kHz and 10 μs, respectively. The amplitude of voltage pulses was regulated from 500 to 1100 V.

3. Results and Discussion

Figure 3a shows oscillograms of the current and voltage macro pulse on one of the DMSS targets in the bipolar mode. From oscillograms it can be seen that the macro pulse is a sequence of micro pulses of short duration. Figure 3b, 3c shows the shape of micro pulses of voltage and current in bipolar and unipolar modes on a smaller scale. Voltage pulses have a complex shape. At the beginning of the pulse, there is a surge to the maximum value of –800 V, after which the voltage drops to –600 V. At the very beginning of the negative impulse, the entire voltage of the storage capacitor is applied to the discharge gap. With a rapid increase in the discharge current, a part of the voltage is applied to the inductances L₁ or L₂, (see the diagram in figure 2). Between the negative voltage pulses in the unipolar mode there is a pause, and in the bipolar mode a positive impulse with amplitude of 20–30 V is formed. In this case, the positive voltage increases during the pulse duration. Positive and negative current pulses in the bipolar mode have the same amplitude, whereas in the unipolar mode, the positive current pulses have smaller amplitude than the negative ones.

![Figure 3](image)

**Figure 3.** Oscillograms of macro (a) and micro pulses (b) of discharge voltage and current in bipolar mode; (c) oscillograms of voltage and current micro pulses in the unipolar mode, at a discharge voltage of 800 V.

The decrease in the amplitude of positive current pulses in the unipolar mode is due to the fact that in this case a significant part of the electrons from the plasma goes to the walls of the chamber.
Approximately one third of the total current flows through the target, the rest of the current flows through the chamber walls.

Figure 4a shows the dependences of the average values of the discharge current during a macro pulse on the discharge voltage in the unipolar and bipolar DOMS modes. The discharge voltage increased to the values at which the discharge current limiter (200 A) was triggered. In the unipolar mode, the maximum voltage was 1000 V, in the bipolar mode – 1100 V. In both modes, the discharge current increases linearly with increasing voltage. The maximum value of the average current in both modes was about 50 A, which corresponds to the current density on the target surface – 0.5 A cm\(^{-2}\). As can be seen in figure 4a, in the full voltage range, the average current value in the unipolar mode is about 3 A higher than in the bipolar mode. The decrease in discharge current in bipolar mode is explained by the redistribution of voltage in the discharge gap. An increase in anode voltage drop is accompanied by a decrease in cathode voltage drop. The average discharge power during a macro pulse was in the range of 6–50 kW, while the power density on the target surface was 60–500 W cm\(^{-2}\).

Figure 4b shows the dependence of plasma concentration on discharge voltage, obtained using probe measurements. Despite the higher discharge current, the plasma concentration in the unipolar mode was on average 20% lower than in the bipolar mode.

The maximum plasma concentration in the unipolar mode was \(4 \times 10^{11}\) cm\(^{-3}\). Due to a wider range of voltage regulation in bipolar mode, it was possible to achieve a plasma concentration of \(7 \times 10^{11}\) cm\(^{-3}\). The electron temperature measured with a triple probe was practically independent of the sputtering regime and was in the range of 3–4 eV over the full discharge voltage range. As shown in figure 4c, ion current density increases linearly with increasing discharge voltage. In the bipolar mode, the ion current density is on average 30% higher than in the unipolar mode. As noted earlier, most electrons in the unipolar mode go to the chamber walls, which lead to a decrease in plasma concentration and ion current density in the central part of the system where the probe was located. An increase in plasma concentration in the bipolar mode can also be facilitated by an additional discharge that forms at the surface of the target, which serves as the anode.

In figure 5a and 5b probe current-voltage characteristics are presented, which allow to determine the value of the floating potential, plasma potential and self-bias potential. The plasma potential \(V_{pl}\) is determined by the inflection point of the characteristic on a logarithmic scale. The floating potential \(V_{fl}\) was determined by the coordinate of the intersection of the curve with the abscissa at zero current per probe. The potential of self-bias, which determines the energy of ions bombarding a substrate having a floating potential, is found as \(V_{fl} - V_{fl}\). The floating potential in the unipolar mode has a negative value (-4.7 V), in the bipolar mode it is positive (1.5 V). The potential of plasma in unipolar and bipolar modes is 7.5 and 15.5 V, respectively. Oscillograms shown in figure 5c, allow us to trace the dynamics of changes in the floating potential during a macro pulse. The frequency of \(V_{fl}\) pulsation matches the repetition rate of the micro pulses (33 kHz). The oscillation amplitude in unipolar mode is higher than in bipolar one. The dotted lines in the oscillograms show the average values of the floating potentials.
It should be noted that the use of dual DOMS modes allowed providing a high (4–18 mA cm⁻²) ion current density per probe during the duration of the macro pulse. HIPIMS allows higher instantaneous values of current density to be achieved, but ion bombardment of the substrate is carried out for a short period of time, usually not exceeding 200 μs. In DOMS, a high ion current is maintained continuously for a long period of time (1–3 ms). During this time, the quasi-stationary state is established, the target material is intensively sputtered and the ion effect on the substrate surface is intense. However, the average discharge power and the ion current density on the substrate can remain at a fairly low level.

Figure 5. Single probe current-voltage characteristics in unipolar (□) and bipolar (■) DOMS modes (a, b); dynamics of change of floating potential (c) in DOMS modes. Al targets, discharge voltage of 800 V.

It is known that ion bombardment of the substrate plays an important role in the process of magnetron sputtering. The energy transferred by ions to the growing coating affects its physical and mechanical properties. If the substrate is under floating potential, the energy transmitted to the coating can be calculated by the formula [14, 15]:

$$E_{bi} = (V_{pl} - V_{fl}) \frac{J_{avg}}{a_D}$$

where $V_{pl}$ – the plasma potential, $V_{fl}$ – floating potential, $J_{avg}$ – average ion current density on substrate, $a_D$ – the deposition rate.

To compare the energy impact on the substrate in the bipolar and unipolar DOMS modes, the above parameters were measured. Two regimes were selected, the parameters of which are listed in table 2. To maintain the same average discharge power (1 kW) in both modes, when switching from the bipolar mode to the unipolar, it was necessary to increase discharge voltage by 4 V. An increase in the discharge voltage caused a slight decrease in the discharge current.

Table 2. Deep oscillation magnetron sputtering modes.

| Mode  | $U_d$ (V) | $I_d$ (A) | $I_{max}$ (A) | $I_{mp}$ (A) | $P_d$ (kW) | $P_{mp}$ (kW) | $f$ (kHz) | $F$ (Hz) | $\tau_{mp}$ (ms) | $k$ (a.u.) |
|-------|-----------|-----------|---------------|--------------|------------|--------------|-----------|---------|----------------|-----------|
| Bipolar | 803       | 1.24      | 60            | 15.7         | 1          | 12.5         | 33        | 80      | 1000          | 0.08      |
| Unipolar | 799       | 1.25      | 60            | 15.7         | 1          | 12.5         | 33        | 80      | 1000          | 0.08      |

where $U_d$ – discharge voltage, $I_d$ – average discharge current, $I_{max}$ – maximum impulse current, $I_{mp}$ – average current during a macro pulse, $P_d$ – average discharge power, $P_{mp}$ – average power during the macro pulse, $f$ – the frequency of micro pulses, $F$ – the frequency of macro pulses, $\tau_{mp}$ – the duration of the micro pulses, $k$ – relative duration of macro impulses equal to the ratio of their duration to the repetition period.

Table 3. Parameters of ion impact on the substrate.

| Mode  | $U_{p} - U_{sa}$ (V) | $J_{mp}$ (mA cm⁻²) | $J_{avg}$ (mA cm⁻²) | $a_D$ (nm min⁻¹) | $P_{mp}$ (mW cm⁻²) | $P_{avg}$ (mW cm⁻²) | $E_{bi}$ (mJ cm⁻³) |
|-------|---------------------|-------------------|-------------------|------------------|-------------------|-------------------|-----------------|
| Unipolar | 12.3                | 9                 | 0.72              | 41               | 111               | 8.9               | 0.13            |
| Bipolar | 14.3                | 11                | 0.88              | 45               | 157               | 12.6              | 0.17            |
where $U_p - U_s$ – self-bias potential, $J_{mp}$ – ion current per probe during macro pulse, $J_{avg}$ – the average ion current to the probe, $a_o$ – the deposition rate, $p_{mp}$ – power density on the substrate during the macro pulse, $p_{avg}$ – average power density on the substrate, $E_{bs}$ – energy transferred to the sputtered coating.

Table 3 presents the parameters of the deposition process of aluminium films in two DOMS modes. The self-bias voltage of the substrate in bipolar mode is higher by 2 V than in unipolar mode, which indicates a higher electron temperature. In addition to the higher ion current density, the bipolar mode provides a slightly higher deposition rate of the metal film.

The results of calculations show that in the bipolar regime the substrate is exposed to a higher energy impact. Due to the higher ion current density and self-bias potential, in bipolar mode, the sputtered coating receives 30 % more energy as a result of ion bombardment compared to the unipolar mode.

Conclusion
In this paper, we studied two modes of the dual DOMS, differing in the way of connecting the power source to the magnetron targets and the vacuum chamber. In bipolar mode, when the magnetron targets are isolated from the chamber walls and the anode has a smaller area, the plasma concentration and the ion current density per probe are higher than in unipolar mode, when the targets were connected to the chamber walls and the anode has a larger area. We associate the decrease in plasma concentration in unipolar mode with the redistribution of the electron current between the MSS targets and the chamber walls, which is confirmed by the oscillograms of the pulsed current flowing through the targets.

A change in plasma parameters causes a change in the energy impact on the substrate. Due to the higher values of the ion current density and the self-bias potential of the substrate, the growing coating in bipolar mode receives 30 % more energy than unipolar mode. The deposition rate of Al film in bipolar DOMS mode is 10 % higher than in unipolar one.

Regulation in a wide range of the ion current density during the duration of the macro pulse, together with a change in the method of connecting the power supply to the DMSS, allows controlling the level of energy impact on the growing film and providing optimal regimes of obtaining coatings with the desired characteristics.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research (grant No. 18-42-703005).

References
[1] Ehiasarian A, New R., Münz W, Hultman L and Helmersson U 2002 Vacuum 65 147
[2] Helmersson U, Lattemann M, Bohlmark J and Ehiasarian A 2006 Thin Solid Films 513 1
[3] Kouznetsov V, Macák K, Schneider J and Helmersson U 1999 Surf. Coat. Technol. 122 209
[4] Solovyev A A, Oskirko V O, Semenov V A, Oskomov K V and Rabotkin S V 2016 J. Electron. Mater. 45 4052
[5] Solovyev A A, Semenov V A, Oskirko V O, Oskomov K V, Zakharov A N and Rabotkin S V 2017 Thin Solid Films 631 72
[6] Zakharov A N, Solovyev A A and Oskomov K V 2017 Russian Physics Journal 60 1336
[7] Ferreira F, Serra R, Oliveira J and Cavaleiro A 2014 Surf. Coat. Technol. 258 249
[8] Ferreira F, Oliveira J and Cavaleiro A 2016 Surf. Coat. Technol. 291 365
[9] Lin J and Sproul W D 2015 Surf. Coat. Technol. 276 70
[10] Oskirko V, Semenov V, Pavlov A and Zakharov A 2019 Proc. of 14th International Scientific and Technical Conference "Vacuum Engineering, Materials and Technology" (Moscow) 128
[11] Glocker D, Romach M, Christie D and Sproul W 1993 J. Vac. Sci. Technol. 11 2989
[12] Frach P, Goedicke K, Gottfried C and Bartzsch H 2001 Surf. Coat. Technol. 142 628
[13] Chen S and Sekiguchi T 1965 J. Appl. Phys. 36 2363
[14] Musil J, Sicha J, Herman D and Cerstvy R 2007 *J. Vac. Sci. Technol.* **25** 666
[15] Musil J 2012 *Surf. Coat. Technol.* **207** 5