Computer simulation of a power source based on a bipolar pulse shaper for magnetron sputtering systems

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Abstract. The research object is a pulsed bipolar power supply based on a bipolar pulse shaper of increased frequency for magnetron sputtering systems. The research subject is the electrophysical and electromagnetic processes occurring in the bipolar pulse shaper when it is operated with a magnetron sputtering system, as well as the control characteristics. The purpose of the paper is the possibility of creating a pulsed power supply with a power of up to several tens of kW, which makes it possible to increase the stability of the magnetron sputtering system. Besides, the outcomes of computer simulation of a power source based on a bipolar pulse shaper and control algorithm ensuring its stable and reliable operation in association with a magnetron sputtering system are reflected in the paper. The results show that the deviation of the output control characteristics of the bipolar pulse shaper from the analytically obtained characteristics does not exceed 3%. Circuit modeling is carried out in the Swicher CAD/LTspice software package. The mathematical SPICE models of the field-effect STY112N65M5 transistor, transistor IGBT of IRF4PF50WD and STTH8006 diode are taken from the websites of STMicroelectronics and International Rectifier manufacturers.

1. Introduction
Currently, high quality thin films and coatings are used as conductive, insulating and semiconducting layers in electronics, allowing electronic components to be downsized. Methods of ion-plasma spraying of coatings in vacuum are used for the deposition of thin films and coatings, in particular, magnetron sputtering (MS), since they favorably differ in high controllability, repeatability of results and low level of impurities in the sprayed coating in comparison with other methods.

The main feature of MS is the use of crossed electric and magnetic fields providing:
- high plasma concentration and gas ionization level;
- high spraying speed, coating uniformity and low substrate temperature.

MS allows spraying almost any material: metals, alloys, simple and complex dielectrics, semiconductors and ceramics. Various materials can be combined to form multi-layer coatings. MS is used to form nanocomposite and nanostructured bulk and thin-film materials [1,2].

The advantage of MS is its high controllability which makes it possible to obtain films with the required structural and operational characteristics by changing the plasma parameters during the coating process.

Direct current sources that make it possible to obtain metal coatings were used at the initial stage of MS development. The problem of the frequent occurrence of electric arcs on the surface of the magnetron target limited their application in the coatings deposition processes of complex
composition. The formation of dielectric coatings became possible owing to the use of high frequency (HF) power supplies (PS). However, the disadvantages inherent in HF systems are manifested: low spraying rate, low efficiency, the complexity of matching the load and PS [3].

The possibility of high-quality implementation of the use of pulsed power supply systems with a frequency from 400 to 60 kHz [4] to solve the problem of arcing and dusting the anode surface during the deposition of coatings with dielectric properties appeared in the 90s, when the production of powerful semiconductor switches with the required frequency characteristics began. The creation of pulsed PS with a power of several tens of kW and a pulse shaping frequency from 1 to 1000 kHz has become possible on the basis of such devices. The sources have substantially determined the success of reactive MS technologies, in which coatings of a complex composition are obtained in an environment of chemically active gases by sputtering targets of a relatively simple composition.

In addition to the problem of arcing, pulse power supply allows [5]:
- eliminating the problem of anode surface dusting;
- increasing the speed of spraying complex coatings;
- improving the properties of coatings;
- enhancing the controllability of sputtering processes;
- enlarging the maximum pulse power relative to the average power of the magnetron discharge.

Continuous increasing requirements for functional coatings, growing MS sizes and new practical applications of magnetron technologies are driving the development of new pulse PSs with higher power, controllability and reliability. Solving complicated technological problems requires deep integration of the power supply system and technological devices. For this, a contemporary PS must have a set of sensors, feedbacks, a control algorithm and external data exchange channels. Therefore, the research topic is relevant.

2. Simulation of bipolar pulse shaper (BPS) with MS

Simulation makes it possible to check whether the designed device meets the requirements of the technical task, allows for an accurate calculation of schemes, taking into account a large number of parameters [6].

Computer simulation of the circuits was conducted in the Swicher CAD/LTspice software package [7,8]. The program is a free full-fledged SPICE simulator that simulates analog-to-digital circuits. The mathematical SPICE models of the field-effect STY112N65M5 transistor, transistor IGBT of IRF4PF50WD and STTH8006 diode were taken from the websites of STMicroelectronics and International Rectifier manufacturers [9,10].

Figure 1 presents the final BPS circuit with damping circuits (DC) and displays the main parameters of its elements. DCIncludescapacitances $C_2$ – $C_6$, chokes $L_3$ – $L_5$, diodes $VD_4$ – $VD_9$ and $R_2$ resistor, and it is used to form the trajectory of the operating point of the $VT_1$ transistor. The trajectory formation of the operating point movement of $VT_2$ transistor is carried out using DC, which involves $VD_{10}$ diode and $C_7$ damping capacitance.

![Figure 1 – BPS circuit with damping circuits and element parameters](image)
The BPS model was developed on the basis of the scheme (Figure 1). A number of changes have been made to the BPS model from the initial scheme. The constant voltage source $E$ is used instead of the storage capacitor $C_1$.

Shapers $G_1$, $G_2$ and $G_3$, having an internal series resistance of 1 Ohm, form transistor control signals. The control sequence of transistors corresponds to the developed BPS control algorithm.

It should be noted that the model, according to which the connection between the transformer windings is determined by a fictitious circuit element called $K_{cc}$, coupling coefficient, is adopted in SPICE-simulators [11]. In this case, $K_{cc}$ between chokes $L_1$ and $L_2$, forming an autotransformer, is equal to 0.99. The leakage inductance is set to 3 µH.

MS electrical model shown in Figure 3, was developed on the basis of the MS electrical equivalent circuit (Figure 2).

Table 1 shows the element parameters that are comprised of the MS model. The $E_{v}$ voltage triangular pulse generator synchronized with BPS is used in the model.

Table 1. Parameters of MS model elements

| Element | $R_{s1}$ | $R_{s2}$ | $R_{s3}$ | $C_{v1}$ | $C_{v2}$ |
|---------|----------|----------|----------|----------|----------|
| Value   | 8.7 Ohm  | 100 Ohm  | 50 Ohm   | 10 nF    | 10 nF    |

Figure 4 presents the curves of the output voltage, current and BPS power obtained as a result of simulating the shaper operation with the MS model.
Surge current in the interval of \([t_1, t_2]\), due to capacity charging of \(C_{v1}\), simulates the cathode layer formation at the beginning of a negative pulse. The duration of the surge current is approximately 1 \(\mu\)s \([11]\). The initial surge current subsequently leads to a recharge of \(C_{v1}\) capacitance and a surge voltage across the load.

At \(t_1\), a triangular pulse generator \(E_v\) generates a voltage of 370 V. Then, the voltage across the generator linearly decreases to zero during the plasma recovery interval \(t_{pr}\) (interval \([t_1, t_3]\)). As the voltage reduces to \(E_v\), the voltage applied to \(R_{v1}\) resistance enhances. As a result, the output current of the BPS grows. At \(t_3\), a growth of in the output current stops. The load resistance in the steady state is determined by the formula:

\[
R_{H} = \frac{R_{H_1} \cdot R_{H_2}}{R_{H_1} + R_{H_2}} = 8 \text{ Ohm} \quad H, H_1, H_2, V, V_1, V_2
\]

\[\text{Figure 4} \quad \text{– Diagram of the output voltage, current and BPS power when working with MS model, at} \quad F = 50 \text{ kHz,} \quad t_s = 4 \mu\text{s,} \quad E = 330 \text{ V} \]

Output power is less than steady state during the plasma recovery stage. Additional voltage on the interval \([t_3, t_4]\) allows increasing the pulsed output BPS power up to 17 kW and compensating for the decrease in power at the plasma recovery stage. As a result, the average output power is the same as when operating with a resistive-inductive load (10.8 kW).

Consider the processes occurring in the circuit during a positive output pulse. The surge of positive voltage across \([t_5, t_6]\) gap is caused by the recharging of the damper \(C_7\) and \(C_{d2}\) capacitances, which simulates the electron current at the beginning of the positive output pulse. Recharging is carried out along the circuit of \(C_7\)-\(R_1\)-\(VT_3\)-\(L_2\)-\(VD_{v2}\)-\(C_{v2}\)-\(VT_3\).

After recharging, the \(C_{v2}\) capacitance is discharged through the resistance of \(R_{v3}\). In steady state, the positive voltage of the \(L_2\) choke is distributed between \(R_1, R_{v1}, R_{v2}\) resistances.

The BPS control characteristic was obtained during the simulation when working with the MS model (Figure 5), that is the dependence of the conversion factor of the pulsed output voltage of \(K_p\) on the relative duration of \(\gamma\) negative pulse at a pulse shaping frequency of 50 kHz. The duration of the positive pulse was adjusted from 3 to 8 \(\mu\)s, while \(\gamma\) varied in the range from 0.6 to 0.85, the parameter \(d\) was equal to 2 \(\mu\)s.

The control characteristic is shown with a dashed line in Figure 5. The characteristic repeats the control characteristic obtained when simulating BPS with a resistive-inductive load.
The deviation of the characteristics obtained as a result of computer simulation from the characteristics obtained by theoretical calculations in [11] is 3%.

The duration of the triangular voltage pulse generated by the \( E \) shaper was changed during the simulation and, thus, the plasma recovery time in the discharge gap was controlled in the range from 2 to 8 \( \mu \)s. The duration of the positive pulse remained constant \( t_+ = 4 \). A change in the plasma recovery time \( t_{pr} \) did not affect the value of the conversion coefficient \( K_p \). Although the average voltage remained constant during the negative pulse, the shape of the output voltage pulse changed. The voltage at the initial interval of the negative pulse increased as the plasma recovery time grew, and the voltage at the main interval of the negative pulse decreased.

\[
E = 330 \text{ V}, \quad F = 50 \text{ kHz}, \quad t_+ = 3 / 8 \mu \text{s}, \quad d = 2 \mu \text{s}, \quad L_1 = 0 \mu \text{H}
\]

**Figure 5** – BPS control characteristic when working with MS model

Figure 6 a) shows an increase in \( d \) parameter, which causes a decline in the current flowing in \( L_1 \) choke and at the shaper output. A small enlargement in the current in \( L_1 \) chokerelative to BPS output current begins at \( d < 0.5 \mu \text{s} \), which indicates the emergence of \( L_1 \) additional current circulating through the \( VD_2 \) reverse diode. To prevent an undesirable current increase when working with MS, it is essential for \( d \) parameter to be more than 0.5 \( \mu \)s. We take into account that an increase in \( d \) parameter leads to a decrease in the conversion coefficient of the output pulse voltage of \( K_p \), as shown in Figure 6 b).

\[
E = 330 \text{ V}; \quad F = 50 \text{ kHz}; \quad t_+ = 4 \mu \text{s}; \quad t_{pr} = 4 \mu \text{s}; \quad R_1 = 8 \text{ Ohm}
\]

**Figure 6** – a) Dependence of BPS output current and \( L_1 \) choke current on \( d \) parameter; b) Dependence of \( K_p \) coefficient on \( d \) parameter
As a result of computer simulation, it is possible to create not only the BPS model, but also the models of the assumed loads using models of tangible elements and electrical equivalent circuits. These models allow making an accurate calculation of the parameters and obtaining the shaper characteristics in conditions close to real.

3 Conclusion
The considered MS computer model permits adequate simulation of the nonlinear load behavior in the mode of increased frequency, as evidenced by the obtained diagrams of output pulses of voltage and current. The influence of \( d \) parameter, which establishes the relationship between the durations of the initial interval of the negative positive pulses, on the BPS operation in the increased frequency mode was investigated during the BPS simulation. A disproportionate current increase in the BPS choke relative to the average output current occurs when \( d \) parameter decreases below the threshold value. An enlargement in \( d \) parameter leads to a decline in the amplitude of negative voltage pulses. It is necessary for \( d \) parameter to be in the range from 2 to 2.5 \( \mu \)s to prevent a drop in the output negative voltage and the current magnification in the choke.

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