Power supply output inductance effect on arc parameters of high-power impulse magnetron sputtering

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Abstract. The paper studies the influence of the power supply output inductance on the arc parameters, which form on the sputtered target surface during high-power impulse magnetron sputtering. The arc energy, lifetime and maximum current are measured by the up-to-date power source and the proposed arc simulation circuit at various output inductance values. The experimental data are compared with the simulation results. The paper presents a brief model description for the arc parameter calculations. According to the experimental data, the decrease in the output inductance leads to the increase in the peak current, arc lifetime and energy. It is shown that the energy recuperation stored in the output inductance allows reducing the arc energy. Also, self-locking of control transistor occurs at a lower value (~1 µH) of the output inductance, leading to the reduction in the current amplitude and the additional decrease in the arc energy.

1. Introduction

An important problem that occurs in the magnetron sputtering process is the formation of electric arcs on the target. During arcing, droplets spread from the cathode spots and fall onto the substrate, making defects in the coating sputtered. The size and number of microdroplets depend on many parameters, including the arc energy. Up-to-date power sources of the magnetron sputtering systems can limit the arc energy to a few units or even fractions of mJ, which allows avoiding the defect formation [1–4]. Such a low arc energy is much more difficult to provide during the high-power impulse magnetron sputtering (HIPIMS) process. The fact is that the pulsed discharge current in HIPIMS can be hundreds or even thousands of times higher than in conventional direct current magnetron sputtering or mid-frequency magnetron sputtering. As the current increases, the probability of the arc formation grows, which requires much longer time to suppress it. Due to the quadratic dependence, the inductive energy stored in the power supply output circuit greatly grows with increasing current. If no special measures are taken, the inductive energy enters the arc, thereby increasing its lifetime. Thus, the output inductance and the current in it determine the arc energy and, consequently, the quantity of microdroplets generated. To reduce the arc energy in HIPIMS power sources (HPS), special measures must be taken to increase the arc detection rate, power shutoff, and prevent a transfer of the inductive energy in load [6].
The aim of this work is to investigate the influence of the HPS output inductance on the arc parameters such as the peak current, lifetime, and energy. In our experiments we use the electric circuit capable of returning the inductive energy back to the source. Due to the fact, that this function can be switched off, it is possible to evaluate the role of the inductive energy recuperation in the arc suppression process. In order to avoid the use of a complex and expensive vacuum equipment, the experiments are carried out on the proposed arc simulation circuit. The experimental results are compared with the simulation results of the arc suppression. A brief description is given to the proposed model for calculating the arc parameters.

2. Model for arc parameter calculation
In figure 1a, one can see a simplified HPS circuit and magnetron sputtering system (MSS). The HPS includes the DC source, charge-storage capacitor, and switch. The HPS negative output is connected to the MSS cathode (target) via cable; the target is placed in a vacuum chamber. The HPS positive output is connected to the vacuum chamber, its inner walls being anode of the discharge system. The pulse generation occurs through the switch closure resulting in the connection between the storage tank and the load.

Figure 1. Simplified HPS circuit (a), equivalent circuit of HPS and load (b), HIPIMS discharge current and voltage pulses at the formation of an arc (c).

Figure 1c presents the oscillograph records of the discharge current and voltage pulses during arcing. The low-current preliminary discharge interval, high-power magnetron discharge pulse, arcing, and pause between pulses are shown in the oscillograph records. Arcing is accompanied by a drop in the discharge voltage followed by the linear growth in the discharge current. The HPS detects the arc when the discharge current reaches the level \( I_{det} \). After the arc detection, the discharge current continues to grow during the time required for switching off. After the switch break, the discharge current reduces to zero. Arcing is supported by the inductive energy stored in the output circuit. The current reduction rate depends on the output inductance, arcing voltage, and HPS operating mode.

Figure 1b illustrates the equivalent circuit of HPS and load. The HPS includes the pulse voltage source \( E_{hps} \), parasitic resistance \( R_{hps} \), and inductance \( L_{hps} \). In the HPS without the inductive energy recuperation, the pulse voltage source \( E_{hps} \) forms unipolar voltage pulses. And in the HPS with the inductive energy recuperation, the pulse voltage source \( E_{hps} \) forms bipolar voltage pulses. The cable possesses the inductance \( L_{cab} \) and resistance \( R_{cab} \). The load includes two circuits, which simulate magnetron and arc discharges. The magnetron sputtering system is a discharge system of the diode type, i.e., the load resistance depends on the polarity of the voltage applied. This effect is gained by the diode \( VD_{load} \) in the equivalent circuit. The load has the inductance \( L_{load} \) and pure resistance \( R_{load} \). Unlike the magnetron discharge, the arc voltage is low-dependent on the discharge current and is
usually in the range of 20 to 100 V. Since the arc voltage is low-dependent on the discharge current, the arc simulation is provided by the constant voltage source $E_{\text{load}}$.

Based on the equivalent circuit, presented in figure 1b, a mathematical model is proposed to calculate the arc parameters during the impulse magnetron sputtering [6]. To simplify our calculations, several assumptions are accepted for the model. During arcing, the arc parameters are constant, namely: the source voltage, output inductance, and arcing voltage. The parasitic resistance of the circuit is accepted to be zero. According to the proposed model, the total arc energy $E_{\text{arc}}$, peak current $I_{\text{max}}$, and lifetime $t_{\text{del}}$ can be calculated as follows during the current arc detection:

$$E_{\text{arc}} = \frac{(I_{\text{det}}^2 - I_1^2)L_{\text{out}}U_{\text{arc}}}{2(U_+ - U_{\text{arc}})} + \left(I_{\text{det}} + \frac{U_+ - U_{\text{arc}}}{2L_{\text{out}}}t_{\text{del}}\right)U_{\text{arc}} + I_{\text{max}}^2 \frac{L_{\text{out}}^2U_{\text{arc}}}{2(U_{\text{arc}} + U_+)} ,$$

$$I_{\text{max}} = I_{\text{det}} + \frac{U_+ - U_{\text{arc}}}{L_{\text{out}}}t_{\text{del}} ,$$

$$t_{\text{arc}} = \frac{I_{\text{det}} - I_1}{U_+ - U_{\text{arc}}}L_{\text{out}} + \left[I_{\text{det}} + \frac{(U_+ - U_{\text{arc}})}{L_{\text{out}}}t_{\text{del}}\right]L_{\text{out}} - \frac{U_+ + U_{\text{arc}}}{U_+} + t_{\text{del}} ,$$

where $I_1$ is the arc formation current; $I_{\text{det}}$ is the arc detection current; $U_+$ is the amplitude of negative voltage pulses of $E_{\text{hps}}$; $U_{\text{arc}}$ is the arcing voltage; $t_{\text{del}}$ is the voltage off-delay after arc detection; $L_{\text{out}} = L_{\text{hps}} + L_{\text{cub}} + L_{\text{load}}$ is the total output inductance of discharge electric supply; $U_-$ is the amplitude of the positive voltage pulses of $E_{\text{hps}}$, which is used in the inductive energy recuperation mode.

### 3. Test bench

Figure 2 illustrates the test bench that includes the HPS (APEL-M-5HPP-1000, Applied Electronics LLC, Tomsk, Russia) and the arc simulation circuits. Table 1 gives the main HPS parameters. The output pulse former of the HPS is based on a two-transistor forward converter. The HPS operating mode is switched by the switch $SW_1$. When $SW_1$ is closed, the energy stored in the output circuit enters freely in the load after switching off the control transistors. This operating mode is called the non-recuperation mode. When $SW_1$ is open, the inductive energy partially returns to the HPS. This operating mode is called the energy recuperation mode. After switching off the transistors $VT_1$ and $VT_2$, the inductive energy returns to capacitor $C_1$ via $VD_3$ and $VD_2$ diodes. The current is controlled by the driver and the bridge $R_1$ positioned in the emitter circuit $VT_1$. When the current in the bridge reaches the threshold value of $I_{\text{det}} = 300$ A, the driver switches off $VT_1$. The time required for the driver to switch the transistor is about 500 ns.

Figure 2. HPS and ASC circuits.

| Table 1. Parameters of HPS |
|---------------------------|
| **Parameter** | **Value** |
| Average output power | up to 5 kW |
| Out signal type | Pulse/DC |
| Stabilization mode | voltage / current / power |
| Max. pulse out power | 240 kW |
| Average output current | up to 10 A |
| Pulse voltage | 50–1000 V |
| Pulse frequency | 0.1–15.0 kHz |
| Pulse duration | 3–250 $\mu$s |
| Arc detection method | Overcurrent |
| Arc detection current | 300 A (fixed) |
| Overcurrent protection delay | 0.5 $\mu$s |
As can be seen from figure 2, the arc simulation circuit (ASC) includes the capacitor $C_2$ with 1 mF capacity, which functions as a constant voltage source $E_{hps}$. The capacitor $C_2$ is charged by the autotransformer $T_1$ via the rectifying diode $VD_1$ and the limiting resistor $R_2$. The resistor $R_3$ is used for the capacitor $C_2$ discharge. The switch $SW_2$ is a button, which must be pressed for the arc generation. The choke $L_1$ is arranged at the HPS output, on a ferrite gap core. During the experiment, the output inductance $L_{out}$ is controlled by the number of turns on the choke $L_1$. Voltages $U_{C1} = U_c = 600$ V and $U_{C2} = U_i = 100$ V of the respective capacitors $C_1$ and $C_2$ are constant. The discharge current and voltage pulses are recorded by the oscillograph and sensors $A_1$ and $V_1$. The obtained oscillograph records are used to measure the amplitude, current pulse time and transfer of the inductive energy in load. The output inductance $L_{out}$ can be calculated from

$$L_{out} = \left(U_{C1} - U_{C2}\right) \left(\frac{di}{dt}\right)^{-1},$$

where $\frac{di}{dt}$ is the output current growth rate measured during the first 0.5 $\mu$s.

4. Results

The oscillograph records shown in figure 3a, belong to the discharge current pulses obtained at different output inductance in the energy recuperation mode. Dashed lines indicate the current pulses resulting from simulation. The experimental data are in good agreement with the theoretical calculations in the range of $2.0 \div 10.6$ $\mu$H. The decrease in the output inductance $L_{out}$ leads to a reduction in the current pulse time and an increase in the peak current. A strong divergence between the experimental data and theoretical calculations is observed at $L_{out} = 1$ $\mu$H. The experimental current pulse amplitude is two times lower than the theoretical value.

At the triangle pulse current, the time of the current reduction is shorter than the time of its growth. The output current reduction rate depends on the output inductance voltage. During the current growth, the output inductance $L_{out}$ is exposed to voltage equaling the voltage difference on $C_1$ and $C_2$ capacitors. During the current reduction, the output inductance $L_{out}$ generates voltage approximately equaling the sum of voltages of $C_1$ and $C_2$ capacitors.

According to figure 3b, the arc energy grows during the pulse time. The energy growth decelerates with increasing output inductance $L_{out}$, whereas the pulse time increases. Therefore, the arc energy becomes higher. Thus, at $L_{out} = 1$ $\mu$H, the arc energy is less than 50 mJ, and at 10.6 $\mu$H, it is higher than 200 mJ.

Theoretical and experimental dependences of the peak current, arc energy and lifetime on the output inductance are presented in figure 4. Dashed lines indicate the theoretical calculations based on relations (1)–(3). They mean that depending on the output inductance $L_{out}$, the arc lifetime and energy in the recuperation mode are 1.5–3 times lower than in the non-recuperation mode. The peak current is not affected by the inductive energy recuperation. Most of points obtained in the experiment coincide with the theoretical calculations within the measurement error. As an exception, the values obtained at...
$L_{\text{out}} = 1 \, \mu\text{H}$ in both modes and at $L_{\text{out}} \geq 10.6 \, \mu\text{H}$ in the non-recuperation mode. The experimental data in these cases are significantly lower than theoretical calculations.

According to the experimental data, the arc energy in the recuperation mode reduces by approximately 6 times with decreasing output inductance, while in the non-recuperation mode, it reduces by 11 times. The lowest arc energy at 370 A peak current is 43 and 67 mJ in the recuperation and non-recuperation modes, respectively.

![Figure 4](image)

**Figure 4.** Theoretical and experimental dependences of peak current, arc energy and lifetime on output inductance in non-recuperation (a) and recuperation (b) modes.

### 5. Discussion

The theoretical dependences show that the arc energy behavior is nonmonotonic during a change in the output inductance. In the recuperation and non-recuperation modes, the arc energy is minimum at $L_{\text{out}} \approx 1 \, \mu\text{H}$. According to (1), the arc energy depends on the peak current $I_{\text{max}}$ and the output inductance $L_{\text{out}}$. At $L_{\text{out}} < 1 \, \mu\text{H}$, the arc energy grows due to the increase in the peak current $I_{\text{max}}$, while at $L_{\text{out}} > 1 \, \mu\text{H}$, it grows due to the increase in the output inductance $L_{\text{out}}$. It has been noted that the experimental data coincide with the mathematical modeling results within the measurement error. As an exception, the values obtained at $L_{\text{out}} = 1 \, \mu\text{H}$. The low inductance leads to a high current growth rate, which can cause self-locking of control transistor. This is because some of the supply voltage is applied to the total inductance of the emitter. The total inductance of the emitter means the inductance common to the collector and the gate current. The total inductance of the emitter is the additional feedback between the collector and the gate. It is easy to note that the voltage drop at this inductance is subtracted from the gate-source voltage in switching on the transistor and is added to it when switching off. The total inductance of the emitter thus retards the switching process and can lead to self-locking of control transistor at a high current growth rate. This phenomenon is like the Miller effect but occurs at a high growth rate of the current rather than the voltage. To eliminate this effect, it is necessary to reduce the total inductance of the emitter down to the minimum, that is determined by the parasitic inductance of the transistor housing. In our case, self-locking of control transistor results in a positive effect since it considerably reduces the arc energy.

The experimental data do not match the theoretical calculations at $L_{\text{out}} > 10 \, \mu\text{H}$ in the non-recuperation mode. In this case, the current reduction rate reaches several tens of microseconds. During this time, the significant part of the inductive energy scatters over the parasitic resistance of the output circuit. Since the proposed model does not consider the ohmic losses in the output circuit, the theoretical values of the arc energy are higher than the experimental.
6. Conclusions
Based on the results it can be concluded that the reduction in the electrical circuit inductance of high-power impulse magnetron sputtering led to a decrease in the arc energy and lifetime. When the output inductance reduced from 14 to 1 µH, the arc energy became 6 times lower in the recuperation mode and 11 times lower in the non-recuperation mode. The minimum arc energy reached at the maximum discharge current of 370 A, was 43 and 67 mJ in the recuperation and non-recuperation modes, respectively. When the output inductance reduced to 1 µH, self-locking of control transistor occurred, there by leading to the reduction in the current amplitude and the additional decrease in the arc energy. The results of the simulation and experiment showed a good match not in the all investigated range of changes in the output inductance. To reduce the discrepancy between theoretical and experimental values, it is necessary to increase the accuracy of calculations by refining the analytical model, which should take into account the parasitic resistance of the power supply and wires, as well as the inductance of the control transistor emitter.

Funding
This work was supported by the government contract No. FWRM-2021-0006 of the Institute of High Current Electronics SB RAS.

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