https://doi.org/10.46813/2024-154-057

DYNAMIC AND ENERGY CHARACTERISTICS OF THE DISCHARGE AT DIFFERENT INITIAL POLARITY ON THE PLASMA DIODE ELECTRODES

Ya. Hrechko[1], I. Sereda[1], N. Azarenkov[1,2], P. Kahanovskyi[1]

[1]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[2]National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine

E-mail: ya.hrechko@karazin.ua

The paper is devoted to determination of the effect of initial polarity of the high-voltage electrode connection of the plasma diode on the dynamic and energy characteristics of the discharge. It has been shown that it is possible to change the direction of charged particles beams, accelerated in the double layer, at the same levels of power and energy released in the discharge by changing the polarity of the high-voltage electrode connection. This is important for determining the sample location when it is irradiated with powerful pulse flows of charged particles that are formed and accelerated in the double layer of space charge, immediately in front of the sample surface.

PACS: 52.50.Dg, 52.59.-f, 81.15.Jj

INTRODUCTION

Highly concentrated energy sources such as plasma flows, laser, ion and electron beams are widely used in modern material processing technologies. Low-energy high-current pulsed electron beams are promising, as they allow to regulate the electrons energy, the depth of their penetration into the metal, the dynamics of temperature and stress in a wide range. The volumetric nature of the energy release and the possibility of changing the pulse duration make the pulsed electron beam a universal source. Low-energy beams have advantages over high-energy beams, as they allow to provide a high energy density (up to 35 J/cm^2) of the electron beam at low acceleration voltage and electron energy (doesn't exceed 20…30 keV), which significantly simplifies the radiation protection [1].

The interaction of low-energy high-current (1…100 A/cm^2 and higher) pulsed ($10^{-8}…10^{-5}$ s) electron beams with the material is accompanied by various phenomena, including extremely rapid heating and cooling of the surface layer, creation of large pressure gradient, and various phase transitions of material [2]. As a result, it is possible to modify the properties of the metal surface layer with a depth of several tens of microns and obtain a significant improvement in the operational characteristics of the material [3].

Traditional target irradiation to modify its surface layer occurs as follows. A high-current pulsed beam of electrons or ions is generated by an external source (accelerators of charged particles, vacuum diodes with an explosive emission cathode, etc.). Then it is transported to the target in a magnetic field that directs and magnetizes the beam [4]. In some cases, the creation and implementation of systems for the formation and transportation of beams is a difficult task, especially when transporting high power beams. An alternative is the formation and acceleration of high-current pulse beams in a double electric layer of space charge which is formed in a current conductive plasma, directly in the target processing zone. The double layer provides the efficient energy transfer from the external electric field to the energy of bipolar movement of charged particles. The beam, accelerated in the layer electric field, releases its energy immediately behind the acceleration zone at a distance comparable to the thickness of the layer. In this way, local and fast energy release in the irradiation zone is ensured.

Our previous studies have shown that under the conditions of double layer formation it is possible to locally input a pulsed power of more than 100 MW at a specific power of more than 2 GW/cm^2 with a stored energy of a capacitor bank of up to 200 J [5]. These studies were carried out using a discharge cell of a high-current pulsed plasma diode with a limited working surface of a high-voltage electrode (Fig. 1). When irradiating a target with powerful beams of charged particles accelerated in a double layer it is important to choose the optimal zone of its location in the discharge gap to obtain the specified parameters. The type of charged particles, electrons or ions, that will irradiate the target, as well as the energy level of the beam that will be released on the target surface depends on the target location during a certain period of discharge current oscillations. Thus, the purpose of this work was to determine the effect of initial polarity of the high-voltage electrode connection of the plasma diode on the dynamics of the discharge and the level of active power and energy released in the discharge.

1. EXPERIMENTAL SETUP

Fig. 1 shows a scheme of the discharge cell of the high-current pulsed plasma diode. The plasma diode includes two copper electrodes: the rod high-voltage electrode 1, which is directly connected to the capacitor bank, and the tubular grounded electrode 2, which is connected to the capacitor bank through the reverse current circuit 7. The side surface of the high-voltage electrode is covered with a ceramic insulator 3, so that only the end of the electrode remains working.

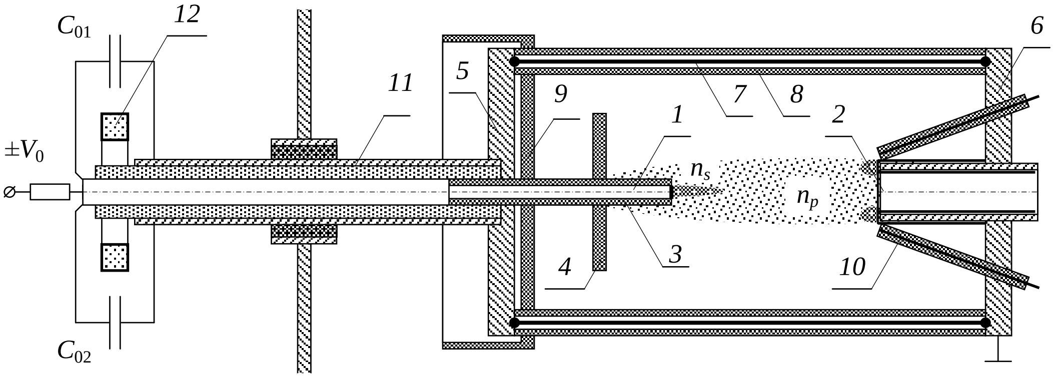

Fig. 1. The scheme of the discharge cell of the high-current pulsed plasma diode:
1 – high-voltage electrode (HVE); 2 – grounded electrode; 3, 4 – ceramic insulator; 5, 6 – fixing flanges;
7 – reverse current bus; 8, 9 – glass insulators; 10 – ignition electrode; 11 – vacuum input; 12 – current sensor

The working surface area of the high-voltage electrode is 0.05 cm^2 (the diameter of the electrode is 0.25 cm, respectively), and the working surface area of the grounded electrode is 2.35 cm^2 (the diameter and length of the electrode are 1 and 3 cm, respectively). This limitation of the high-voltage electrode working surface plays a key role, since it contributes to the concentration of a high discharge current density (up to 2 MA/cm^2) on the electrode and ensures the formation of a double layer of space charge near its surface. The distance between the electrodes is 5 cm and it isn't variable. The diode electrodes are attached to the fixing flanges 5, 6, which are connected by the reverse current bus 7. In order to avoid shorting the current on the wall of vacuum chamber, all current-conducting elements of the discharge cell are closed with glass insulators 8, 9.

The discharge excitation occurs at a low pressure of ~ $5\cdot10^{-6}$ Torr after applying a voltage pulse of ~ 1 kV to the ignition electrodes 10. Primary plasma with a density of up to 10^{12} cm^{-3} fills and closes the discharge gap. After the discharge gap is closed, a capacitor bank with a capacity of 2 µF (a charging voltage from 6 to 12 kV) is discharged and a discharge current begins to flow. At this stage, a double layer is formed near the surface of the high-voltage electrode. All voltage applied to the discharge gap is concentrated on the double layer. Depending on the initial polarity of the high-voltage electrode connection, electrons (with positive polarity) or ions (with negative polarity) of the primary plasma, accelerating in the double layer, irradiate the electrode working surface, which leads to its heating and evaporation. Due to electron impact ionization a dense near-electrode plasma with a density of up to 10^{16}…10^{17} cm^{-3} is created. Fig. 2 shows a schematic representation of the double layer formation near the high-voltage electrode in the 1st half-period of the discharge current at positive and negative polarity.

When the dense plasma expands deep into the discharge gap, the discharge current gradually increases, which in turn leads to a decrease in the active resistance of the discharge. At the moment when the discharge active resistance becomes less than the doubled wave resistance, the discharge passes from a high-voltage to a high-current inductive stage with a maximum current amplitude of up to 35 kA and an oscillation period of ~ 3.5 µs. At this moment, the double layer near the high-voltage electrode disappears, since the conditions for its existence are violated (the restriction on current flow disappears due to the increase in plasma concentration). However, periodically in the discharge gap, other double layers are formed and disappear, changing their localization and the magnitude of the potential drop in the layer.

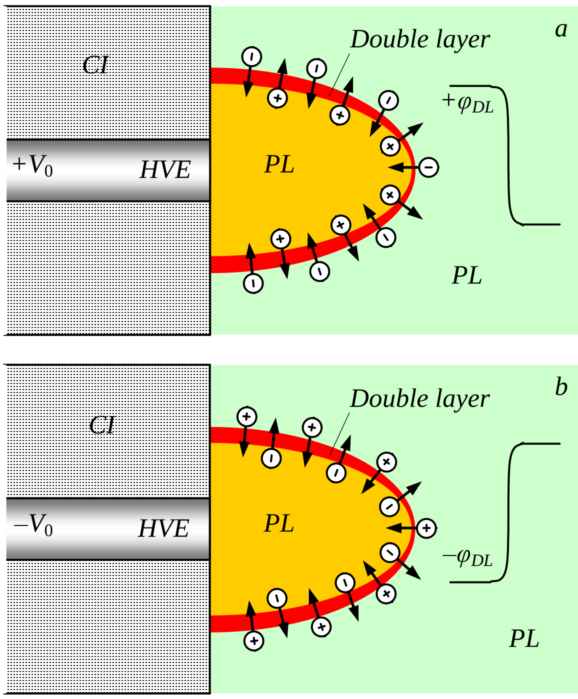

Fig. 2. Schematic representation of the DL formation near the HVE in the 1st half-period of the discharge current at positive (a) and negative (b) polarity.
HVE – high voltage electrode; CI – ceramic insulator;
PL – plasma; V_0 – charging voltage;
φ_{DL} – DL potential drop

2. RESULTS AND DISCUSSION

In our previous studies [5–7] it has been determined that the formation of zones of local energy release in the discharge depends on the double layer location and the direction of the electron beam acceleration. Four main zones of local energy release in the plasma diode discharge cell have been identified. It has been shown that the main share of energy (about 70%) is released in the 1st half-period of the discharge current oscillations in the dense near-electrode plasma. Further local energy release in the discharge has a peak character (duration of 100…200 ns) and is observed mainly at the discharge current maximum in the corresponding half-period. These studies have been carried out with a positive initial polarity of the high-voltage electrode connection. To determine the effect of the initial polarity of the electrode connection on the discharge dynamics, it is necessary to compare the dynamic characteristics of the discharge at positive and negative polarity.

Fig. 3 shows the dynamics of discharge current (a), active discharge voltage *(b)*, active discharge power (c) at positive (red curve) and negative (black curve) polarity of high-voltage electrode connection. The dynamics of the active discharge voltage and power were calculated based on the dynamics of the discharge current measured by the induction current sensor. The presented time dependences of the discharge characteristics were obtained at the charging voltage of the capacitor bank V_0 ~ 11 kV which corresponds to the initial stored energy W_0 ~ 115 J.

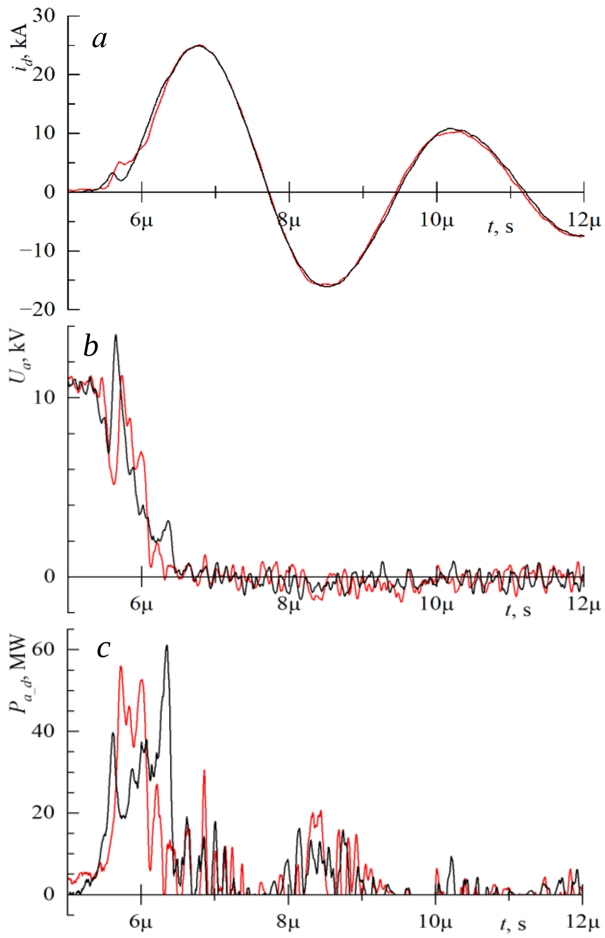

Fig. 3. Dynamics of discharge current (a), active discharge voltage (b), active discharge power (c) for positive and negative polarity of the HVE connection at charging voltage V_0 ~ 11 kV

Fig. 4 shows the dynamics of the specific energy released in the discharge at positive (red curve) and negative (black curve) polarity of the high-voltage electrode connection and charging voltage V_0 ~ 11 kV. The specific energy is the ratio of the energy released in the discharge to the energy stored in the capacitor bank. This time dependences was calculated from the dynamics of active power presented in Fig. 3,c. Comparing the dynamics of specific energies for positive and negative polarity, one can see that the share of energy released at negative polarity is on average 6% higher than at positive polarity. This increase is observed only in the 1st half-period of the discharge current oscillations. In order to find out the reason for such an increase in energy when the polarity is changed, it is necessary to investigate the energy released in the discharge for different values of the energy stored in the capacitor bank.

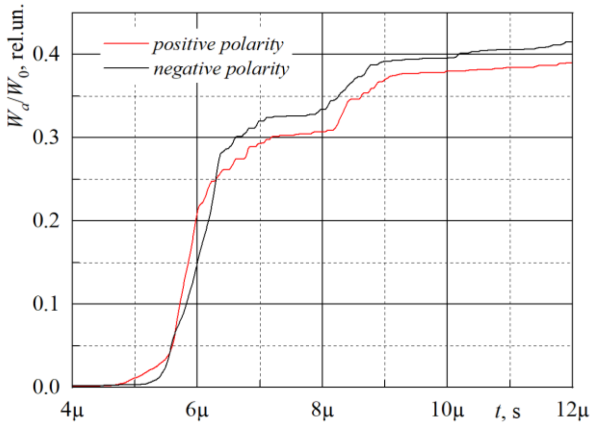

Fig. 4. Dynamics of the specific energy released in the discharge at positive and negative polarity of the HVE connection at the charging voltage V_0 ~ 11 kV

Figs. 5 and 6 shows the dependence of the energy and, respectively, the specific energy released in the discharge in the 1st half-period of the discharge current on the energy stored in the capacitor bank. The red color of the curves corresponds to the positive polarity, the black color – to the negative polarity.

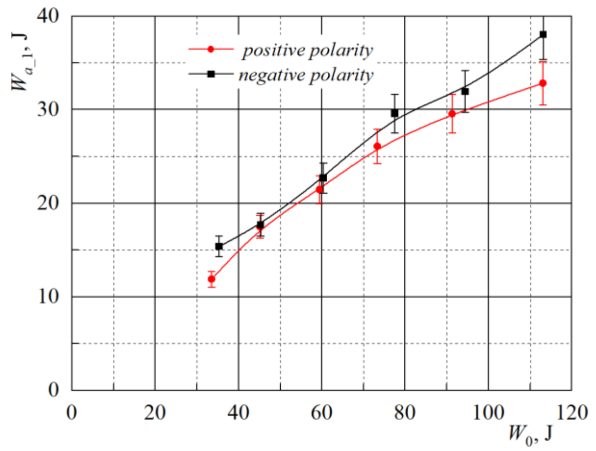

Fig. 5. Dependence of the energy, released in the discharge in the 1st half-period of the discharge current, on the energy stored in the capacitor bank

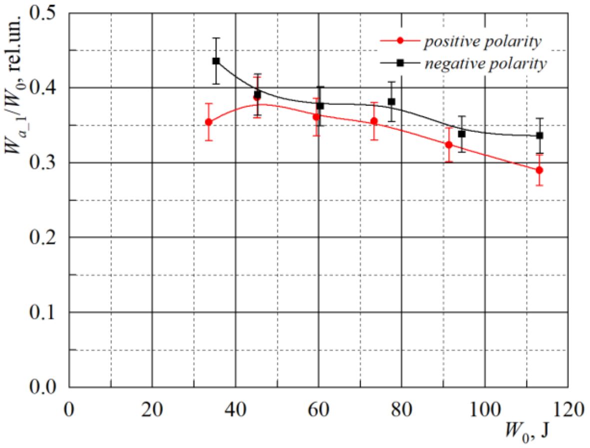

Fig. 6. Dependence of the specific energy, released in the discharge in the 1st half-period of the discharge current, on the energy stored in a capacitor bank

The 1st half-period was chosen for comparison, since the main (about 70%) energy release in the discharge occurs in this half-period. One can see that the energy values released in the discharge at negative polarity exceed the values at positive polarity in the entire presented range of the energy stored in the capacitor bank. However, this excess is not significant, up to 10%, and lies within the margin of error.

CONCLUSIONS

Thus, the studies of the effect of initial polarity of the high-voltage electrode connection of the plasma diode on the dynamic and energy characteristics of the discharge show that the change in polarity doesn't lead to their significant changes. The level of active power released in the discharge under conditions of double layer formation has practically the same values. The study of the energy released in the discharge from the energy stored in the capacitor bank showed a non-significant, within margin of error, increase in energy at negative polarity. This result indicates the possibility to change the movement direction of the charged particles beams, accelerated in the double layer, at the same levels of active power and energy released in the discharge by changing the polarity of the high-voltage electrode connection. This is important for determining the sample location when it is irradiated with powerful pulse flows of charged particles that are formed and accelerated in the double layer of space charge, immediately in front of the sample surface.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Education and Science of Ukraine (state registration project numbers: 0123U101803 & 0124U000972).

REFERENCES

1. V.V. Kvasnitskii et al. A high-current electron beam application for the surface modification of iron, stainless steel, and heat resistant alloys // *Surface Engineering and Applied Electrochemistry*. 2009, v. 45, p. 180-185.
2. D. Levko et al. Numerical simulation of the plasma generated by the interaction high-current electron beam with Al target // *Journal of Applied Physics*. 2013, v. 113, Iss. 12, p. 123302.
3. J. X. Zou et al. Mechanisms of hardening, wear and corrosion improvement of 316 L stainless steel by low energy high current pulsed electron beam surface treatment // *Thin solid films*. 2010, v. 519, Iss. 4, p. 1404-1415.
4. W. An et al. Characterization of high-current electron beam interaction with metal targets // *Journal of Applied Physics*. 2011, v. 110, Iss. 9, p. 093304.
5. Ya. O. Hrechko et al. Self-Sustained Plasma-Beam Discharge at High Energy Density // *IEEE Transactions on Plasma Science*. 2018, v. 46, Iss. 10, p. 3541-3546.
6. I. V. Borgun et al. Double electric layer influence on dynamic of EUV radiation from plasma of high-current pulse diode in tin vapour // *Physics Letters A*. 2013, v. 377, Iss. 3-4, p. 307-309.
7. I.V. Babenko et al. Matrix detector to determine the spatial distribution of VUV-radiation from plasma diode // *Physics of Plasmas*. 2021, v. 28, Iss. 5, p. 053502.

Article received 30.09.2024

ВПЛИВ ПОЧАТКОВОЇ ПОЛЯРНОСТІ ПІДКЛЮЧЕННЯ ЕЛЕКТОДІВ ПЛАЗМОВОГО ДІОДА НА ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ РОЗРЯДУ

Я. Гречко, І. Середа, М. Азарєнков, П. Кагановський

Робота присвячена визначенню впливу початкової полярності підключення високовольтного електрода плазмового діода на динамічні та енергетичні характеристики розряду. Показана можливість, змінюючи полярність підключення високовольтного електрода, змінювати напрямок руху пучків заряджених частинок, що прискорюються в подвійному шарі, при однакових рівнях потужності та енергії, що виділяється в розряді. Це важливо для визначення місця розташування зразка при його опроміненні потужними імпульсними потоками заряджених частинок, що формуються та прискорюються у подвійному шарі об'ємного заряду, безпосередньо перед поверхнею зразка.