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NON-SELF-SUSTAINED ARC DISCHARGE IN MAGNETIC FIELD: MAIN CHARACTERISTICS OF THE ARC DISCHARGE IN ZIRCONIUM VAPOR AND THE PARAMETERS OF THE GENERATED PLASMA FLOWS

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The paper presents the results of studies of non-self-sustained arc discharge in zirconium vapors. The method of initiating a vacuum arc discharge is described. Its main characteristics are given. The influence of the external magnetic field on the characteristics of the discharge and generated plasma flows is shown. The values of the plasma potential in the flows are determined. It was found that the anodic potential drop in the discharge has a positive value and decreases with grows of the discharge current. The values of the electron temperature, plasma density and floating potential in the generated flows of the zirconium vapor plasma were determined. Data on the growth rate of deposited films are given and it is shown that the ionization coefficient in plasma flows is (60-90) % at various currents of the discharge.

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INTRODUCTION

It is believed that the concentrated energy flows (pulsed electron flows and plasma flows) can be an effective tool in the development of new corrosion-resistant steels and protective coatings. Plasma streams allow not only alloying of the material, but also finishing of the surface layers of parts. It is proposed to use both metal coatings and coatings of metals compounds with various gases [1].

Plasma generators based on the cathodic vacuum arc discharge even when using filtering elements of different designs do not allow to completely get rid of the presence of drops of the working material in the created flows [2]. To reduce the porosity of the coatings created with their help, it is necessary to significantly increase their thickness. Therefore, it is desirable to use sources without droplet plasma streams for applying coatings with a minimum number of pores. Such plasma flows are capable of generating a non-self-sustained arc discharge in vapors of the anode material [3].

Zirconium refers to materials that are considered in nuclear energy as the most promising for solving the problems of anti-corrosion protection of uranium products. As a structural material, zirconium belongs to the group of refractory materials and has a very small thermal neutron capture cross section. This is the reason for the wide use of zirconium and its alloys in nuclear energy in the manufacture of heat-dissipating elements and other structures of nuclear reactors. It has high chemical resistance, is used in the manufacture of various acid-resistant components in devices and equipment of the chemical industry.

Zirconium is also characterized by high resistance and inertness to the influence of biological environments and is widely used in medicine for the creation of bone and joint prostheses, various surgical instruments. A wide range of areas of zirconium use allows us to talk about the possibility and expediency of using zirconium coatings on cheaper materials. All this makes the development and research of the sources plasma streams of zirconium vapor without droplet important and relevant.

1. EXPERIMENTAL SET-UP AND DIAGNOSTIC INSTRUMENT FOR PLASMA OF DISCHARGES IN VAPORS OF METALS

The schematic diagram of the experimental device is shown in Fig. 1. A non-self-sustained arc discharge was "ignited" between the water-cooled anode 4 and the grounded cathode 1 in vapors of the working material 2.

In these experiments, the working material was single-crystal zirconium, which was placed in a graphite crucible 3, installed on the upper surface of the anode 4 of the main arc discharge. The distance between the cathode of discharge 1 and the working material 2 was 5…7 mm. The discharge cathode was made of the 1 mm diameter tungsten wire and connected to the power source through a 10 Ω resistor. The cathode heated current was usually 60 A. The magnetic coil 6 was used for creating of magnetic field in the area of the discharge.

The cylinder 5 ensured the absence of a direct flow of discharge plasma on the inner surface of the magnetic coil 6. It also served to create an electric field transverse to the magnetic field and could be used as an anode of the additional electric discharge in the crossed E×H fields between electrode 5 and the discharge cathode 1. Electrode 8 was used to measure the ion current in the plasma flows at the exit from the plasma source. Usually it had a negative potential -200 V relative to the grounded cathode of the discharge. The distance between electrode 8 and the anode was 18 cm.

To study the plasma parameters in streams generated by a non-self-sustained arc discharge in pure zirconium vapors, we developed a suitable design of the flat probe with a guard ring 7. The design included the recorder flat probe element with a diameter of 4 mm made of non-magnetic stainless steel. The protective electrode surrounding the probe had the form of a cylinder with a diameter of 6 mm and providing the invariance of the ion and electron registration surface of the probe at different values of the probe potential.

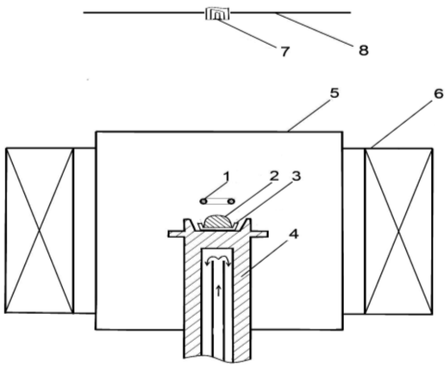

Fig. 1. Experimental device:
1 – heated cathode; 2 – working material;
3 – crucible; 4 – cooled anode; 5 – cylindrical electrode; 6 – magnetic coil; 7 – flat probe;
8 – ion collector

The construction of the probe in general had an outer diameter of 8 mm and was located in the center of the electrode 8 through a hole with a diameter of 10 mm. The probe was installed in such a way that its measuring part was 4 mm below the lower surface of the electrode 8. The probe, its protective electrode and its screen were electrically isolated from each other. A constant resistance of 100 Ω was used as a measuring resistance for the probe. When processing the probe characteristics, we also used the possibility of accounting of voltage drop on the measuring resistance and more accurate determination of the potential of the probe. The protective electrode of the probe was connected in the measuring circuit after the measuring resistance. The probe screen had a negative potential – 200 V. Usually the pressure in the vacuum chamber was $p \leq (1\ldots2)\cdot10^{-3}$ Pa. In the conditions of the films deposition the pressure in the vacuum chamber did not exceed $p = 2\cdot10^{-3}$ Pa.

2. THE FEATURES OF INITIATION AND CHARACTERISTICS OF A NON-SELF-SUSTAINED ARC DISCHARGE IN ZIRCONIUM VAPORS

To initiate the arc discharge in zirconium vapors, we used the additional gas discharge in crossed electric and magnetic fields between cylinder 5 and heated cathode 1 [4, 5]. The gas discharge was formed at the pressure of argon in the vacuum chamber $p = (2\ldots3)\cdot10^{-2}$ Pa and the presence of a positive potential on the cylindrical electrode 5. The volt-ampere characteristic of the arc discharge, under the conditions of its initiation, is shown in Fig. 2, curve 2. In the described experiments, the gas discharge current was $I_5 = 3$ A. After the "ignition" of the gas discharge in the E×H fields the voltage was applied between the anode 4 and the cathode 1. The corresponding current was generated, Fig. 2, curve 2, section A. The increase of voltage and discharge current was accompanied by heating of the working material 2 and the change of the working medium composition in the discharge gap.

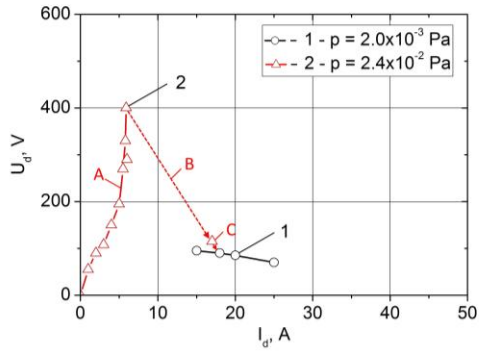

Fig. 2. Volt-ampere characteristics of the vacuum arc discharge at the its initiation in zirconium vapors using the gas discharge in E×H fields

At the electric power $W_d \approx 2.4$ kW was invested in the discharge, the formed pressure of zirconium vapor ensured the transition of the discharge into a self-consistent mode of existence, section B of curve 2 of Fig. 2. At point C, the main arc discharge and the discharge in the E×H fields simultaneously existed at the same time. The working medium of both discharges under these conditions were the mixture of argon and zirconium vapor. However, the zirconium vapors were the main component in the working environment of two discharges. It pressure were sufficient for the existence of the non-self-sustained arc discharge in the mode of self-generation of the working medium. Stopping the supply of argon to the vacuum chamber led to the "burning" of both discharges only in zirconium vapors at the pressure in the vacuum chamber $p \leq 2\cdot10^{-3}$ Pa and currents I_d=18 A and I_5=3 A. In the future, it was possible to move to the stable existence of only the main arc discharge in pure zirconium pairs at $I_5 = 0$. The volt-ampere characteristic of this discharge is shown in Fig. 2, curve 1.

The typical current-voltage characteristic of a non-self-sustained arc discharge in pure zirconium vapor is shown in Fig. 3 curve 1, in more detail at $B=80\cdot10^{-4}$ T and I_5=0. It can be seen that as the discharge current increases from 20 to 40 A, the discharge voltage decreases from 140 to 85 V.

At the same time, the electric power of the stationary existing discharge in zirconium vapors is in the range of W_d=2.8…3.4 kW. The minimum electric power of the discharge in zirconium vapors, under the conditions of these experiments, was approximately $W_{dm} \approx 2.2$ kW. In Fig. 3, curve 2 shows the value of the ion current on the ion collector 8 placed in the center of the plasma flow. Usually, the electrode 8 in the experiments had a size of 0.08x0.08 m and a negative potential "-200 V" relative to the cathode of the discharge. The total current of ions on this electrode increases with the growth of the discharge current and under experimental conditions is 55…110 mA. At the currents over 30 A, the growth of the ion current is close to linear.

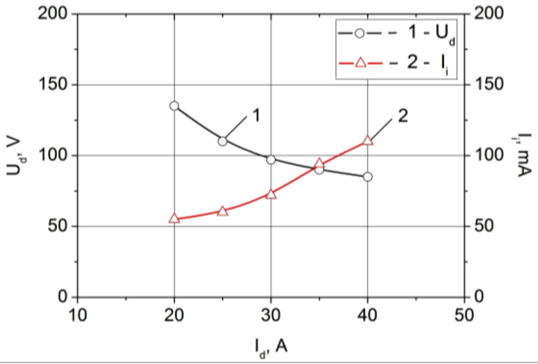

Fig. 3. The voltage of the main arc discharge in zirconium vapors, U_d, and the ion current on the ion collector, I_i, at the discharge current, I_d

The data obtained in these experiments are in good agreement with the values of ion current which are calculated according to the formula

$$I_i = I_{i0} \, [\, 1 + ([I_d - I_{do}] / I_{do})^{\,2}]. \qquad (1)$$

Here I_i is the ion current on electrode 8, I_{io} is the ion current on electrode 8 at the minimum discharge current I_{do}, I_d is the current of the "burning" discharge. In our case, $I_{do} = 20$ A, and $I_{io} = 55$ mA. Thus, expresion (1) can be used, at least, for an approximate estimate of the possible ion current in the generated plasma flows. At the same time, the distribution of the flow of ions along the radius of the electrode 8 is significantly different from the uniform one [3]. The possibility of using thus expression for appropriate estimates of the ion current in a wider range of discharge currents is of practical interest, but requires further experimental verification.

From the point of view of practical use of plasma flow sources, one of their most important properties is the ability to ensure the appropriate growth rate of the applied films or coatings, as well as good adhesion of applied films, which is largely related to the proportion of ions in the deposited plasma flow. The growth rate of zirconium films, q, deposited on the dielectric sital substrate at different arc discharge currents, I_d, is presented in Fig. 4, curve 1. In this experiment the pressure in the vacuum chamber was $p = (1…2)·10^{-3}$ Pa, I_5=0, B=$80·10^{-4}$ T. The presented data show that in the range of arc discharge currents up to 40 A, the growth rate of films q has the linear dependence on the current of the arc discharge and is $q = (5…17)·10^{-10}$ m/s, or q = 2…6 µm/h.

The fraction of ions in the flows, or the flow ionization coefficient, K_{ion}, is also the important characteristic of the generated plasma streams. It is defined by the expression:

$$K_{ion} = n_i·v_i/(n_i·v_i + N_a·V_a). \qquad (2)$$

Here n_i, N_a are the densities of ions and atoms in the flows, and v_i, V_a are the velocities of ions and atoms. The calculation of the ionization coefficient of plasma flows is described in more detail in publications [3].

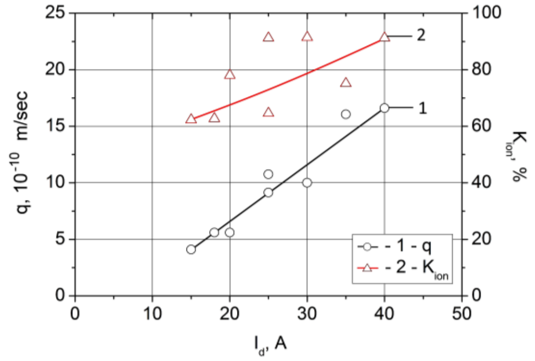

Fig. 4. The films growth rate, q, and the ionization coefficient of the plasma flow, K_{ion}, from the current of the main arc discharge, I_d

The curve 2 in Fig. 4 shows the values of the ionization coefficients of flows generated by an arc discharge in zirconium vapor at different discharge currents. The values are calculated taking into account ion sputtering of deposited films and singly ionized zirconium ions in the flow. It is obvious that the non-self-sustained arc discharge in vapors of anode material really creates plasma flows with a large part of the ions in the stream. In our experiments, the ionization coefficient of plasma flows was $K_{ion} \approx 60…90\%$.

3. THE INFLUENCE OF THE EXTERNAL MAGNETIC FIELD

The influence of the external magnetic field, which is created by coil 5, on the voltage of the main arc discharge is shown in Fig. 5, curve 1.

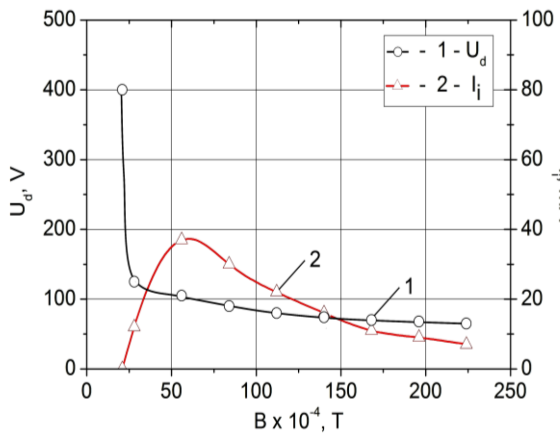

Fig. 5. The voltage of the arc discharge in zirconium vapors, U_d, and ion current on the electrode 8, I_i, at different induction of the external magnetic field, B

In this case, the main discharge current was $I_d = 25$ A, and $I_5 = 0$. The vacuum in the discharge chamber was $p = 1.2·10^{-3}$ Pa.

The presence of the magnetic field leads to the decrease in the requirements for the conditions of existence and ignition of the discharge. According to the given data, the increase in the magnetic field leads to a significant decrease of the discharge voltage: at $B = 20 \cdot 10^{-4}$ T, we have $U_d = 400$ V. And at $B \geq 60 \cdot 10^{-4}$ T, $U_d \leq 100$ V. At lower values of B, the discharge stops. The magnetic field also significantly affects on the part of ions in the created plasma flows. Curve 2 in Fig. 5 shows the dynamics of the ion current on the ion collector 8 when the induction of the external magnetic field changes. The arc discharge current in zirconium vapors is $I_d = 25$ A, while the discharge current in E×H fields is $I_5 = 0$. The change in the magnetic field leads to the change in the total ion current in the streams by almost 4 times, from 10 to 40 mA. It can be seen that the flows of zirconium plasma have the largest ion current at magnetic fields $B = (40…100) \cdot 10^{-4}$ T.

The change of the external magnetic field intensity , affecting on the processes of the ionization in the volume, leads to the change of the discharge voltage and thus significantly affects on the electric power of the discharge. Thus, at I_d=25 A and I_5=0, a change of the magnetic field from $B = 30 \cdot 10^{-4}$ T to $B = 150 \cdot 10^{-4}$ T is accompanied by the decrease in the electric power of the main arc discharge from $W_d = 3$ kW to $W_d \approx 2$ kW (Fig. 6, curve 1).

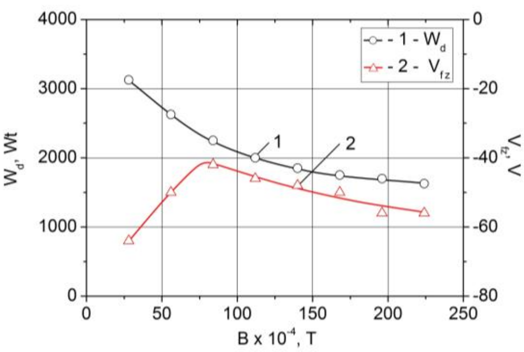

Fig. 6. The electrical power of the arc discharge in zirconium vapors, $W_d = I_d \times U_d$, and the potential of the isolated electric probe, V_{fz}, depending on the induction of external magnetic field, B

The potentials of the isolated electrical probe 7 were determined at different values of the external magnetic field induction. The data are shown in Fig. 6, curve 2.

These data show that the potential of the isolated probe at different values of magnetic field induction is negative relative to the potential of the grounded discharge cathode and varies in the range $V_{fz} \approx 40…60$ V. It should be noted that the changes of the magnetic field also lead to changes in spatial characteristics and the geometry of the created plasma flows.

4. PLASMA PARAMETERS OF THE GENERATED FLOWS

The flat probe 7 was used to determine the plasma potential, temperature of electrons, and density of electron in the generated plasma flows at I_5=0 and $B = 80 \cdot 10^{-4}$ T. The results of probe measurements and the main characteristics of the arc discharge were obtained in one experiment and were confirmed in other experiments. The probe was located in the center of the generated plasma flows at the distance of 18 mm from the discharge anode 5. The obtained values of plasma potentials at different discharge currents are shown in Fig. 7, curve 1. The researches were showed that the plasma of the flow at a distance of 18 cm from the discharge anode has a positive potential in several units of volts. At the same time, the plasma potential slow increase up to approximately +7 V in the range of discharge currents up to $I_d = 30…35$ A. Then plasma potential is reduced to +2 V retains a positive value.

The question of the value of plasma potential in streams at higher discharge currents in zirconium vapors remains open.

Probe measurements, which were made at different distances from the anode 4, allow estimating the longitudinal intensity of the electric field in the plasma flows as $E_{long} \approx 1.5$ V/cm. We also measured the plasma potentials on the various radiuses of the plasma streams. These measurements showed that the plasma potential varies from +6 V in the center to +5 V at the radius of 6 cm.

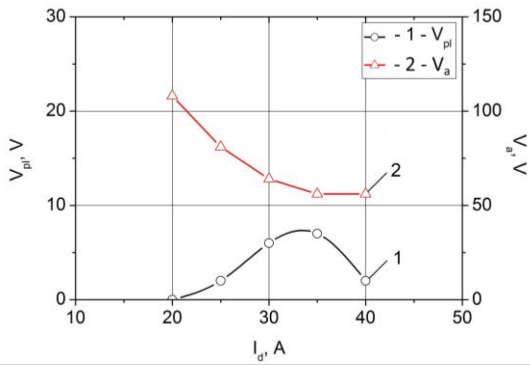

Fig. 7. The dependence of plasma potential, V_{pl}, and anode potential fall, V_a, on the current of arc discharge, I_d.

These data indicate that the intensity of radial electric field in the plasma streams is approximately 0.2…0.3 V/cm. The anodic potential drop was estimated based on the discharge voltage, plasma potential values and the longitudinal electric field strength obtained in the experiments. The obtained results are presented by curve 2 in Fig. 7. They indicate that in a given arc discharge, the anode potential fall is positive and decreases as the discharge current increases. According to the presented data, in the range of discharge currents, it decreases from approximately +100 to +50 V.

The characteristics of the probe made it possible to determine the temperature of electrons in the plasma flow. The obtained data are shown in Fig. 8, curve 1. It was found that at a distance of 18 cm from the anode, under conditions of zero potential on cylinder 5, the temperature of electrons in the plasma streams is $T_e = 12…14$ eV. These are quite high values, especially considering that the single ionization potential of zirconium atoms is 6.835 eV, and the double ionization potential is 12.92 eV. The presence in plasma streams of the electrons with a fairly high energy explains the really high degree of ionization of the plasma stream, 70…100%. High-energy electrons can also lead to the direct double ionization of zirconium atoms in the discharge.

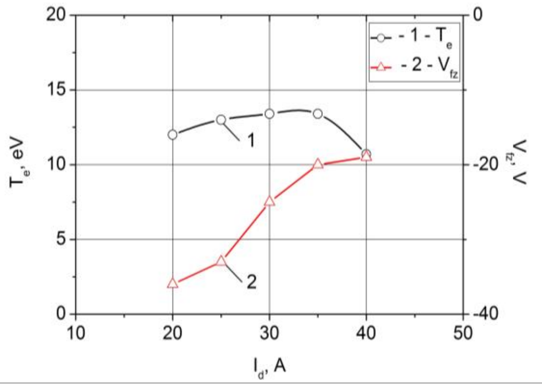

Fig. 8. The dependence the temperature of plasma electrons, T_e, and "floating" potential of the electric probe, V_{fz}, on the arc discharge current, I_d

A more detailed description of this process requires confirmation and clarification in experiments, as it is of the practical interest, for example, in the development of sources of metal ions. From the data of Fig. 8, curve 1, it can be seen that at the discharge currents of more than 30 A, when there is the increase of the ions current to the electrode 8 and the vapor pressure in the discharge gap, there is a tendency to decrease the values of the electron temperature.

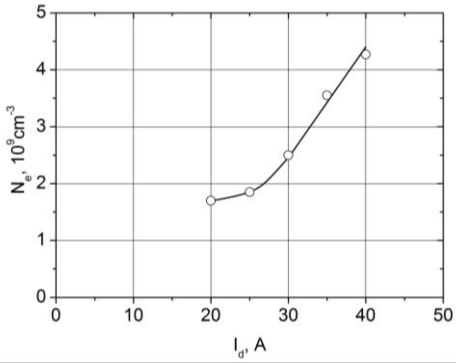

Fig. 9. The dependence the density of plasma electrons, N_e, on the arc discharge current, I_d

Using the flat probe with a guard electrode, we were able to measure the value of the electron density in the plasma for different discharge currents. Measurements were made at the distance of 18 cm from the discharge anode. The probe was placed in the center of the plasma flow. The measurement results are presented in Fig. 9.

It can be seen that at a discharge current of 20 A, the electron density in the plasma flow is about $N_e = 2{\cdot}10^9$ cm^{-3}. The increase of the discharge current to 40 A leads to the increase in the electron density to $N_e = 4{\cdot}10^9$ cm^{-3}. In general, this dependence is not linear. Although, according to the given data, at the discharge currents $I_d \approx 30…40$ A, there is a tendency for the linear dependence of the plasma electron density on the discharge current.

In Fig. 10 shows the dependence of the electron density in the zirconium vapor plasma on the ion current at electrode 8. It can be seen that there is a sufficiently good linear dependence of the values. Thus, the value of the ion current on electrode 8 can be used to determine the plasma electron density.

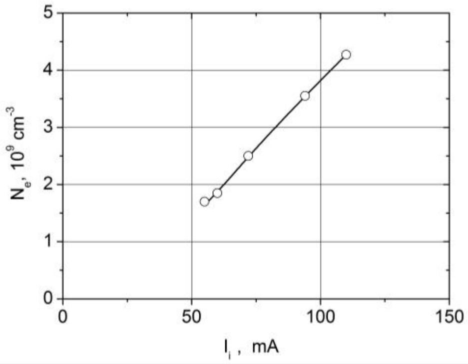

Fig. 10. The dependence the density of plasma electrons, N_e, on the ion current on electrode 8, I_i, at various discharges current

The dependence of the electron density of the discharge plasma, N_e, on the "saturation" current of ions on the flat probe with a negative potential of -200 V, I_{isat}, is shown in Fig. 11.

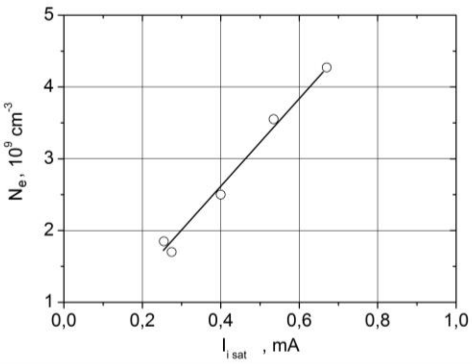

Fig. 11. The dependence the density of plasma electron, N_e, on the ion current "saturation" on the flat probe, I_{isat}

As expected, the electron density in the plasma changes linearly with the increase in the "saturation" ion current on probe 7 in the entire range of its values.

This obtained data indicate that to estimate the density of electrons in the plasma of the non-self-sustained vacuum arc discharge in zirconium vapors can be used as the values of ion saturation current on the probe 7 at a negative potential -200 V, and the full current of ions on the electrode 8.

CONCLUSIONS

The publication presents the results of experimental studies of non-self-sustained arc discharge in pure vapors of single-crystal zirconium. The given data describe the conditions for the stable existence of a vacuum arc discharge and determine the power of the electricity sources that are necessary for "ignition" and the conditions for a stable arc discharge. They also show the influence of external magnetic field on the main discharge characteristics in zirconium vapors.

The paper describes the results of studies of plasma parameters in generated flows at different discharge currents: plasma density, plasma electron temperature and plasma potential values. It was established that the temperature of electrons in the plasma of flows significantly exceeds the potential of single ionization of atoms of the working medium and varies in the range of T_e = 12…14 eV. It is proved that the total current of ions in the generated plasma flows on electrode 8 and the saturation current of ions on the flat probe 7 have a linear dependence on the density of plasma electrons in the generated flows.

In the article the value and behavior of the potential fall near anode of the discharge are evaluated. It is shown that in this arc discharge the fall of anode potential is positive and decreases with increasing the discharge current.

It is shown that at the use of generated plasma flows of zirconium vapors can ensure the growth of deposited zirconium films with growth rates up to q = 6 μm/h.

The paper shows that the ionization coefficient of plasma flows generated by a non-self-sustained arc discharge in zirconium vapors at different operating modes of the discharge are high and amount to K_{ion} = 60…90%.

Data indicate that zirconium vapors plasma flows which are capable generating the discharge of this type can be used to apply films and coatings on metallic, semiconductor, and dielectric materials because they have a compensated volume charge.

The presented research results indicate the expediency and relevance of further studies of this type of discharge in various working environments with the aim of developing new and improving existing plasma technologies for various purposes.

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НЕСАМОСТІЙНИЙ ДУГОВИЙ РОЗРЯД У МАГНІТНОМУ ПОЛІ: ОСНОВНІ ХАРАКТЕРИСТИКИ ДУГОВОГО РОЗРЯДУ В ПАРАХ ЦИРКОНІЮ ТА ПАРАМЕТРИ ГЕНЕРОВАНИХ ПЛАЗМОВИХ ПОТОКІВ

А.Г. Борисенко

Представлено результати досліджень несамостійного дугового розряду в парах цирконію. Описано методику ініціювання вакуумного дугового розряду. Наведено його основні характеристики. Показано вплив зовнішнього магнітного поля на характеристики розряду та генерованих плазмових потоків. Визначено значення потенціалу плазми в потоках. Встановлено, що прианодне падіння потенціалу в розряді має позитивне значення та зменшується зі збільшенням розрядного струму. Визначено значення температури електронів, щільність плазми та плаваючий потенціал у генерованих потоках плазми парів цирконію. Наведені дані щодо швидкості зростання плівок, що осаджуються, і показано, що значення коефіцієнта іонізації в плазмових потоках становлять 60…90% у різних режимах роботи розряду.