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DYNAMICS OF THE ION ENERGY DISTRIBUTION AND PLASMA PARAMETERS IN FLOWS OF THE NON-SELF-SUSTAINED ARC DISCHARGE IN MOLYBDENUM VAPORS

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In these experiments, the energy distribution functions of ions and plasma parameters in the generated flows of a non-self-sustained arc discharge in pure molybdenum vapors and in a mixture of molybdenum vapors with gas were investigated. It is proved that there are practically no ions with energy over 100 eV in the flows, and that the maximum of the ion distribution function shifts to lower values of the ion energy when the vacuum arc discharge current increases. The values of the plasma potential in the flows, the density and temperature of the plasma electrons at different discharge currents were determined. It is shown that the working medium of the discharge in pure molybdenum vapors is formed during the diffuse evaporation of the working material, which ensures the absence of droplets of the working material in the generated flows. Growth rates of deposited molybdenum films at different operating modes of the discharge were determined. It has been proven that the plasma flow created by a discharge of this type in molybdenum vapors has a compensated volume charge and can be used to apply metal films and coatings to substrates made of various materials, including dielectric ones.

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INTRODUCTION

Currently, in nuclear power, such metals as Zr, Mo, Nb, Ti, Ni, Ta, V, Cu are considered the most promising for solving the problems of anti-corrosion protection of uranium products. In order to improve their corrosion properties, it is considered appropriate to use metal coatings made of molybdenum and coatings made of its compounds with various gases [1]. A non-self-sustained arc discharge in the vapors of the diffusely evaporating anode is capable of generating highly ionized and droplet-free plasma streams [2-9]. Therefore, the study of the discharge characteristics and parameters of the plasma flows generated by this discharge are relevant and necessary, both in the case of discharge in pure molybdenum vapors and discharge in vapors-gas working medium.

1. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Fig. 1. A non-self-sustained main arc discharge was initiated between the grounded cathode 1 and the water-cooled anode 3 in pairs of the working material 2. In these experiments, the working material was molybdenum. Initially, the Mo sample had the form of a cylinder with a diameter of 0.01 m and a height of 0.02 m and was directly placed on the upper plane of the anode 3. The distance between the cathode of discharge 1 and the working material 2 was 0.005...0.007 m. The discharge cathode was made of a tungsten wire with a diameter of 1 mm. The cathode glow current was usually 60 A. A resistance of 10 Ω was used to stabilize the main discharge.

An additional gas discharge in the crossed magnetic and electric fields between electrode 4 and the cathode of discharge 1 was used to initiate the main arc discharge. The magnetic field in the discharge gap with a strength of $B=80\cdot10^{-4}$ T was created using magnetic coil 5. Cylindrical electrode 4 was used as anode of the additional discharge. After “ignition” of an additional discharge in argon, the electric voltage that fell between electrodes 1 and 3 led to the formation of the main arc discharge in the working environment, the composition of which changed. At low currents, the main discharge existed in the gas. The increase of the discharge current was accompanied by the evaporation of the molybdenum and the formation of a vapors-gas working medium.

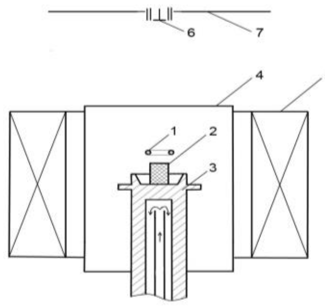

Fig. 1. Experimental device:
1 – heated cathode; 2 – working material; 3 – cooled anode; 4 – cylindrical electrode; 5 – magnetic coil; 6 – flat Langmuir probe;
7 -ion collector -substrate holder

Special constructions of the flat probe with a protective ring 6 and the electrostatic analyzer of the charged particles energy were developed to study the parameters of plasma flows generated by a non-self-sustained arc discharge in pure molybdenum vapors. Electrode 7 was used to measure the current of ions in the plasma flow at the exit from the plasma source. It was usually a negative potential “-200 V”.

Electrode 7 could also be used to place pads. The distance between electrode 7 and the anode was 0.18 m. Usually, the pressure in the vacuum chamber was $p = (1…2)\cdot10^{-3}$ Pa. The pressure in the vacuum chamber decreased significantly during the deposition of molybdenum films and was $p \le 1\cdot10^{-3}$ Pa. Stopping the supply of gas to the vacuum chamber led to the transition of the main discharge in the vapors-gas mixture to its "burning" mode in pure metal vapors.

2. EXPERIMENTAL RESULTS

The volt-ampere characteristic of a non-self-sustained arc discharge in a mixture of molybdenum vapors with argon, curve 1, and pure molybdenum vapors, curve 2, is shown in Fig. 2.

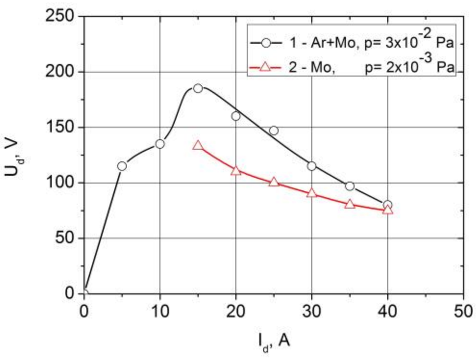

Fig. 2. Volt-ampere characteristics of non-self-sustained arc discharge in a mixture of molybdenum vapors with argon, curve 1, and in pure molybdenum vapors, curve 2

It can be seen that the formation of a vapors-gas mixture takes place at $I_d \ge 10$ A and already at $I_d \ge 15…20$ A the influence of molybdenum vapors on the characteristic is significant. Functions of the ion energy distribution at different discharges currents are presented in Fig. 3. The curves 1-3 are correspondent of the data for discharges in gas and mixtures of metal vapors with gas at $p = 2.0\cdot10^{-2}$ Pa.

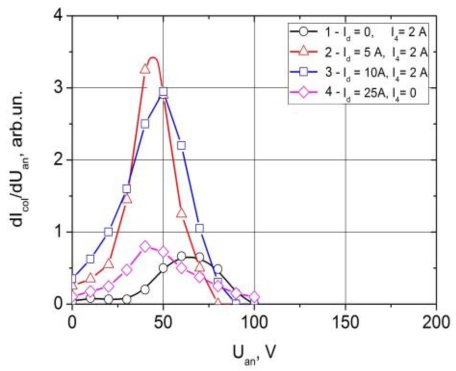

Fig. 3. Ion energy distribution at different currents of the main, I_d, and additional, I_4, discharges

The curve 4 is presented characteristics for main discharge in pure molybdenum vapors at $p = 2.0\cdot10^{-3}$ Pa. The values of electron temperature and plasma potential in the generated flows at different main discharge currents are shown in Fig. 4. It can be seen that the electron temperature is $T_e \approx 12…13$ eV, curve 1. The plasma potential, curve 2, is positive and changing in the interval V_{pl} = 8...10 V. At the same time, the voltage between the anode and cathode of the main discharge in molybdenum vapors under these conditions significantly decreases from 135 to 75 V. The given data show that under the conditions of the described experiments, the reduction of the potential jump in the anode layer can be a characteristic feature of this type of discharge.

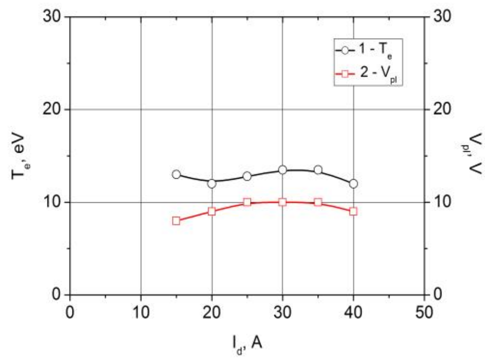

Fig. 4. Electron temperature and plasma potential of the main arc discharge in molybdenum pairs: $I_4 = 0$ A; $p = 2.0\cdot10^{-3}$ Pa

Fig. 5 shows the changes in the ion current on the ion collector 7 and the value of the plasma density in different operating modes of the discharge. The data show that under the conditions of the described experiments, the plasma density varies in the range of $N_e \approx (1.1…1.9)\cdot10^9$ cm^{-3}. At the same time, the value of the ion current on electrode 7 has a non-linear dependence on the discharge current. The given data also show that the increase in the discharge current from 15 to 40 A leads to an increase in the value of the ion current, which increases almost 5 times, changing from 28 to 130 mA.

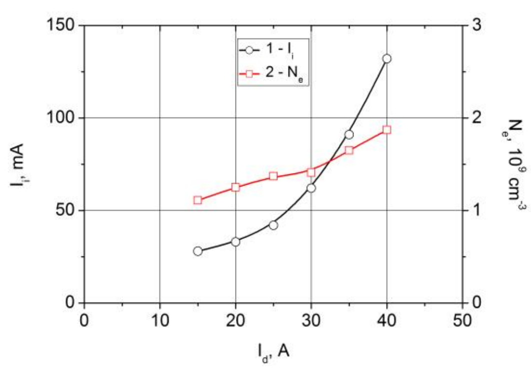

Fig. 5. Dependence of the ion current on electrode 7, curve 1, and the plasma density, curve 2, on the main discharge current: $I_4 = 0$ A; $p = 2.0\cdot10^{-3}$ Pa

Fig. 6 shows the energy distribution of ions in the main arc discharge in pure molybdenum vapors at different discharge currents. It can be seen that there are practically no ions with energy over 100 eV in the flows.

The maximum of the ion distribution occurs at the energy much lower than the corresponding potentials of the anode. The anode potentials in this case are 100 V for curve 1 and 90 and 80 V for curves 2 and 3, respectively. The data also show that when the discharge current increases, the maxima of the ion distribution shift to lower ion energy values.

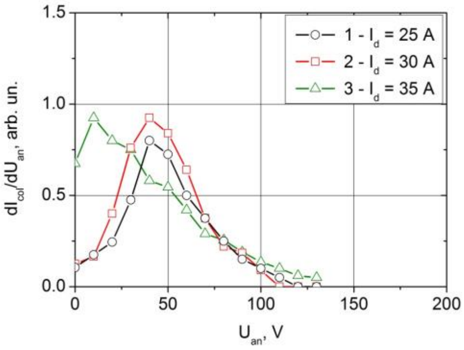

Fig. 6. Ion energy distribution at different currents of the main arc discharge, I_d, in pure molybdenum vapors: $I_4 = 0$ A; $p = 2.0 \cdot 10^{-3}$ Pa

The growth rate of the molybdenum film on dielectric sital substrate at different discharge currents is shown in Fig. 7. The pressure in a vacuum chamber was $p \le (1.2...2.0) \cdot 10^{-3}$ Pa. The substrates were placed at a distance of 18 cm from anode 3.

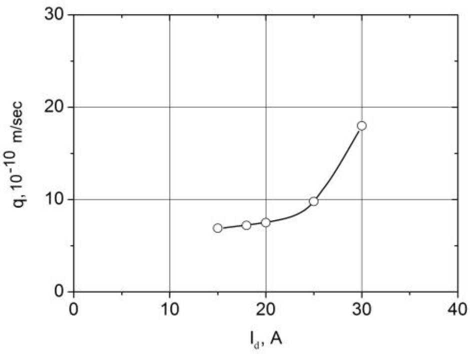

Fig. 7. Growth rate of the molybdenum films, q, on the value of the main discharge current, I_d

The speed of films deposition q has a non-linear dependence on the main discharge current in the range of up to 30 A and is $q = (5...15) \cdot 10^{-10}$ m/s, or q = 1.8...6.5 μm/h.

Fig. 8. Photo of the working material, molybdenum, after its use in the main arc discharge

A photo of a sample of molybdenum working material, after its use in research is presented in Fig. 8. The upper surface of the sample has a mirror appearance without any local inclusions. This indicates that the working environment in the discharge was formed by homogeneous diffuse evaporation of the upper layer of the working material.

CONCLUSIONS

This publication presents the results of experimental research on the physics of generation processes and the stable existence of a non-independent arc discharge in pure molybdenum vapors and a discharge in a mixture of molybdenum and argon vapors. The functions of the ion energy distribution in the generated flow at different operating modes of the discharge and in different working environments were studied. It is shown that in the generated plasma flows there are practically no ions with an energy exceeding the value of the discharge voltage. It was found that an increase in the discharge current leads to a decrease in the values of the average energy of the directional movement of ions in the generated flows. The main characteristics of the discharge in various working mediums are presented. It is shown that the plasma flows of the arc discharge in molybdenum vapors and the discharge in molybdenum vapors with gas have a compensated volume charge and can be used for the deposition of films and coatings on metal, semiconductor, and dielectric materials.

The presented results of the experiments indicate the expediency and relevance of further studies of this type of discharge in various working environments and may be important for the development of new and improvement of existing plasma technologies for various purposes.

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ДИНАМІКА РОЗПОДІЛУ ІОНІВ ЗА ЕНЕРГІЄЮ ТА ПАРАМЕТРИ ПЛАЗМИ У ПОТОКАХ НЕСАМОСТІЙНОГО ДУГОВОГО РОЗРЯДУ У ПАРАХ МОЛІБДЕНУ

А.Г. Борисенко

У цих експериментах були досліджені функції розподілу іонів за енергією в плазмових потоках несамостійного дугового розряду в чистих парах молібдену та параметри плазми в генерованих потоках. Доведено, що максимум функції розподілу іонів за енергією зміщується до менших значень енергії іонів при збільшенні струму вакуумного дугового розряду. Визначені значення потенціалу плазми в потоках, густина та температура електронів плазми при різних струмах розряду. Показано, що робоче середовище розряду в чистих парах молібдену формується при дифузному випаровуванні робочого матеріалу, що забезпечує відсутність у створюваних потоках крапель робочого матеріалу. Визначені швидкості росту осаджуваних плівок молібдену в різних робочих режимах розряду. Доведено, що створюваний розрядом даного типу в парах молібдену плазмовий потік має компенсований об'ємний заряд і може бути використаним для нанесення металевих плівок і покриттів на підкладинки з різних матеріалів, у тому числі і діелектричних.