ION ENERGY DISTRIBUTION AND BASIC CHARACTERISTICS OF PLASMA FLOWS OF NONSELF-SUSTAINED ARC DISCHARGE

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Experimental results on study of the nonself-sustained arc discharge basic characteristics at currents up to 35 A are presented. The ion energy distributions and dynamics of the directed motion average energy of plasma flow ions are studied. Floating potentials in the plasma flows are measured. Ionization coefficients of the generated plasma flows and their dependence on the discharge current are studied. It is shown that at the discharge currents equal 20…30 A the vacuum arc discharge in anode material vapors can effectively create dropless and highly ionized plasma flows of different metals and provides films deposition rates, which are comparable to possibilities of the cathode vacuum arc discharge.

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INTRODUCTION

Formation of functional metal films of various solid-state materials for needs of nano- and microelectronics requires the use of plasma sources in which plasma streams there are no material drops. Physical processes that occur in the widely used arc discharge in cathode material vapors, always create plasma flows with the drops of cathode material [1-4]. Droplet sizes vary from a few to tens of microns. Proportion of the droplets of diameter greater than 2 microns in the total weight of the transported material can reach 90% [1]. Therefore, these flows can not be used to solve a number of technological problems and they require development and application of various additional filtering methods [2-4]. However, filtration of flows not only removes the drop phase of working material, but also leads to a significant decrease in the plasma flow intensity at the filter outlet [4, 5]. The nonself-sustained arc discharge in anode material vapors is characterized by diffuse current binding at the anode and generates plasma flows without drops [6]. The mode of local vaporization of the anode material working surface in this type discharge virtually is absent [7]. At the moment, information about the ion energies in plasma flows generated by this type discharge is absent. Also there are no data on characteristics of such a discharge at currents more than 10 A. That is why their study is important from both fundamental and applied perspectives.

1. EXPERIMENTAL SETUP

A scheme of the used experimental device is shown in Fig.1. The discharge was ignited between an anode 3, which was water cooled, and a grounded heated cathode 1 in vapors of working material 2. The working material 2 was placed directly on the anode of the discharge. In experiments described here the working material was nickel or titanium. Thermoelectrons from the cathode reached the working material and heated it up. The discharge initiation took place when the pressure of working material vapors achieved a certain level. The distance between the cathode and working material constituted 5…10 mm. Crossed electric and magnetic fields in the discharge zone were used for simplification of discharge ignition and for control of generated plasma flows parameters. They were created by a cylindrical electrode 4 and the magnetic field coil 5. The electric potential of the electrode 4, U_4, was changing relative to the potential of the grounded discharge cathode. The magnetic field, B, in the area of the discharge gap was $B = 8\times10^{-3}$ T and corresponded to the maximum of ion current to the collector 7 at a fixed discharge current. An additional discharge in the crossed electric and magnetic fields was ignited when applying a positive potential to the cylindrical electrode 4. A flat electric probe 6 was used to measure parameters of the plasma flows. The probe was placed on the axis at a distance of 17…19 cm from the anode or 9…11 cm from the upper surface of the electrode 4. Potential of the probe when measuring the ion current was typically $U_6 = -200$ V. Energy spectra of ions were measured using a 4-electrode electrostatic analyzer. Deposition rates of the films, q, which are listed in the work are averages over the dielectric substrate surface of size 4.8×6 cm. The substrates were placed on the electrode 7 at a distance 18…18.5 cm from the anode. Geometric dimensions of the described plasma source do not exceed the dimensions of a cylinder of diameter

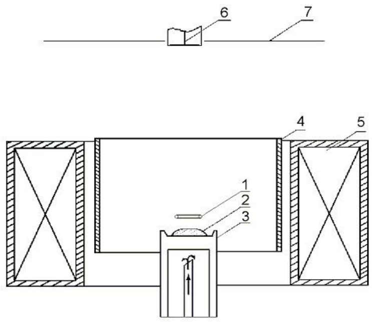

Fig. 1. Scheme of experimental device.
1 – heated cathode; 2 – working material; 3 – cooled anode; 4 – cylindrical electrode; 5 – magnetic coil;
6 – analyzer or a flat Langmuir probe;
7 – substrate holder-ion collector

17 and 20 cm in height. Therefore, the device can easily be placed in a vacuum chamber for vacuum deposition. The gas pressure in the discharge chamber was close to the ultimate vacuum and was not more than 1×10^{-3} Pa. When working with titanium in sputtering mode the pressure in the vacuum chamber diminished by about 10 times. The cathode of discharge in these experiments worked in a free mode when the thermoelectron emission current from the cathode exceeded the total current of primary and secondary discharges.

2. EXPERIMENTAL RESULTS

The volt-ampere characteristic (VAC) of the nonself sustained arc discharge in nickel vapors, that is the dependence of the discharge voltage, U_d, on the value of the discharge current I_d, is shown in Fig. 2, curve 1. As you can see VAC characteristics of this type discharge have an appearance typical of vacuum arcs. Increase in the discharge current is accompanied by a decrease in the discharge voltage. In our case, at increase in the discharge current from 12 to 35 A the discharge voltage decreased from 180 to 85 V. VAC characteristics of the described discharge is radically different from the VAC characteristics of the nonself-sustained arc discharge in gases. In the case of gas discharge the voltage is increased by the rise of discharge current.

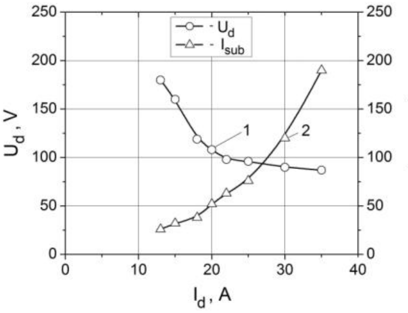

Fig. 2. Discharge voltage U_d and ion current to the substrate holder I_{sub} vs discharge current I_d

The increase in discharge current is accompanied by an increase of the ion current to the ion collector 7 (Fig. 2, curve 2). The ion current density on the electrode 7 increased from 0.4 to 2.9 mA/cm^2, which is about 7 times.

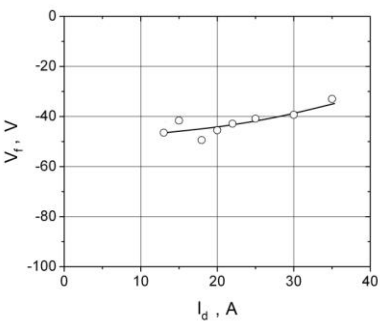

Fig. 3. Floating probe potential V_f on the value of discharge current I_d

Throughout the investigated range of the discharge current the potential of the isolated probe was negative and was equal to -(35…45) (Fig. 3). The floating potential value varies slightly according to the diameter of the plasma flow. These data show that the plasma stream, created by the given discharge has neutralized space charge and it can be successfully used for films deposition on substrates of any material, not only on metals and semiconductors, but also on dielectrics. The growth rates of the nickel and titanium films on dielectric substrates, for various discharge currents are shown in Fig. 4. As it can be seen from the figure, even at discharge currents from 10 to 35 A the generated plasma flows can be used for deposition of nickel films with growth rates $q_{Ni} = (1.5…5.5)\times10^{-6}$ m/h or $q_{Ni} = (4…15)\times10^{-10}$ m/s (see Fig. 4, curve 1). In the case of titanium deposition the films growth rates are $q_{Ti} = (2…10)\times10^{-6}$ m/h or $q_{Ti} = (5…27)\times10^{-10}$ m/s (see Fig. 4, curve 2).

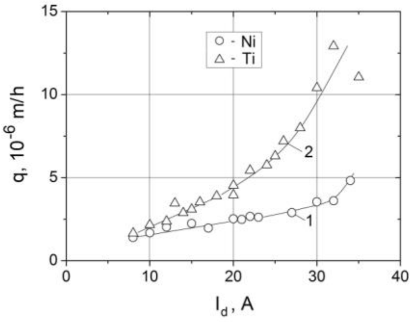

Fig. 4. Rate of films deposition q on the discharge current I_d for Ni and Ti as a working material

Both dependences are nonlinear. The initial linear growth of q at discharge currents greater than 25 A is replaced by more rapid growth. This fact is interesting from the fundamental point of view, since a linear dependence of the growth rate of deposited films on the discharge current value usually presented in the vacuum arc discharge. This is also important from a practical point of view, because it suggests the possibility of increasing economic efficiency of industrial equipment's, which are developed on the basis of the described type discharge. Therefore, further investigations of the discharge, including this feature are appropriate and necessary. Results of the growth rate measurements and measured value of ion currents to the substrate allowed to determine the ionic fraction in a plasma stream that is factor of ionization of a plasma stream, α. Calculations of α have been made taking into account the process of ion sputtering of films material. More detailed methodology of α measurement and calculation is described in [6]. The results of measurements for nickel are shown in Fig. 5. The measurements were made at zero potential of the cylindrical electrode 4. The data of Fig. 5 indicate that variation of the discharge current can significantly increase α. It can be seen that ionization coefficient of the plasma flow in a discharge in nickel vapors is about 45% at a discharge current of 10 A and increases almost linearly with the discharge current. It reaches values of the order of 100% at a current of

30 A. That is, this discharge really produces highly ionized flows of metal plasma.

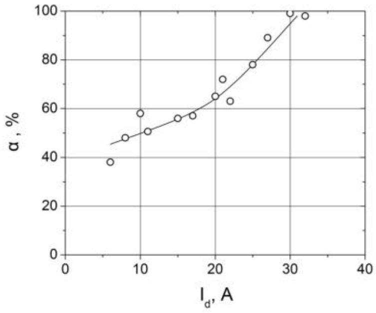

Fig. 5. Ionization coefficient of plasma flow α vs discharge current I_d for Ni

The ion energy distributions in the plasma flows generated at different discharge currents in the nickel vapors are shown in Fig. 6. They have been calculated from the decay curve of collector ions obtained by four-electrode electrostatic analyzer. It is seen that the ions with energies greater than the discharge voltage are absent, in contrast to the vacuum arc discharge in vapor of the cathode material. This indicates that in this discharge the ions leaving the anode surface also absent.

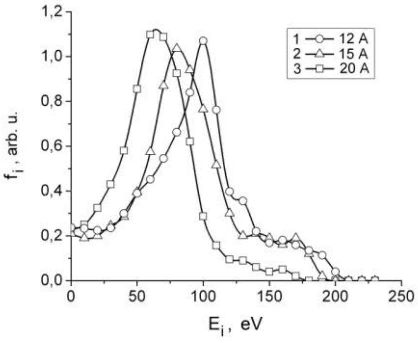

Fig. 6. Ion energy distribution f_i for various discharge currents I_d at $U_4 = 0$: 1 – $I_d = 12$ A; 2 – $I_d = 15$ A; 3 – $I_d = 20$ A

Thus, formation of the discharge working medium occurs by evaporation of the anode material and subsequent ionization of the vapor in the discharge gap zone. The experiments show that the top of the energy distribution of nickel ions decreases with increasing the discharge current. This was also supported by data of Fig. 6. The maximum of ion energy distribution at discharge current of 12 A corresponds to an energy of 100 eV. Increasing the discharge current to 15 A, and then to 20 A leads to a displacement of this peak to the energy of 80 and 60 eV.

Presence of a positive potential on the cylindrical electrode 4 leads to ignition of an additional discharge in the crossed longitudinal magnetic and transversal electric fields. The increase in the potential of electrode 4 induced a small reduction of the discharge potential. The additional discharge not only made it easier the ignition of the main discharge, but it also allowed to influence on certain parameters of the created plasma streams. Fig. 7 (curve 1) shows the values of α and q_{Ni} at the fixed current of main discharge I_d = 10 A and at different values of the additional discharge current I_4.

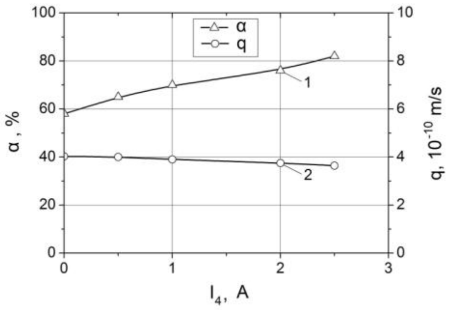

Fig. 7. Ionization coefficient of plasma flow α and rate of Ni film deposition q vs current of additional discharge I_4

It is see that the additional discharge even at low currents can significantly affect on the α and change its value from 58 to 82%, which is almost 1.5 times. From the data of Fig. 7, curve 2, it is visible that increase of α takes place at almost stable rate of films deposition q: at presented conditions the reduction of q is not more than 10 % of its initial value. The influence of the additional discharge on ion energy distribution is shown in Fig. 8.

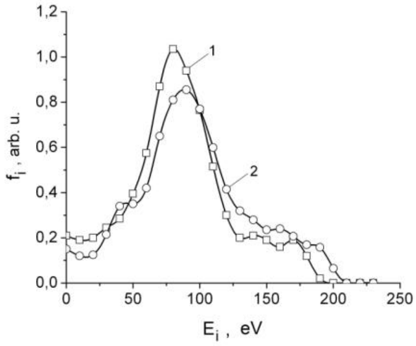

Fig. 8. Ion energy distribution f_i for various additional discharge currents I_4: 1 – $I_4 = 0$; 2 – $I_4 = 2$ A

Here there are energy distributions of Ni ions, measured at the main discharge current I_d = 15 A, and in the absence (curve 1) or in the presence of the additional discharge with current of I_4 = 2.5 A (curve 2). The potential of the cylindrical electrode 4 in this case had been changed from 0 to 110 V. It is evident that additional discharge apparently has a little effect on the ion energy distribution of the main discharge. In this case, there is only a slight shift of the ion distribution function peak to higher energies, which does not exceed 10 V (from 80 to 90 V).

CONCLUSIONS

The results of experimental studies of the main characteristics and the energy spectra of ions in a plasma of the nonself-sustained vacuum arc discharge with currents up to 35 A are presented. It has been established, that in the generated plasma streams the ions, with energies equal or greater than the discharge voltage, are absent. This indicates that the discharge does not contain the ions which enter into the discharge zone directly from the anode surface. The obtained data also indicate that the basic physical mechanism providing formation of the discharge working medium is evaporation of the anode material. The most probable mechanism of plasma formation is ionization of atoms of working substance directly in the discharge zone. The ion energy distributions were measured and it was established that the maximum of ion distribution shifted to smaller values at increase of the discharge current. That is, a decrease in the directed motion energy of ions takes place. It was shown that even at currents of 20…30 A the discharge generated highly ionized plasma streams, and could provide deposition rates of metallic films that were comparable with possibilities of the vacuum cathode arcs. The data presented in this article shows that the further researches of plasma sources on the basis of the nonself- sustained arc discharge in vapors of anode material are actual and necessary.

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РАСПРЕДЕЛЕНИЕ ИОНОВ ПО ЭНЕРГИЯМ И ОСНОВНЫЕ ХАРАКТЕРИСТИКИ ПОТОКОВ ПЛАЗМЫ НЕСАМОСТОЯТЕЛЬНОГО ДУГОВОГО РАЗРЯДА

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Представлены результаты исследований основных характеристик несамостоятельного дугового разряда при токах до 35 А. Приведены функции распределения ионов по энергиям, измеренным в создаваемых плазменных потоках при разных значениях тока разряда и показана динамика энергии направленного движения ионов. Определены значения плавающего потенциала. Показано, что при токах 20…30 А вакуумный дуговой разряд в парах материала анода позволяет эффективно создавать бескапельные высокоионизованные потоки плазмы разных металлов и обеспечивать скорости роста осаждаемых покрытий, сравнимые со скоростями роста, обеспечиваемыми в технологиях с катодной формой вакуумной дуги.

РОЗПОДІЛ ІОНІВ ЗА ЕНЕРГІЯМИ ТА ОСНОВНІ ХАРАКТЕРИСТИКИ ПОТОКІВ ПЛАЗМИ НЕСАМОСТІЙНОГО ДУГОВОГО РОЗРЯДУ

А.Г. Борисенко, Ю.С. Подзирей

Представлено результати досліджень основних характеристик несамостійного дугового розряду при струмах до 35 А. Наведені функції розподілу іонів за енергіями, виміряними в створюваних плазмових потоках при різних значеннях струму розряду і показана динаміка енергії спрямованого руху іонів. Визначено значення плаваючого потенціалу. Показано, що при струмах 20…30 А вакуумний дуговий розряд у парах матеріалу анода дозволяє ефективно створювати безкрапельні високоіонізовані потоки плазми різних металів і забезпечувати швидкості росту покриттів, які є порівняними зі швидкостями росту плівок, що забезпечуються в розрядах з катодною формою вакуумної дуги.