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BOMBARDMENT OF THE SURFACE BY A LOW-ENERGY ION FLOW ACCELERATED IN THE NEAR-SURFACE LAYER OF THE SPACE CHARGE

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The paper presents a method for the formation of low-energy ion flow for creation and treatment of functional coatings without radiation damage. Plasma source based in arc discharge with filament cathode creates the primary plasma in the volume of vacuum chamber where the treated sample is placed. The formation of low-energy ion flow takes place in the layer of space charge near the samples surface. The behavior of the ion current density depending on the potential drop in the layer has been studied for various experimental parameters and conditions. The sample surface treatment by low-energy ion flow has been also evaluated.

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INTRODUCTION

Intense charged particles beams are widely used in modern technologies. The processes occurring in a solid body when irradiated by charged particles are used for technological purposes and form the basis of an electron-ion technology. Such processes include: heating during particles braking in a substance, cathodic sputtering, the defects formation in the crystal lattice, ions implantation deep into a solid body, etc. Some processes that don't give a technological effect can be used to control the progress of the technological process (secondary emission, radiation, etc.).

A relatively large potential difference is usually used for the formation of intense ion beams in Piers, quasi-Piers or other systems. This is necessary in order to form a beam and weaken the space charge effect. However, for some applications it is necessary to form ion beams with energies of tens to hundreds of electron volts. The bombardment of the substrate surface by the intense ion flow of low-energy allows one to remove all surface impurities and several upper lattice layers of the original substance, without changing its structure, and contributes to heating the surface to the required temperature [1]. Both of these effects provide a high adhesion degree of coatings to the substrate surface and a reduction in the coating internal stress. In addition, intense ion flows of low energy are necessary to avoid radiation damage to the treated surface [2], as well as for plasma chemical coatings deposition [3].

When forming low-energy ion beams, the use of conventional devices at an extractor potential of tens or hundreds of volts doesn't allow one to obtain an appropriate energy beam. This becomes possible using the braking mechanism of the accelerated beam to the required energy by classical plasma-optical means [4]. When creating real technological systems, this process is limited by a certain thermal stability of materials. In RF capacitive discharges an ion beam is formed in the near-surface layer. The use of this method makes it possible to create an ion flow directly in the surface treatment area and excludes the transportation space. However, in such systems, due to the discharge conditions, low ion energy corresponds to low ion current density [5].

To obtain an increased current density at low ion energy, it is possible to form an ion flow in the plasma of an arc discharge with a filament cathode with further ion acceleration in the near-surface layer of the treated object space charge. Due to this fact, it is possible to obtain a system with a high density of low-energy ion flow, in which the ion current and energy are regulated relatively independently.

The paper is devoted to the study of the mechanism of near-surface formation of intense low-energy ion flow for creating and treatment functional coatings without radiation damage and improving their technological characteristics.

1. EXPERIMENTAL SETUP

Experimental studies were carried out in a system with a plasma source based on an arc discharge with a filament cathode. Fig. 1 shows the general scheme of the experiment. The plasma source was located in the upper part of the vacuum chamber *1*, which made it possible to form a vertical diverging plasma flow. A wire spiral tungsten filament cathode *2* with a diameter of 2 cm was attached to the end of a water-cooled discharge tube *3* made of stainless steel with an inner diameter of 4 cm and a length of 27 cm. The discharge tube served as an anode and was grounded. Filament cathode had a negative potential of 0...400 V. To prevent plasma electrons from directly hitting the discharge tube wall, the discharge gap was located in a longitudinal magnetic field with a maximum intensity of up to 600 Oe. The magnetic field was formed by a system of magnetic coils *4*. Argon was used as the plasma-forming gas, which was supplied to the plasma source in the filament cathode zone. The pressure in the plasma source was an order of magnitude higher than in the vacuum chamber. At a pressure in the vacuum chamber of $p_{vc} \sim 3 \cdot 10^{-4}$ Torr, the plasma source creates a diverging plasma flow with a density near the source outlet of $n_{pl} \sim (1...3) \cdot 10^{11}$ cm^{-3} at an electron temperature of $T_e \sim 2$ eV.

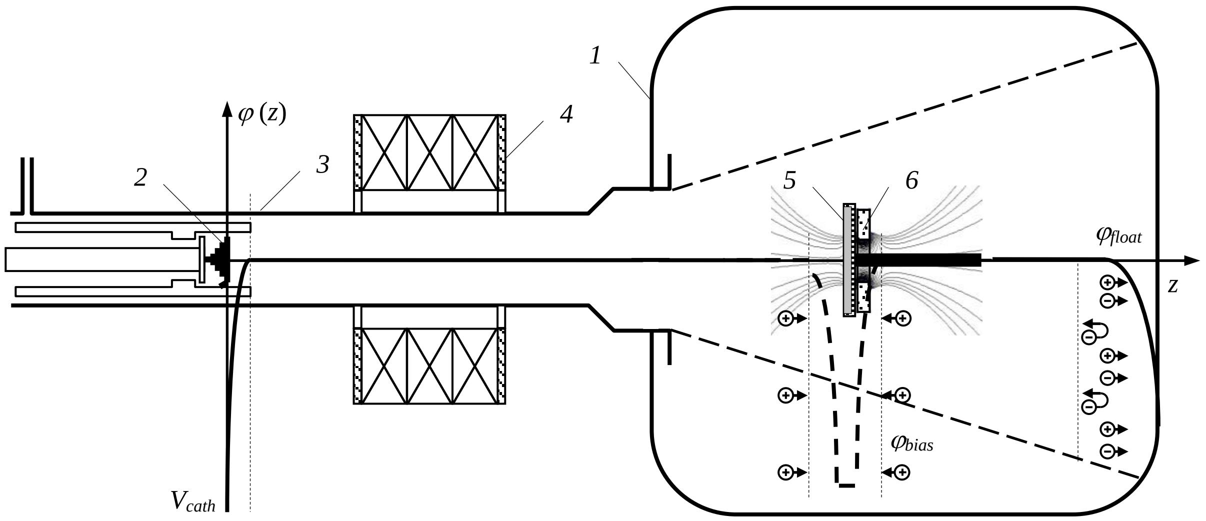

Fig. 1. The general scheme of the experiment:
1 – vacuum chamber; 2 – filament cathode; 3 – discharge tube; 4 – magnetic field coils; 5 – sample holder; 6 – permanent ring magnet with the distribution of force lines of magnetic field

The flat copper table with a diameter of 10 cm was used as a sample holder. The holder side surface was covered with a glass insulator. Thus, the total area of the holder working surface was $S_t \sim 78.5\ \text{cm}^2$. The holder was located at a distance of ~ 20 cm from the plasma source outlet and its location could change relative to the axis of the plasma source. Depending on the experimental conditions, the holder was either electrically isolated from the conductive elements of the vacuum chamber, or had a negative potential of up to 1 kV, which was supplied from an additional power source. The qualitative potential distribution in the system is shown in Fig. 1.

2. RESULTS AND DISCUSSION

The mechanism of formation of intense low-energy ion flow is the following. Electrically isolated sample holder is placed in the source plasma flow. During the treatment of conductive object, as well as dielectrics, their surface is charged negatively by an electron beam that comes out of the plasma source together with the plasma [6]. In this case, the sample surface has a floating potential φ_{float}. The negative surface charge begins to attract plasma ions and an additional ion beam is formed on the surface. Ions are accelerated in the near-surface layer to energy $\varepsilon_i = q_i \cdot \varphi_{float}$. It should be noted that during treatment of grounded conductive objects, their surface is not charged and an additional ion beam is not formed.

The floating potential value is determined by the current density balance of the primary electron beam j_{be0} and plasma ions j_{pi}. The floating potential is comparable to the discharge voltage of the plasma source at large j_{be0} and small j_{pi}.

Fig. 2 shows the waveforms of the current (black curve) and potential (red curve) of the sample holder. In this case the electrically isolated holder was located on the same axis as the plasma source, as shown in Fig. 1. The floating potential of the holder varies from -105 to -85 V and is comparable in magnitude to the discharge voltage of the plasma source. It is clearly seen that the current on the holder initially takes negative values, which indicates that electrons are going to the holder surface and charging it to a negative potential. Then an ion flow with a current of up to 1.5 mA (ion current density ~ 20 μA/cm^2) is formed. At the discharge voltage of plasma source of ~ 50...200 V, the potential bias will also fluctuate within these limits. Therefore, the energy of the ions bombarding the sample surface will be less than 200 eV for the case of single ionization. Since the floating potential directly depends on the discharge voltage of the plasma source, the energy of the formed ions depends on the minimum and maximum possible discharge voltage. The minimum discharge voltage depends on the discharge ignition conditions. The maximum discharge voltage depends on the characteristics of the power source.

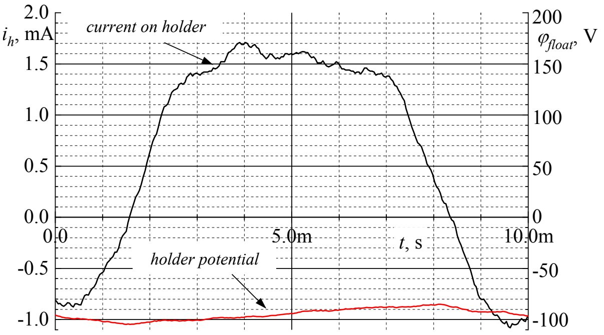

Fig. 2. Waveforms of current and potential of the holder

Another way to increase the ion energy is to apply an additional negative potential bias to the holder. In this case a layer of space charge is formed near the holder surface with a negative potential drop of φ_{bias} (see dotted line on Fig. 1). Acceleration of plasma ions takes place in the near-surface layer and intense ion flow is formed with energy $\varepsilon_i = q_i \cdot \varphi_{bias}$.

Dependencies of the ion current density on the holder negative potential bias for different values of discharge current of the plasma source are shown in Fig. 3. Dependencies corresponds to the case when the holder is located on the same axis as the plasma source outlet and the pressure in vacuum chamber of $p_{vc} \sim 4 \cdot 10^{-4}$ Torr. Regardless of discharge current of the plasma source the smallest values of the ion current density ~ 25…30 μA/cm^2 is observed in the case when the holder has a floating potential of about 150 V (see the points in Fig. 3). An increase of discharge current in the plasma source doesn't lead to a significant increase of ion current density.

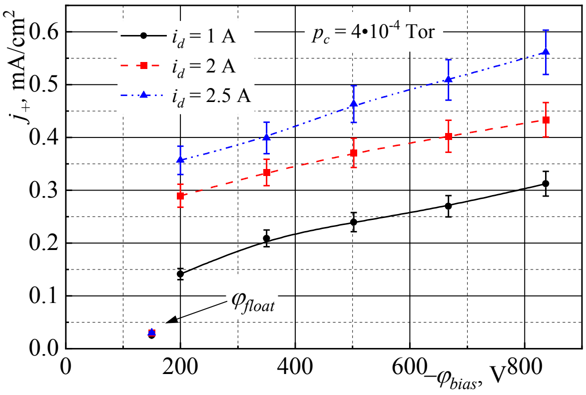

Fig. 3. Dependencies of the ion current density on the holder negative potential bias for different values of the plasma source discharge current

A significant increase in the ion current density is observed when an additional negative potential bias is applied to the holder. It is clearly seen that the ion current density is 0.29 mA/cm^2 at the holder negative potential bias of 200 V and the discharge current of the plasma source of 2 A. There is a smooth increase of the ion current density with increasing the potential bias, so that the ion current density reaches 0.43 mA/cm^2 at the holder negative potential bias of 840 V. In this case the balance of currents in the system is maintained, since the greater the discharge current of the plasma source, the greater the ion current from the plasma.

Studies of the dependence of the ion current density on the pressure in the vacuum chamber show that the ion current density increases with increasing the pressure. Thus, the ion current density increases from 0.28 to 0.43 mA/cm^2 when the pressure increases from $1.6 \cdot 10^{-4}$ to $4 \cdot 10^{-4}$ Torr at the discharge current of the plasma source of 2 A and the holder negative potential bias of 840 V. Moreover, the ion current density significantly depends on the distance of the holder from the plasma source axis. Thus, moving the holder 13 cm away from the plasma source axis leads to a decrease of the ion current density from 0.43 to 0.13 mA/cm^2 at the above parameters and the pressure of $4 \cdot 10^{-4}$ Torr.

The possibility of increasing the ion current density due to the use of a permanent ring magnet was studied separately. The characteristic feature of a permanent ring magnet is the presence of the magnetic field inversion point, which arises due to the bifurcation of the field flows. As a result, the magnetic field topology in the form of the magnetic trap is formed on the magnet axis. The dimensions and location of the ring magnet were chosen so that the holder working surface was in the magnetic trap area. Fig. 1 schematically shows the location of the ring magnet in the experiment with the distribution of force lines of magnetic field. The maximum magnetic field intensity of the magnet was ~ 850 Oe.

Dependencies of the ion current density on the holder negative potential bias for the case of using a permanent magnet (dashed curve) and without a magnet (solid curve) are shown in Fig. 4. Dependencies corresponds to the discharge current of the plasma source of 2 A and the pressure in the vacuum chamber of $2.5 \cdot 10^{-4}$ Torr. It is clearly seen that in case of using permanent magnet the ion current density significantly increases from 0.35 to 8.52 mA/cm^2 at the holder negative potential bias of 800 V. This is due to the fact that the source plasma flow is compressed by the magnetic field and focused only on the holder surface with an area of ~ 1.76 cm^2, which is much smaller than the total holder surface. Thus, a permanent ring magnet should be used when treatment small or single objects, the sizes of which is comparable to the plasma focusing area. This makes it possible to process an object with an increased ion current density.

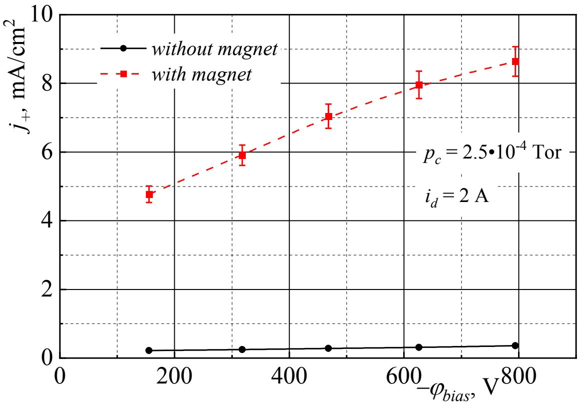

Fig. 4. Dependencies of the ion current density on the holder negative potential bias for the case of using a permanent ring magnet

Knowing the ion current density j_i from the plasma, it is also possible to determine the electron current density j_e using the well-known Langmuir ratio: $j_e = j_i(M_i / m_e)^{½}$, where M_i – ion mass, m_e – electron mass. Direct determination of the plasma electron current density is complicated by the fact that when working with the plasma electron current the probe heats up strongly. On the one hand, this can lead to the destruction of diagnostic tools, and, on the other hand, can significantly affect the system parameters. Estimates show that the ion current density of argon plasma of 8.52 mA/cm^2 corresponds to the electron current density of 2.31 A/cm^2. Such values of the electron current density at a surface potential of more than 600 V can lead not only to heating the surface to high temperatures, but also to the formation of dense thermoionic plasma near the surface [7].

Fig. 5 shows SEM image of the surface of the (TiZr/TiSi)N sample before (*a*) and after (*b*) sample treatment by the ion flow from the plasma. In this case a negative potential bias of ~ 800 V was applied to the sample holder, without plasma magnetic focusing on the surface. The sample holder was located in the center of the plasma source axis. Treatment time was ~ 5 min. One can see that the surface treatment by the low-energy ion flow from the plasma leads to the cleaning of the surface layer from various impurities without damages. It is expected that such bombardment of the sample surface with a low-energy ion flow will increase the adhesion of the coating to the substrate surface during further thermoionic deposition of the coating.

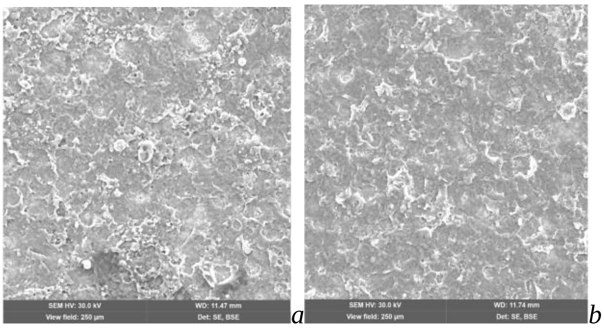

Fig. 5. SEM image of the surface of the (TiZr/TiSi)N sample before (a) and after (b) sample treatment

CONCLUSIONS

The ion current density from the plasma created by the source based on an arc discharge with a filament cathode has been studied. It has been determined that in order to irradiate the sample surface by the ion flow with energy of up to 100…150 eV the sample holder should be electrically isolated from the conductive elements of the vacuum chamber and have a floating potential. The holder floating potential directly depends on the discharge voltage of the plasma source. Ions acceleration occurs in the layer of space charge near the samples surface. In this case, the ion current density on its surface is up to 30 μA/cm^2. To obtain a higher ion current density, it is necessary to apply an additional negative potential bias to the holder. In this case, the ion current density increases to 290 μA/cm^2 with at the additional negative potential bias of 200 V (ε_i ~ 200 eV). The ion current density increases smoothly with an increase of the negative potential bias. Dependencies of the ion current density on the working pressure in the vacuum chamber and the holder position relative to the plasma source axis have been determined. It has been shown that the use of a permanent ring magnet significantly increases the ion current density on the sample surface due to the plasma magnetic focusing. This is relevant for the treatment of small or single samples, whose total area coincides with the magnetic focusing area of plasma. Preliminary treatment of the surface of (TiZr/TiSi)N sample by the ion flow from the plasma has been carried out. It has been shown that this treatment leads to the cleaning of the surface layer from various impurities without damages and creates a substrate for further thermoionic deposition of the coating with a high degree of adhesion.

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БОМБАРДУВАННЯ ПОВЕРХНІ НИЗЬКОЕНЕРГЕТИЧНИМ ПОТОКОМ ІОНІВ, ПРИСКОРЕНИМ У ПРИПОВЕРХНЕВОМУ ШАРІ ОБ'ЄМНОГО ЗАРЯДУ

Я. Гречко, Є. Бабенко, І. Середа, М. Азарєнков

Представлено спосіб формування низькоенергетичного потоку іонів для створення та обробки функціональних покриттів без радіаційних пошкоджень. Джерело плазми на основі дугового розряду з катодом розжарення створює первинну плазму в об'ємі вакуумної камери, де розміщується зразок, що обробляється. Формування низькоенергетичного потоку іонів здійснюється у шарі просторового заряду біля поверхні зразків. Досліджено поведінку густини іонного струму в залежності від падіння потенціалу в шарі для різних експериментальних параметрів і умов. Також було оцінено обробку поверхні зразка потоком низькоенергетичних іонів.