FEATURES OF ELECTRON BEAM EVAPORATION UNDER SURFACE ELECTRON BEAM FORMATION

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In this paper, the features of the dense plasma generation under the thermal substance evaporation by an electron beam, formed directly at the crucible surface, have been investigated. Peculiarities of the research are the following: the initial plasma is used as the electron emitter and the electron acceleration occurs in the layer between the initial and thermionic plasma. It has been shown that in the case of the thermionic plasma formation, the crucible current can be several times higher than the discharge current of the primary plasma source due to the redistribution of voltge drop (100…200 V) from the crucible to the wall.

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INTRODUCTION

The electron-beam evaporation is widely used in various forms of vacuum-plasma processes [1]. In the classic version the electron beam generated by the electron gun is delivered to the evaporated material by electromagnetic lenses. Such high-power systems require the high voltage (~ 20 kV) due to the peculiarities of the beam transportation [2]. Because of the risk of electrical breakdown the high voltage often becomes the barrier for widespread use of this method. The high current (to provide the necessary capacity) electron source should be located directly at the vaporized substance. However, due to the penetration of the vaporized material steam into the gun the ionization in the accelerating gap increases and insulators are intensively covered by the conductive material that can lead to the breakdown of the gun. This makes it impossible to realize an electron-beam evaporation using classical techniques. However, the classical electron gun can be replaced by the plasma type source. Then the electrons are emitted by initial plasma, and the electron acceleration occurs in the space-charge layer near the vaporized material surface [3]. The advantage of this approach as compared with conventional electron beam evaporation is that the sample is heated uniformly on all sides. And the system appears to be insensitive to the pressure rising during the material evaporation since the voltage is less than 1 kV. If the electron beam power in the surface layer is high enough then the intense ionization of the material vapor and the dense thermionic plasma generation occur that can lead to appearance of high-energy ions. For the practical application of this technology it is important to know the ways of regulating the energy and power of the electron beam, as well as the parameters of thermionic plasma, which is the purpose of the present work.

1. EXPERIMENTAL SETUP

Experiments on the production and study of intense thermionic flows were carried out using the plasma source based on a discharge with a filament cathode (Fig. 1). Such a method of producing the plasma provides at low pressures (~ 10^{-4} Torr) rather dense (~ 10^{11} cm^{-3}) plasma at relatively low energy consumption. Coiled tungsten cathode of direct heating (2) with the diameter of 2 cm was placed in a water-cooled end of the discharge tube (1) made of stainless steel with the diameter of 4 cm and length of 27 cm. The discharge tube served as the anode and was grounded, and the negative voltage (V_{cat} = 0…300 V) was applied to the filament cathode. In the source volume the longitudinal magnetic field with the bell-shaped distribution was induced with the field strength maximum up to 600 Oe. The magnitude and configuration of the magnetic field were selected in the way to generate divergent flow of the primordial plasma in the vacuum chamber. The thermionic plasma (4) was formed around the tungsten crucible (3) from the evaporating substance. The substance and the substrate holder for the processed objects were located in the vacuum chamber. The voltage + V_t positive relative to the grounded chamber was applied on the crucible with the help of additional power supply. The crucible with the substance played the role of the second anode with the voltage that was for hundreds of Volts higher than that of the discharge tube of the plasma source (first anode). In comparative experiments thermionic plasma was simulated by spherical electrode of 5 cm in diameter to match the characteristic dimensions of thermionic plasma. This electrode was placed instead of the crucible. To investigate the dynamics of the floating voltage of the plasma a flat probe (7) with the working surface of 1 cm^2 was used. The probe was set in the chamber out of the plasma source column. To prevent the deposition of the insulator the probe side was protected by the screen. Usually, for the primary plasma formation the argon was used, that was injected into the area of the filament cathode. The typical operating pressure in the vacuum chamber was $(1…5)\cdot10^{-4}$ Torr.

2. RESULTS AND DISCUSSIONS

Considering the processes of the dense thermionic plasma generation and formation of the intense electron and ion beams, the specific features of this system should be taken into account. It is the generation of the additional ion beam during processing of dielectric

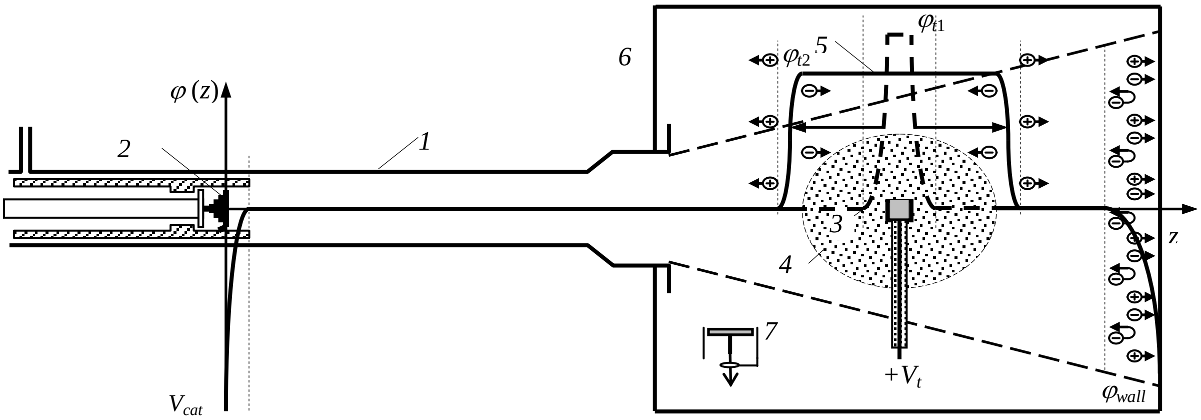

Fig. 1. The scheme of thermo-ionic plasma creation.
1 – discharge tube; 2 – filament cathode; 3 – crucible with metal; 4 – thermionic plasma; 5 – potential distribution by the crucible; 6 – vacuum chamber; 7 – flat probe

materials. Surface of a dielectric object placed in the pri mary plasma column is charged negatively in relation to the plasma voltaage φ_{wall} by the initial electron beam that comes out of the plasma source together with the plasma (see Fig. 1). Negative surface charge begins to attract the plasma ions which produce an additional ion beam to the surface. In the surface layer the ions are accelerated to the energy $W_i = q_i \cdot \varphi_{wall}$. Magnitude of the voltage φ_{wall} is determined by the balance of the current densities of the initial electron beam j_{be0} and plasma ions j_{pi}. For large j_{be0} and small j_{pi} the voltage φ_{wall} is of the same order of magnitude as the voltage of the plasma source. With increasing of j_{pi} the ions effectively discharge the surface, and the voltage φ_{wall} decreases to the value – 25 V.

Obviously, the surface is not charged during the processing the grounded conductive object, and the ion beam is absent further. However, if the sample holder is electrically isolated, the negative charge that was brought by an electron beam does not drain, so the surface of the object becomes charged to a voltage negative in relation to the plasma. The additional ion beam takes place in this case as well. In the first case the electrons pass the gap once, and in the second case they oscillate between the filament cathode and the object. Therefore, in the first case usually there is the arc discharge with filament cathode, while in the second case the reflective discharge is more efficient. In the case of the reflective discharge at the pressure of $3 \cdot 10^{-4}$ Torr in the vacuum chamber, the plasma source produces the divergent initial plasma flow with a current density of $(1\ldots3) \cdot 10^{11}$ cm^{-3} and the electron temperature of $T_e \approx 2$ eV near the input hole.

The mode of plasma gun was realized when the crucible with an evaporated substance was connected to the voltage positive in relation to the grounded chamber. In this case, the space charge layer with the potential drop φ_{t1} was formed at the crucible surface. In this layer the primary plasma electrons were accelerated and the electron flow was formed. This flow heated the crucible. (The qualitative picture of the voltage distribution in the case of galvanically isolated object is shown in Fig. 1.) With crucible heating the evaporated substance atom flux appeared. A part of this flux was ionized due to the electron impact. The bipolar current appeared when these ions have been accelerated by the electric field of the layer.

Thermionic plasma was formed between the layer of the space charges and the crucible surface, as soon as the rate of ion generation at the surface has reached such a value that the number of produced particles exceeded the number of particles which have leaved through the layer. At the front of the thermionic plasma the original layer of the negative space charge φ_{t1} was converted to the double electric layer (DL) φ_{t2}. Due to the gas-kinetic pressure the thermionic plasma expanded. DL moved away from the crucible, and this was accompanied by increase of the current through the layer due to the increase of its surface. Such expansion took place until the violations of existence conditions of DL. With the disappearance of the electron beam the layer disappeared. This leaded to stop of the crucible heating and the thermionic plasma forming. After the collapse of the dense thermoionic plasma near the crucible the layer of charge with a voltage drop φ_{t1} was formed again and the whole process repeated.

Initially it was assumed that the necessary condition for the existence of the layer near the crucible surface was that the current on the crucible had to be less than current of plasma source. When this condition breaks down the layer should disappear. However, it was observed in experiments, that the current on the crucible during the formation of thermionic plasma can be several times (3-6 times) greater than the discharge current of the plasma source. And this was quite unexpected, since at the initial analysis it seemed that an imbalance of currents took place: electron current removed from the plasma to crucible was by several times larger than the electron current delivered to the plasma by the filament cathode. This is clearly noticeable from given oscillograms of the system parameters (see Fig. 2). One can see that at the discharge current of the plasma source (the filament cathode current) of $I_d = 1$ A ($U_d = 100$ V) the maximum crucible current I_t has reached 4 A. (The voltage on the crucible was of $V_t = 224$ V.)

Study of the dynamics of the voltage distribution in the vacuum chamber made it possible to resolve this paradox. It has been found that when $I_t > I_d$ was applied to the crucible then the voltage V_t was split between the layer near the crucible φ_{t2} and layer near the chamber wall φ_{bulk} (see Fig. 2). If the current on the crucible was less than the current of the plasma source, then all positive voltage applied to the crucible was concentrated in the layer near the crucible, and the voltage φ_{bulk} had a small negative value of the order of $\sim T_e / e$. When the current on the crucible reached the value of I_d, then plasma voltage was equal to the wall potential. When I_t exceeded I_d at the wall then positive voltage drop has appeared, and it increased with the growth of I_t. Thus, the excess current of the crucible $I_{ed} = I_t - I_d$ was caused by the ion current to the chamber wall. And that ion current was several times higher than current of the plasma source.

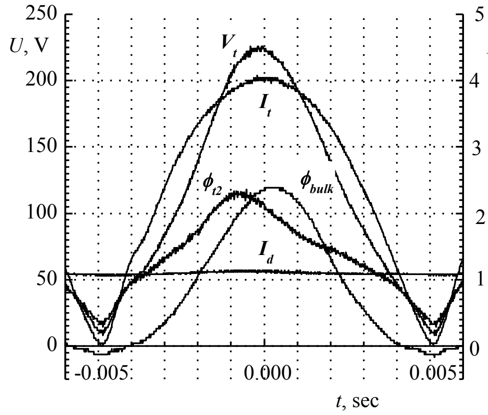

Fig. 2. Oscillograms of the voltage V_t and current I_t of the crucible, the plasma voltage φ_{bulk}, the voltage drop in of the crucible φ_{t2} and the current of plasma source I_d

Value of this ion current was mainly determined by the efficiency of ion generation by plasma source. With the high generation efficiency (when one electron on average produces several ions) the positive potential drop near the wall φ_{bulk} was relatively small and almost all the voltage applied to the crucible was concentrated in a layer near the crucible. Thus, in the case shown see in Fig. 2 when $I_t = 3$ A ($I_t / I_d = 3$) the potential drop near the wall φ_{bulk} was about of ~ 25 V, which was 25 % of the applied voltage. But when $I_t = 4$ A ($I_t / I_d = 4$) the voltage drop near the wall increased to 120 V that was 54 % of the applied voltage. This indicated that to ensure the crucible excess current there were not enough ions generated by the plasma source. In that case the system had to be reconstructed to compensate the absence of ions due to excitation of additional discharge (non-self-glow discharge) between the chamber wall and the crucible. The chamber wall began to play the role of the cathode with the cathode voltage drop sufficient to increase the ion generation. In other words, to maintain the excess current in the absence of ions the system transmitted part of the input energy for heating the crucible to increase the ion generation.

White dots in Fig. 3 demonstrate the dependence of φ_{bulk} / V_t on I_t / I_d. It is seen that this dependence is almost linear one. When $I_t / I_d < 1$ then the voltage φ_{bulk} takes negative values. This is explained by the greater electron mobility as compared to that of ions. The DL in this case was not formed. At the point of $I_t / I_d = 1$ the classical conditions of charged particle transport violate and the DL appears on the front of thermionic plasma. The additional source of ion generation occurs with the appearance of thermionic plasma. Thus, there are three typical methods for ions generating in respect of I_t / I_d value. When $I_t / I_d < 1$ then ions are generated by the plasma source. When $I_t / I_d > 1$ then ions generation is caused by formation of thermionic plasma. These ions are accelerated from the crucible to the chamber wall by DL. When $I_t / I_d >> 1$ then the third mechanism switches on, that is the ions are generated throughout the chamber by means of the non-self glow discharge.

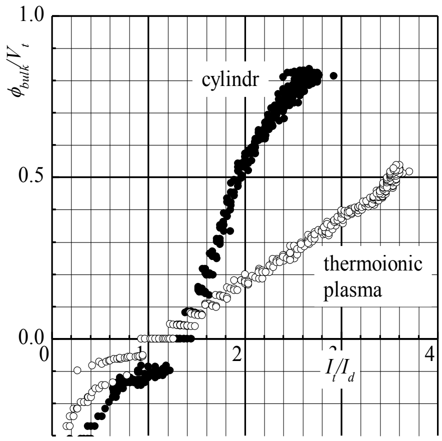

Fig. 3. The dynamics of redistribution of the voltage between the layers near the crucible φ_t and the wall φ_{bulk} depending on the ratio of current to the crucible to the discharge current I_t / I_d

With the purpose to clearly highlight the third mechanism of ion generation the comparative experiments were carried out in which the second generation mechanism was excluded (thermionic plasma was absent). To provide this, spherical electrode was placed instead of the crucible. The voltage positive in relation to the grounded chamber was applied to the electrode as in the previous case. The shape and size of the electrode corresponded to the shape and size of thermionic plasma, which were determined using photography. The other parameters corresponded to the parameters of the original experiment.

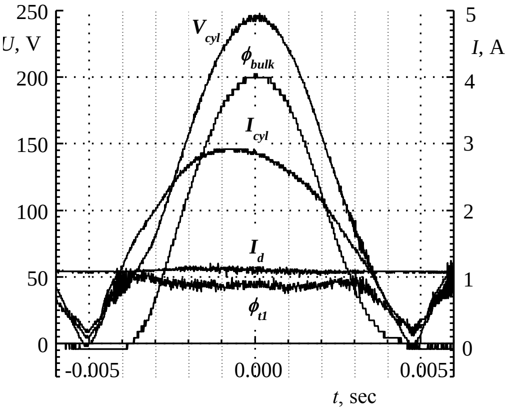

Fig. 4. Oscillograms of the voltage V_{cyl} and current I_{cyl} of cylinder, the plasma voltage φ_{bulk}, the voltage drop in the cylinder φ_{t1} and current of plasma source I_d

Oscillograms of the system parameters in the comparative experiment are shown in Fig. 4. Main difference is in significantly higher near-wall potential drop

φ_{bulk}. In this case, the voltage drop in the layer near the surface of the spherical electrode is in the form of a meander with amplitude ~ 45 V. Relative change φ_{bulk} / V_t versus the ratio I_t / I_d is shown see in Fig. 3 by the black dots. One can see that in the absence of thermionic plasma (the second mechanism of ion generation) system is forced to over-react due the lack of ions by excitation of the non-self glow discharge at an earlier stage. The probe (7 in see Fig. 1) was installed to determine in what proportions the voltage is split between the layers in the vacuum chamber. The signals from the probe with the current and voltage at the crucible and the discharge current source of initial plasma were transmitted to 4-th ray oscilloscope. The typical fragments of oscillograms obtained in this manner are shown see in Fig. 2. The bell-shape oscillograms are stipulated by absence of the filter capacitor in the power supply of the crucible. Power supply gave out pulsating direct voltage with no smoothing. This was done deliberately in the event of breakdown to eliminate the appearance of high pulse currents due to the filter capacitor discharging.

In comparative experiments (see Fig. 4) exact match of the current and voltage on the cylinder and crucible could not be reached because of the size mismatch of thermionic plasma and modeling electrode. Therefore the close in value of V_{cyl} and I_{cyl} were taken. Curves φ_{bulk} were taken from the probe, and corresponded to the plasma voltage in the chamber. Assuming that the voltage applied to the crucible V_t is redistributed only between DL on the front of the anode plasma φ_{t2} and the grounded chamber wall, the DL voltage was defined as $\varphi_{t2} = V_t - \varphi_{bulk}$. Thus, the curve φ_{t2} see in Fig. 2 is the result of subtracting the space voltage from that applied to the crucible (or cylinder). Similar arguments were used to obtain the curve φ_{t1} see in Fig. 4.

Thus, the magnitude of the wall voltage was maintained in a way to provide the generation of a sufficient number of charged particles for the formation of the electron current on the crucible.

CONCLUSIONS

Thus, due to self-consistency of the system, the formation of the electron beam and the generation of thermionic plasma strongly affect on each other. As soon as the current in the crucible exceeds the current of initial plasma source the potential drop near the surface of the chamber, that can reach half of the voltage applied to the crucible, appears. This is due to the necessity to cause an additional generation of charged particles in the chamber. The wall of the vacuum chamber begins to play the role of cathode of non-self glow discharge. The anode is the crucible. This allows using of relatively low power initial plasma source (I_d = 1…3 A, V_d = 50 V) to form the electron beam on the crucible with the current of 4…12 A and energy up to 400 eV. On the other hand, the formation of the voltage drop at the wall leads to transition of the part of power to the chamber wall. Energy of the electron beam in this case becomes less than voltage applied to the crucible, which should be considered during the technological processes.

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ОСОБЕННОСТИ ЭЛЕКТРОННО-ЛУЧЕВОГО ИСПАРЕНИЯ В УСЛОВИЯХ ПРИПОВЕРХНОСТНОГО ФОРМИРОВАНИЯ ЭЛЕКТРОННОГО ПУЧКА

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Исследуются особенности генерации плотной плазмы при термическом испарении вещества электронным пучком, который формируется непосредственно у поверхности тигля. Особенность исследований состоит в том, что эмиттером электронов пучка служит первичная плазма, а ускорение происходит в слое объемного заряда между первичной и термоионной плазмой. Показано, что ток на тигель при образовании термоионной плазмы может в несколько раз превышать разрядный ток источника первичной плазмы, что связано с перераспределением части напряжения (100…200 В) между тиглем и стенкой.

ОСОБЛИВОСТІ ЕЛЕКТРОННО-ПРОМЕНЕВОГО ВИПАРОВУВАННЯ ЗА УМОВ ПРИПОВЕРХНЕВОГО ФОРМУВАННЯ ЕЛЕКТРОННОГО ПУЧКА

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Досліджуються особливості генерації щільної плазми при термічному випаровуванні речовини електронним пучком, який формується безпосередньо біля поверхні тигля. Особливість досліджень полягає в тому, що емітером електронів пучка є первинна плазма, а прискорення відбувається в шарі об'ємного заряду між первинною та термоіонною плазмою. Показано, що струм на тигель при утворенні термоіонної плазми може в декілька разів перевищувати розрядний струм джерела первинної плазми, що пов'язано з перерозподілом частини напруги (100…200 В) між тиглем та стінкою.