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DEFINING OF ENERGETIC EFFICIENCY OF TRIODE GLOW DISCHARGE ELECTRON GUNS WITH PLANE ADDITIONAL ELECTRODE

The mathematical model of triode high-voltage glow discharge electrodes' system with the plane additional electrode is considered in the article. The proposed model is based on defining the plasma boundary position on the base of solving cubic equation with taking into account the real electrodes' geometry. The formula for recalculation of plasma boundary position from one-dimensional model to electrodes' system with conic anode is obtained. The results of calculation of energetic efficiency for real parameters of electron gun are presented and analyzed in the article. Calculation results are compared with experimental data. Obtained accuracy of calculation, in comparing with experimental results, is nearly 10 – 15%.

Keywords: high voltage glow discharge, anode plasma, triode electrodes' system, plane electrode, one-dimensional model.

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ВИЗНАЧЕННЯ ЕНЕРГЕТИЧНОЇ ЕФЕКТИВНОСТІ ТРІОДНИХ ЕЛЕКТРОННИХ ГАРМАТ ВИСОКОВОЛЬТНОГО ТЛІЮЧОГО РОЗРЯДУ ІЗ ПЛОСКИМ ДОПОМІЖНИМ ЕЛЕКТРОДОМ

У статті описується математична модель тріодних електродних систем високовольтного тліючого розряду із плоским допоміжним електродом. Такі електронні гармати знаходять широке впровадження у промисловості для виконання технологічних операцій зварювання, паяння, відпалювання виробів, нанесення композитних керамічних покриттів та для переплавлення тугоплавких металів з метою їх очищення від шкідливих домішок. Запропонована математична модель базується на визначенні положення плазмової межі через аналітичне розв'язування кубічного рівняння з використанням формул Кордано з урахуванням реальної геометрії електродів. Задача пошуку положення плазмової межі в електродній системі високовольтного тліючого розряду вирішується через розв'язок рівняння балансу заряджених часток у розрядному проміжку. Спочатку задача визначення положення плазмової межі відносно катода була розв'язана для аксиально-симетричної системи із лінійною геометрією електродів. У статті розглянута структурна схема такої електродної системи та визначені базові параметри сформованої математичної моделі. Після цього, також через аналітичне розв'язування кубічного рівняння з використанням формул Кордано, отримана формула для перерахунку положення плазмової межі з одномірної системи до системи із конусним анодом. У статті також отримані формули для розрахунку енергетичної ефективності тріодної електронної гармати із конусним анодом та пламтинчатим електродом. Наведені та проаналізовані результати розрахунку енергетичної ефективності реальної електронної гармати. Розрахункові результати порівнюються з експериментальними даними. Всі експерименти були проведені в лабораторії електронно-променевої технологічних пристроїв Національного технічного університету України «Київський

політехнічний інститут імені Ігоря Сікорського». Отримана точність розрахунків, порівняно із експериментальними даними, складає біля 10 – 15%. Отримані в статті наукові результати є вкрай цікавими та важливими для науковців та інженерів, які займаються розробкою електронно-променевого технологічного обладнання та його впровадженням у сучасне виробництво.

Ключові слова: високовольтний тліючий розряд, анодна плазма, триодна електродна система, плоский електрод, одновимірна модель.

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ОПРЕДЕЛЕНИЕ ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ ТРИОДНЫХ ЭЛЕКТРОННЫХ ПУШЕК ВЫСОКОВОЛЬТНОГО ТЛЕЮЩЕГО РАЗРЯДА С ПЛОСКИМ ВСПОМОГАТЕЛЬНЫМ ЭЛЕКТРОДОМ

В статье описывается математическая модель триодных электродных систем высоковольтного тлеющего разряда с плоским вспомогательным электродом. Предлагаемая модель основана на определении положения границы плазмы путём решения кубического уравнения для реальной геометрии электродов. Получена формула для пересчета положения плазменной границы из одномерной системы в систему с коническим анодом. В статье приведены и проанализированы результаты расчета энергетической эффективности реальной электронной пушки. Результаты расчетов сравниваются с экспериментальными данными. Полученная точность расчета относительно экспериментальных данных составила 10 – 15%.

Ключевые слова: высоковольтный тлеющий разряд, анодная плазма, плоский электрод, одномерная модель.

Analysis of Recent Researches and Publications

High Voltage Glow Discharge (HVGD) electron guns are widely used in industry for electron beam welding, brazing, deposition of metallic and ceramic coatings, refining of refractory metals, as well as for annealing of thin-wall items [1–6]. Using for maintaining of HVGD the cathodes from different metals and different operation gases, including active and noble ones, in range of operation pressure 0.1 – 10 Pa, is possible [1, 2]. The advantages of this type of electron guns are follows [1 – 6]:

- choosing of suitable gases and its mixes can be defined mostly by the requirements of technological process;
- relatively low price both of the electron guns and of evacuation system for technological installation;
- simplicity of disassembling and repairing of electron guns with changing of spare details, including the cathodes, which can spoiled after hundreds hours of uninterrupted operation in the difficult vacuum conditions;
- possibility of control of discharge current both by changing operation pressure [7] and by lighting additional low voltage discharge [8, 9].

Problem Statement

Especially interesting for advanced industrial application is triode HVGD electron guns with the third additional electrode, where the fast control of beam current in the time range of tens or hundreds microsecond is possible [8, 9]. Such fast control is lead to the stable power of HVGD electron gun during long time of operation, as well as to its advanced possibilities with using pulse regime of operation [8 – 10, 12]. For example, such physically-complex technological processes, as deposition of ceramic multicomponent coatings [4, 5, 10] or obtaining of chemically-complex alloys

with mixing in alternative magnetic field [6], are possible to realizing in the pulse regime of operation of HVGD electron gun in the soft vacuum.

Purpose of the Study

Unfortunately, suitable simplified mathematical models for engineering calculation of triode HVGD electrodes' systems still don't exist today. By this reason elaboration and manufacturing application of advanced triode HVGD electron guns with fast control of discharge current in uninterrupted regime and with pulse regime of operation are still restrained. Therefore describing of simplified mathematical model of the triode glow discharge electron gun electrodes' system with the plane additional electrode is the subject of this paper.

Description of Main Material of Research

General structured scheme of considered HVGD triode electrodes' system.

Really, triode electrodes systems with different geometry are used for fast control and precision changing of HVGD current [8, 9, 11, 12]. Main of these systems' are follows:

- system with the ring-like positive electrode, placed in the plasma volume;
- system with the cylindrical negative electrode, placed near the cylindrical anode;
- system with the plane positive additional electrode, placed in the body of electron gun outside the anode surface, scheme of which presented at Fig. 1.

The electrodes' system consists on metallic spherical cathode 1, located on the top of gun construction and disposed on the high-voltage insulator 8, capsule of electron gun 10, focusing anode diaphragm 3 and the plane additional electrode 4. Formed electron beam 5 penetrated through ionized anode plasma 6 with sharp boundary 7 and focused by the magnetic lens 11 on the treated item 2. Anode plasma 6 with boundary 7 is usually considered in HVGD electrodes systems as the source of ions and as additional electrode with fixed potential [2, 3, 8, 9].

The main advantage of electrode system, presented in Fig. 1, is the most precision control of discharge current. But, in any case, HVGD system with additional electrode on the theoretical point of view can be considered as the systems with the hollow anode [8, 9, 11]. The acceleration voltage noted in the Fig. 1 as $-U_{ac}$ and the control voltage as $+U_c$.

Equivalent plane one-dimensional HVGD electrodes' system and its external and internal parameters. Since numerical solving of complex problem of finding plasma boundary form and position is very sophisticated and required enormous computer resources, therefore combined theoretic and experimental methodology is usually used for simulation of triode HVGD electrodes' systems. On the first step the approximated values of beam current on the base of one-dimensional model of HVGD system is calculated. Generally such models are analytical and based on solving of cubic equations [8, 9]. But since in real electrodes system square of emission surface is usually different, the value of discharge current has to be recalculated. After that the photographs of discharge gap have to be analysed with using computer image recognising technique for defining plasma boundary position relatively to the cathode surface as the sharp curve, on which the brightness of discharge lighting changing from dark to light area [2, 8].

Geometrical model of one-dimensional HVGD electrodes system, which is equivalent to the two-dimensional axially-symmetric system, was presented in the Fig. 1, is presented in Fig. 2.

It is clear form the Fig. 2, that main geometry parameters of considered modelling one-dimensional system are follows:

1. longitudinal size of the discharge gap l ;
2. its' transversal size d_{tr} ;
3. longitudinal size of the anode plasma in one-dimensional electrodes' system d_{pl} ;
4. distance from the cathode surface to the anode plasma boundary d_{cp} ;
5. the transversal size of cathode r_c .

Another important internal parameter of the formed mathematical model is the residual pressure p_{a0} , which, under conditions of HVGD lighting, with taking into account the lighting of additional discharge, laying in the range 0.1 – 10 Pa. Therefore, physical conditions of main and additional discharge lighting in the HVGD triode electrodes' system are complexly defined by the electrodes' materials, sort of operation gas and its' pressure, the accelerated voltage and the voltage on the additional electrode.

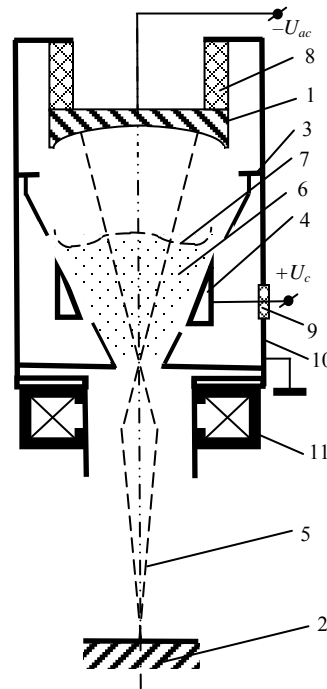


Fig. 1. Scheme of triode HVGD electron guns' electrodes' system with the plane additional electrode. 1 – cathode, 2 – treated item, 3 – anode, 4 – additional plane electrode, 5 – electron beam, 6 – anode plasma, 7 – plasma boundary, 8 – high-voltage insulator, 9 – low-voltage insulator, 10 – guns' capsule, 11 – magnetic lens for focusing electron beam on the treated item

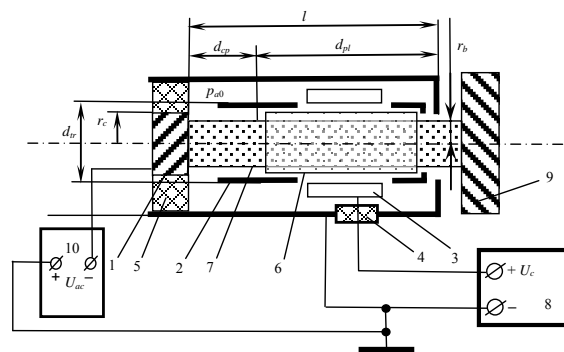


Fig. 2. Geometry parameters of equivalent one-dimensional HVGD electrodes system with the plain cathode and anode [8, 9]. 1 – cathode, 2 – HVGD anode, 3 – plane electrode for lighting of additional discharge, 4 – low-voltage insulator, 5 – high-voltage insulator, 6 – anode plasma, 7 – electron beam, 8 – low-voltage control power source, 9 – treated item, 10 – high-voltage power source

But in conditions of HVGD lighting the interaction of charged particles flows ones with another and with the electrodes' surfaces are also greatly influence to the discharge parameters. Among these processes and corresponded internal discharge parameters mostly important are follows [2, 3, 8, 9, 12].

1. Emission of electrons from the cathode surface under the action of its bombarding by ions. This process is characterized by the generalized factor of secondary ion-electron emission γ_c for using operation gas and cathode material.

2. Physical processes, connected with gas ionization by the fast beam electrons and by the slow electrons, reflected from the surface of HVGD anode. These processes are characterized by the corresponded cross-sections of gas ionizing by the fast electrons Q_{if} and by the slow Q_{is} .

3. Process of ions recharging on the atoms of residual gas. This process for corresponded ion energy E_i and the pressure of residual gas p_{a0} is characterized by the cross-section of recharging Q_{i0} .

4. Process of ambipolar diffusion of ions in the anode plasma, by which the ions moving from plasma to the cathode of additional discharge. This process is characterized by the length of free moving of electrons λ_e and ions λ_i for corresponded pressure of residual gas p_{a0} .

5. Process of secondary ion-electron emission from the cathode of additional discharge under the action of slow ions which moving from the plasma. This process is characterized by the factor of secondary ion-electron emission for using operation gas and HVGD anode material γ_a .

6. The important parameters of anode plasma, by which defined the energetic and geometry parameters of forming electron beam, are the temperature of electrons T_e and its' mobility μ_e . By these parameters defined the volume, occupied by the anode plasma, and, correspondently, the longitudinal size of plasma d_p .

Considered HVGD parameters are used in proposed mathematical model, which will be considered in the next section of the article.

Mathematical model of considered HVGD electrodes' system.

The generalized methodology for theoretical estimations of anode plasma parameters and defining approximate value of longitudinal size of the anode plasma d_p is based on solving the equation of balance of charged particles [3, 8, 9]:

$$z_f + z_s + z_{dis} = z_{dif}, \quad (1)$$

where z_f – efficiency of gas ionizing by the fast beam electrons, z_s – efficiency of gas ionizing by the slow electrons, z_{dis} – efficiency of appearance of ions in additional discharge, z_{dif} – efficiency of living the ions from plasma by process of diffusion.

Equation (1) in the physical conditions of HVGD lighting transforming to cubic equation relatively parameter d_p , which analytical solving with using Cordano formulas given following result [8, 9, 12]:

$$R_1 = A_i U_{ac}^{-a_i} (A_i U_{ac}^{-a_i} + 1) \cdot \sqrt{\frac{kT_e + eU_d}{2\pi m_e}}; \quad R_2 = f \eta_i \eta_U^{-a_i} k_e; \quad R_5 = R_1 R_2 p_{a0} Q_{ep0},$$

$$R_3 = 3(kT_e + eU_d) \cdot N_0 \cdot \alpha_i \sqrt{\frac{kT_e + eU_d}{2\pi m_e}} \exp\left(-\frac{U_i}{\frac{kT_e}{e} + U_d}\right);$$

$$R_4 = \mu_{e0} (kT_e + eU_d) \cdot \left(\frac{\pi}{p_{a0}}\right)^2 \left(1 + \frac{\gamma d_{tr}}{\lambda_e}\right); \quad (2)$$

$$c = -\frac{R_1 + R_3 + R_1 R_2}{R_5}, \quad d = \frac{R_4}{R_5}, \quad p = -\frac{c^2}{3}, \quad q = \frac{2c^3}{27} + d,$$

$$D_{eq} = \left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2, u = \sqrt[3]{-\frac{q}{2} + \sqrt{D_{eq}}};$$

$$v = \sqrt[3]{-\frac{q}{2} - \sqrt{D_{eq}}}; y = u + v, \quad d_p = y - \frac{c}{3},$$

where η_i and η_U – the coefficients of ions reflection from the HVGD anode by the current and by the energy correspondently, k_e – coefficient of elongation of ions trajectories, f – transparent coefficient for HVGD anode, Q_{ep0} – cross-section of ions dissipation on the ions' of residual gas, U_i – potential of gas ionizing, N_0 – Loshmidt constant, T_e – the temperature of electrons in anode plasma, μ_{e0} – mobility of electrons in anode plasma, A_i, a_i, α_i – semi-empirical coefficients, c, d – the coefficients of solving cubic equation, D_{eq} – discriminant of this equation, p, q, u, v and y – additional variables.

For electrodes' system with conic anode, presented at Fig. 1, the plasma longitudinal size d_{pc} can be recalculated with using value of d_{pl} , obtained from equations (2), with using following relations [1]:

$$d_{pc} = \sqrt[3]{\frac{3R_a^2 d_{pl} l_a^4}{2h_a^4 s w^2} - \frac{l_a^{12} R_a^6}{27h_a^{15} s^3 w^2} + \sqrt{\frac{9R_a^4 d_{pl}^2 l_a^8}{4h_a^8 s^2 w^2} - \frac{3l_a^{24} R_a^{12}}{729h_a^{30} s^6 w^6} - \frac{2R_a^8 l_a^{16} d_{pl}}{9h_a^{19} s^4 w^4}}}, \quad (3)$$

$$s = 1 + \left(\frac{R_a}{h_a}\right)^2 - \sqrt{1 + \left(\frac{R_a}{h_a}\right)^2}, \quad w = 3 - \frac{s \cdot h_a^2}{h_a^2 + R_a^2},$$

where R_a – radius of anode basis, h_a – highness of anode, l_a – generatrix line of conic anode surface.

With known longitudinal size of the anode plasma d_{pl} , defined by equations (2, 3), concentration of ions defined by following formulas [8, 9, 12]:

$$C_1 = A_i U_{ac}^{-a_i} (1 + A_i U_{ac}^{-a_i}) \cdot (1 + \eta_i \eta_u^{-a_i} (1 - f(1 - d_p p_{a0} Q_{ep0}))),$$

$$C_2 = \frac{\pi^2 \mu_{i0}}{(d_n p_{a0})^2} \left(1 + \frac{\gamma d_{non}}{\lambda}\right) - 3N_0 \alpha_i \sqrt{\frac{e(kT_e + eU_p)}{2\pi m_e}}, \quad (4)$$

$$C_3 = (kT_e + eU_p) \exp\left(-\frac{U_i}{\frac{kT_e}{e} + U_p}\right) C_2, \quad n_i = \frac{C_1}{C_3}.$$

Without taking into account the losses of electrons' current at the anode, the equation for HVGD current can be written as [8, 9]:

$$I_d = e(A_i U_{ac}^{-a_i} + 1) \cdot \sqrt{\frac{2m_e}{kT_e}} S_a = \pi e d_p (A_i U_{ac}^{-a_i} + 1) \cdot \left(\frac{d_{tr}}{2}\right)^2 \sqrt{\frac{2m_e}{kT_e}}, \quad (5)$$

and for current of additional discharge [8, 9]:

$$I_c = e n_i S_c (1 + \gamma_c) \sqrt{\frac{2eU_c}{m_i}}, \quad (6)$$

where concentration of ions in anode plasma n_i obtained from equation system (4).

With known values of the currents of main and additional discharges, defined by the equations (5, 6), the energetic efficiency of triode electron source for electrodes' system, presented at Fig. 1, calculated as follows [8, 9, 12]:

$$\eta_d = 1 - \frac{2 + k_e(1 + 2k_e\gamma\mu_{e0})}{2k_e(1 + \gamma k_e)}; k_e = lp_{a0}\overline{Q_{i0}}; \quad \eta_r = \frac{\eta_d}{1 + \frac{\eta_d U_c I_c}{U_{ac} I_d}} \quad (7)$$

Simulation results, have been obtained with using equations (2 – 7), will be presented and analyzed in the next part of the article.

Obtained simulation results and its' discussion

Calculations with using equations (2 – 7) have been provided for such HVGD parameters: $l=100$ mm, $d_{tr}=100$ mm, $r_c=700$ mm, $U_i=18$ V, $\gamma=4.6$, $a_i=0.343$, $Q_{ea}=5.3 \cdot 10^{-19}$ m⁻², $\eta_I=0.7$, $\eta_U=0.95$, $\alpha_i=1.452$, $f=0.99$, $A_i=3.8 \cdot 10^{-6}$, $a=2.5 \cdot 10^4 \frac{m}{s}$, $b=25.4 \frac{m^2}{V \cdot s}$. The

results of simulation for different acceleration voltage, operation pressure and voltage of additional discharge, as well as corresponded experimental results, are presented at Fig. 3.

It is clear from obtained simulation results presented at Fig. 3 that energetic efficiency of triode glow discharge electron gun with plane additional electrode is increasing with growing acceleration voltage, control voltage and operation pressure. This fact can be easy explained by higher level of gas ionization, which leads to grates increasing of HVGD current correspondently to current of additional discharge [8, 9]. In any case, lighting of additional discharge lead to increasing of ions' concentration in anode plasma, and in such conditions HVGD current increased by the power low with power index $m > 1$ [3, 8, 9]. The same dependence given experimental results have been obtained and plotted in the Fig. 3 by the circle points. Experimental points at Fig. 3, a, corresponded to curves 3 and 6, and points at Fig. 3, b – to curves 5 and 6. One can see from dependences, plotted at Fig. 3, that disagreement between theoretical and experimental results is not grater, than 10 – 15%.

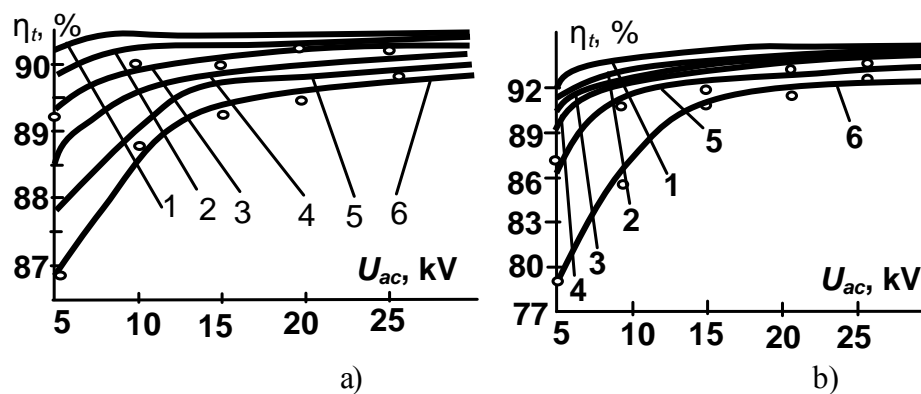


Fig. 3. Dependences of energetic efficiency of HVGD electrodes' system on acceleration voltage, voltage of additional discharge (a) and operation pressure (b):
 a) $p_{a0} = 0,5$ Pa; 1 – $U_c = 240$ V, 2 – $U_c = 210$ V, 3 – $U_c = 180$ V,
 4 – $U_c = 150$ V, 5 – $U_c = 120$ V, 6 – $U_c = 90$ V;
 b) $U_c = 150$ V; 1 – $p_{a0} = 0,2$ Pa, 2 – $p_{a0} = 0,4$ Pa, 3 – $p_{a0} = 0,5$ Pa,
 4 – $p_{a0} = 0,6$ Pa, 5 – $p_{a0} = 0,8$ Pa, 6 – $p_{a0} = 1$ Pa

Conclusions

The mathematical model, proposed in the article, allows defining on the first step of engineering design the energetic efficiency of elaborated triode glow discharge electron gun with the plane additional electrode. Provided analyze also shown that for the system with plane electrode energetic efficiency η_t is on few percents grater, than for the system with the negative ring-like electrode [8, 9]. In any case, the energetic efficiency of such guns is very high and for acceleration voltage 25 kV approve to 90%. Therefore such guns can be successfully used in modern electronics and instrument making industry for deposition of chemically-complex thin films and for refining of refractory metals, alloys and ceramics [4–6].

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