Simulation of Time of Current Increasing in Impulse Triode High Voltage Glow Discharge Electron Guns

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In this article defining of the time of current increasing in triode high voltage glow discharge electron guns for investigation its technological possibilities is considered. Provided analyse is based on calculation the parameters of anode plasma, namely its volume and ions concentration in it. These parameters are defined by analysing balance of created and outgoing ions in the plasma volume. Provided theoretical investigation shown, for acceleration voltage 10 – 30 kV, operation pressure 0.1 – 1 Pa and for voltage on additional electrode range of 50 – 300 V, time of increasing of beam current is in range 20 – 250 μs. Therefore, high voltage glow discharge electron guns can successfully operated in the impulse regime on the industrial electron beam technological equipment.

Симулиране на времето на нарастване на тока в електронна пушка с импулсен триоден високоволтов тлеещ разряд (И. Мелник). *В тази работа е разгледано определянето на времето на токовото нарастване в триодни електронни пушки с високоволтов тлеещ разряд за изследване на технологичните им възможности. Направения анализ се основава на пресмятане на параметрите на анодната плазма, преди всичко на на обема и и на йонната концентрация в него. Тези параметри са определени чрез анализ на баланса между създаваните и уходящите йони в плазмения обем. Направеното теоретично изследване за ускоряващи напрежения 10-30 kV, налягания 0,1-1 Pa и за напрежения на допълнителния електрод от 50 до 300 V, времето на нарастване на тока на лъча е от порядъка на 20-200 μs. Следователно, електронните пушки с високоволтов тлеещ разряд могат успешно да работят в импулсен режим в индустриалното електроннолъчево оборудване.*

Introduction

High voltage glow discharge electron guns [1] are widely used in industry for providing complex technological operations. Such guns are successfully applied today for high rate electron beam welding, for annealing of small items, for films deposition in the medium of different gases, including noble and active ones, as well as for refusing of refractory metals in the soft vacuum. Such guns are characterised by high stability of operation, low costs of guns and of evacuation equipment, and by possibility of beam current control by changing the gas pressure in the guns chamber.

However, flow-dynamics control of beam current is not so fast, as required. Usually the time constant of current regulation is in range of hundreds ms [2]. Therefore, the electric method of beam current control, based on lighting of additional discharge, was proposed and investigated [3]. Such method allows realise the pulse regime of gun's operation, which is very perspective to using in the modern electron-beam technologies [4].

However, providing the estimations of the time of discharge current increasing in triode high-voltage glow discharge (HVGD) electrodes systems are still not investigated. This fact is deterrent the elaboration and providing in industry of perspective triode glow discharge electron guns. Therefore, obtaining of analytical expressions for estimation the time of increasing of discharge current with changing the voltage of additional electrode is the main aim of this article. Theoretical analyse is based on calculation the volume of anode plasma and ions concentration in it. These parameters are defined by solving the equation of ions balance. Therefore, the time of increasing of beam current is defined by the difference between ions' concentration in anode plasma for different values of voltage on the additional electrode. The results of theoretical investigations for acceleration voltage 10 – 30 kV, operation pressure 0.1 – 1 Pa and for voltage on additional electrode range of 50 – 300 V are given and analysed.

Basic Geometry and Main Parameters of Simulated High Voltage Glow Discharge Electrodes System

Basic Conception of Elaborated Model

It is well-known fact from the theory of glow discharge, that the time of increasing of discharge current is depended from the time of development of ionizing processes and for the relaxation time, which is connected with the diffusion of particles in the discharge gap. Therefore, for estimation of time of increasing of discharge current in HVGD most important is the concentration of the particles in anode plasma and it volume. For electrodes systems of impulse electron guns this parameters must be estimated for two regimes: for regime of minimal current in the pause between impulses, and for regime of maximal current during the impulse of voltage on additional electrode. It is clear, that the time of increasing of HVGD current is connected independently with the value of energy, which commutated in discharge, therefore considered in the paper [5] anode plasma parameters can be considered as the initial data for creating the mathematical model, which allow estimating the dynamic of discharge development. It is connected with the fact, that namely in the anode plasma taking place the main ionizing and diffusion processes. Therefore, in impulse regime of HVGD lighting, anode plasma boundary must be considered not only as the source of ions and as the moving electrode with the defined potential [6], it also considerably influence to the complex dynamic of gas discharge. The equation for defining anode plasma volume and concentration of ions in it will be considered in the next part of this article.

Basic Geometry and Parameters of Simulated Electrodes System

The scheme of simulated triode impulse HVGD electrodes' system is presented in Fig. 1. One difference from simple HVGD triode electrodes system [6] is presence of impulse low-voltage power source for modulation the power of electron beam. It is clear, that geometry of HVGD electrodes' systems is not depended from regime of its operation. The main parameters of simulated electrodes' system are: longitude length of discharge gap l, longitude length of anode plasma d_p, distance from the cathode surface to plasma boundary d_{cp}, transversal length of discharge gap d_{tr}, and transversal cathode radius r_c.

The main electric parameters of considered electrodes system is accelerated voltage U_{ac}, as well as the values of controlled voltage in the impulse U_{d1} and in the pause between impulses U_{d0}. The important internal parameter of simulated HVGD electrodes' system is the reduced pressure inside the volume p_{a0}. The values d_{p1} and d_{cp1}, presented on Fig. 1, corresponded to the plasma boundary position for the maximal discharge current in impulse, and values d_{p0} and d_{cp0} – to the its' position for the minimal discharge current between impulses.

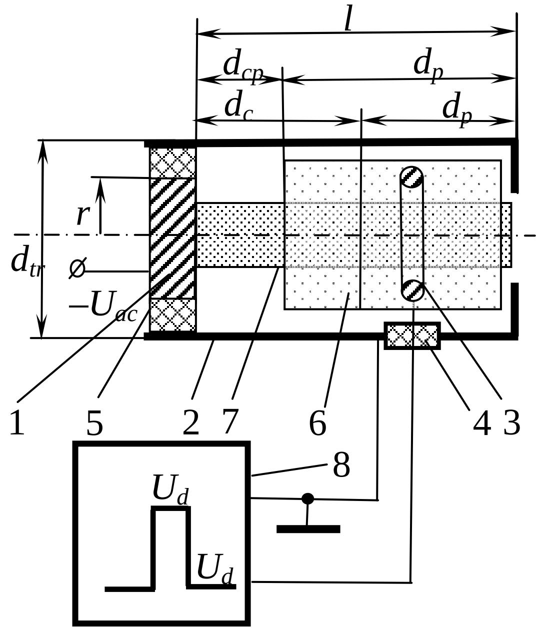

Fig.1 Scheme of simulated HVGD triode electrodes' system. 1 – cathode; 2 – HVGD anode; 3 – electrode for lighting of additional discharge; 4 – low-voltage insulator; 5 – high-voltage insulator; 6 – anode plasma; 7 – electron beam; 8 – low-voltage impulse power source

Methodic of calculation of the time of increasing of discharge current

Therefore, for finding the time of rise of discharge current by action of voltage impulse on the additional electrode, first of all defining of plasma boundary position for minimal voltage on additional electrode between impulses U_{d0} and for maximal voltage U_{d1} is necessary. Corresponded relations for calculation of plasma boundary position in triode HVGD electrodes systems are presented in paper [6]. After that, concentrations of ions in anode plasma for both cases, for small and big value of discharge current, are calculated. Corresponded relations are presented in paper [7]. With known ion concentrations the discharge current and the current of formed electron beam can be defined [7]. And finally, with known plasma volume, ions concentration in anode plasma and discharge current, the relations for the time of increasing of discharge current can be obtained [8].

All obtained mathematical relations are based on the equation of ion balance in anode plasma and on the equation of HVGD self-maintained. All corresponded equations will be presented in the next parts of the article.

Relations for Calculation of Anode Plasma Parameters and Current of Main Discharge

Defining of Plasma Boundary Position

As was pointed out in the pervious section, parameters of anode plasma are defined from the equation of ion balance in it. In triode HVGD systems the residual gas ionized by fast beam electrons, by slow electrons, reflected from the anode, and in additional low voltage discharge. The equilibrium ions concentration in anode plasma is provided by creation of ions in considered above ionization processes and by leaving the ions from plasma as a result of diffusion process. The equation of ions equilibrium can be written in following form [6, 7]:

$$\frac{\pi^2\mu_{i0}(kT_e+eU_d)}{(p_{a0}d_p)^2}\left(1+\frac{\gamma d_{tr}}{\lambda_e}\right)-3(kT_e+eU_d)\times$$

$$\times N_0\alpha_i\sqrt{\frac{e(kT_e+eU_d)}{2\pi m_e}}\exp\left(-\frac{U_i}{\frac{kT_e}{e}+U_d}\right)= \quad (1)$$

$$=A_iU_{ac}^{-a_i}\left(A_iU_{ac}^{-a_i}+1\right)\sqrt{\frac{kT_e}{2\pi m_e}}\times$$

$$\times\left(1+\eta_i\left(1-f\left(1-d_pp_{a0}Q_{ep0}\right)\right)\eta_U^{-a_i}k_e\right),$$

where T_e – temperature of slow electrons in anode plasma, k – Boltzmann constant, e and m_e – electron's charge and mass correspondently, A_i and a_i – empirical constants, η_i and η_U – coefficients of electrons reflection from the anode by the current and by the voltage correspondently, f – transparent coefficient for anode plasma, Q_{ep0} – cross-section of ions scattering at the residual gas molecules, k_e – coefficient of electrons' trajectories longitude, n_e – concentration of free electrons in anode plasma, U_i – potential of gas ionization, N_0 – Loschmidt constant, α_i – empirical constant for given operation gas, μ_{i0} – mobility of ions' in anode plasma, γ_a – secondary ion-electron emission coefficient from anode surface, λ_e – free path of electrons in anode plasma.

After substituting, transforming and simplifying, equation (1) can be rewritten in that way [6, 7]:

$$R_1=A_iU_{ac}^{-a_i}\left(A_iU_{ac}^{-a_i}+1\right)\sqrt{\frac{kT_e+eU_d}{2\pi m_e}},$$

$$R_2=f\eta_i\eta_U^{-a_i}k_e,\ R_5=R_1R_2p_{a0}Q_{ep0},$$

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

$$2)\qquad R_4=\mu_{i0}(kT_e+eU_d)\left(\frac{\pi}{p_{a0}}\right)^2\left(1+\frac{\gamma d_{tr}}{\lambda_e}\right),$$

$$C_{eq}=-\frac{R_1+R_3+R_1R_2}{R_5},\ D_{eq}=\frac{R_4}{R_5},\ p=-\frac{C_{eq}^2}{3},$$

$$q=\frac{2C_{eq}^3}{27}+D_{eq},\ D=\left(\frac{p}{3}\right)^3+\left(\frac{q}{2}\right)^2,$$

$$u=\sqrt[3]{-\frac{q}{2}+\sqrt{D}},\ v=\sqrt[3]{-\frac{q}{2}-\sqrt{D}},\ y=u+v,$$

$$d_p=y-\frac{C_y}{3},\quad d_{cp}=d_l-d_p,$$

where R_1, R_2, R_3, R_4, R_5, p, q, u, v and y – additional variables, C_{eq} and D_{eq} – coefficient of solved cubic equation, obtained form (7), D – discriminant of this equation.

Analysing of theoretical results for plasma boundary position, which have been obtained from equations (2), presented in papers [4, 6].

Defining of Concentration of Ions in Anode Plasma and the current of HVGD

With known from relations (1) the longitudinal length of anode plasma d_p, concentration of ions in plasma can be calculated from following equations [6, 7]:

$$C_1=A_iU_{ac}^{-a_i}\left(1+A_iU_{ac}^{-a_i}\right)\times$$
$$\times\left(1+\eta_i\eta_u^{-a_i}\left(1-f\left(1-d_pp_{a0}Q_{ep0}\right)\right)\right),$$

$$(3)\qquad C_2=\frac{\pi^2\mu_{i0}}{(d_pp_{a0})^2}\left(1+\frac{\gamma d_{tr}}{\lambda_e}\right)-C_4,$$

$$C_3=(kT_e+eU_d)\exp\left(-\frac{U_i}{\frac{kT_e}{e}+U_d}\right)C_2,$$

$$C_4=3N_0\alpha_i\sqrt{\frac{e(kT_e+eU_d)}{2\pi m_e}},\qquad n_i=\frac{C_1}{C_3},$$

where C_1, C_2, C_3 and C_4 is the additional variables.

Therefore, current of high voltage glow discharge simply defined as [6, 7]:

$$(4)\quad I_e = r_c^2 n_i \left(1 + A_i U_{ac}^{-a_i}\right) \sqrt{\frac{\pi e d_p \left(kT_e + eU_d\right)}{2m_e}}\,.$$

Simulation results for HVGD current are presented and analyzed in paper [7]. It was proving, that HVGD current-voltage characteristics in triode electrodes' systems for given value of voltage at additional electrode U_d can be approximated by power dependence [7]:

$$(5)\qquad I_e(U_{ac}) = CU_{ac}^m p_{a0}^n,$$

with empirical coefficients C, m and n. Coefficients m and n in equation (5) are usually greater, than 1, but smaller, than 2. Coefficients C, m and n for the given value of voltage at additional electrode U_d can be defined experimentally [7].

With known from equations (1 – 4) plasma parameters and HVGD current corresponded relations for time of current increasing also can be obtained. Method of calculation the time of current increasing is described in the next section of this paper.

Relations for Calculation of Time of High Voltage Glow Discharge Current Increasing

Theoretical estimations for the time rise of HVGD current have been provided in the paper [8]. There was pointed out, that the time of HVGD lighting t_l usually have two components: the time of statistic delay of discharge lighting t_d and the time of current impulse forming t_f, namely;

$$(6)\qquad t_l = t_d + t_f.$$

For the analysed system, presented in Fig. 1, small discharge current, level of tens mA, is existed between impulses. For such model it is clear, that delay time is not existed, namely, $t_d = 0$.

For calculation the time of current impulse forming t_f model of virtual anode, located on the defined distance from the HVGD anode, is proposed [8]. Corresponding to the theory of virtual anode, dependence of electron current from the HVGD cathode described by the following equation:

$$(7)\qquad I(t) = I_{e0} + (G+1)(t - \tau_i),$$

where I_{e0} – the current of primary electrons from HVGD cathode and τ_i – average time of ions' moving from the plasma boundary to HVGD anode. Coefficient G in equation (7) defined as:

$$(8)\quad G = \exp\left(-\frac{U_i}{\frac{kT_e}{e} + U_d}\right)\left[\gamma\left[\exp(\beta_i U_{ac}) - 1\right] - 1\right],$$

with β_i – coefficient of gas ionization.

For the stable regimes of HVGD lighting, when $t >> \tau_i$, equation (7) can be rewritten as:

$$(9)\qquad I_e(t) = I_{e0}\exp\left(\frac{Gt - \tau_i}{G}\right).$$

From equation (8, 9), taking into account (1 – 4), following equation for estimation average time of HVGD current increasing can be obtained [8]:

$$(10)\qquad \overline{t_f} = \frac{9kT_e\left(d_{p1} - d_{p0}\right)}{8(\pi e)^3 \mu_{io}\gamma G \ln\left(1{,}5 - \sqrt{\frac{kT_e (e\Delta U)^3}{\pi p_{a0}}}\right)}.$$

It is clear from equation (10) that average time of discharge current increasing is defined by changing of plasma volume, taking place with development of discharge, and by the ionising processes in the discharge gap.

The results of calculation of average time of HVGD current increasing with using equations (1 – 4, 10), will be presented in the next part of this paper.

The Simulation Results And Its Analyse

Obtained equations (1 – 4, 10) allow providing the approximated estimations of average time of HVGD current increasing. Furthermore, such approach allows making the quality estimations without making complex calculations. Approximated estimations are especially necessary on the first step af designing of HVGD electron guns.

Testing of obtained relations (1 – 4, 10) was provided for HVGD electrodes systems, presented in Fig. 1. Aluminum was considered as a cathode material, copper as an anode material, and nitrogen as operation gas. These materials and operation gas are usually used in HVGD electron guns. Therefore, in equations (1 – 4, 10), such coefficients were choosing: $U_i = 18$ V; $T_e = 800$ K; $a_i = 0.343$; $\alpha_i = 1.452$; $\eta_i = 0.7$; $\eta_U = 0.95$; $f = 0.99$;

$\mu_{i0} = 1.27 \cdot 10^{-4} \dfrac{m^2}{V \cdot s}$; $Q_{ep0} = 5.3 \cdot 10^{-19} m^{-2}$;

$A_i = 3.8 \cdot 10^{-6}$; $\gamma = 4.6$; $\beta_i = 2.8 \cdot 10^{-4}$. Simulation was provided for the reduced pressure in discharge gap p_{a0} = 0.1 – 1 Pa, acceleration voltages U_{ac} = 10 – 30 kV, control voltages in impulse U_{d1} = 50 – 350 V, and control voltages in pause U_{d0} = 5 – 25 V. The dimensions of simulated HVGD electrodes system were: l = 7 cm, d_{tr} = 7 cm and r_c = 5 cm. Such geometrical parameters of HVGD electrodes systems are typical for diode industrial guns.

Obtained simulation results are presented at Fig. 2. It is clear, that the time of HVGD current increasing is laid in the range 25–300 μs, and that the value of this time increasing with increasing of control voltage in impulse and of operation pressure. The experimental data for real electrodes system was the same, divergence between calculated and experimental data was smaller, then 40%, and this is a good agreement for gas discharge systems with complex processes of particles interaction in volume.

Main conclusion from the obtained simulation result is that time of HVGD current increasing became grater with increasing of control voltage in impulse. This fact can be explained by predominance of ionizing processes in HVGD anode plasma under diffusion processes.

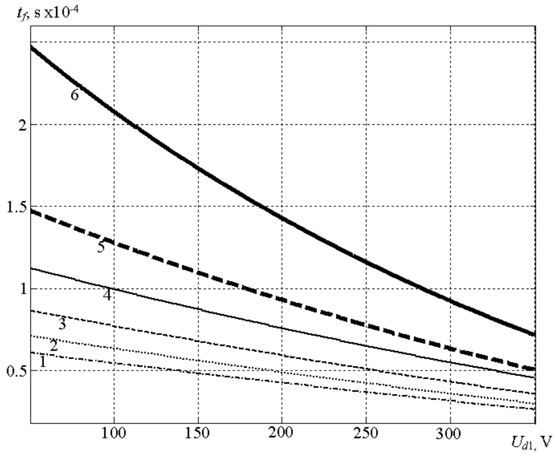

Fig.2 Dependence of the time of HVGD current increasing from the maximal voltage at additional electrode. Reduced pressure is: 1 – 0.7 Pa; 2 – 0.6 Pa; 3 – 0.5 Pa; 4 – 0.4 Pa; 5 – 0.3 Pa; 6 – 0.2 Pa. U_{ac} = 15 kV; U_{d0} = 5 V

Conclusion

Obtained simulation results are very important for the designing of impulse HVGD electron guns and for analyzing the possibilities its' using in the modern electron-beam technologies. It is clear, that with the time of beam current switching range of tens μs applying of impulse regime of heating for many technological processes is very perspective. For example, impulse electron beams can be successfully applied for obtaining polymetals alloys and polymetals films.

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