Electron Collectors in Nonequilibrium Plasma of Gas Discharge

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Abstract – A model of electron collector in gas discharge plasma with electron velocity distribution as a sum two Maxwellian distributions at different temperatures is offered. Gas discharge disturbance by electron collector is considered, disturbance coefficient is introduced. Expressions allowing to calculate disturbance coefficient as well as current-voltage characteristics of the collector in nonequilibrium plasma have been obtained. Calculated and experimental results are compared.

1. Introduction

A.V. Zharinov and Yu.A. Kovalenko in their well-known paper [1] offer a theory of electronic collectors in gas discharge in which plasma has equilibrium (Maxwellian) velocity distribution of electrons. The importance of this work is that it allows to understand the physics of plasma disturbance by electronic collector. It is rather important for research and development of electron sources with plasma emitter.

In many cases in low-pressure gas discharges used in such sources to create emitting plasma, the mean free path of electrons, accelerated in cathode potential drop or in a double electric layer, exceeds the characteristic sizes of area in which plasma is created. Therefore some fast electrons cannot relax in one flight through this area, and the electronic component of plasma will have nonequilibrium velocity distribution. Electron velocity distributions in such conditions observed in experiments point at there being two or even three groups of electrons considerably different in energy. For calculations in such cases nonequilibrium electron distributions are frequently approximated by the sum of two Maxwellian distributions at different temperatures or by the sum of Maxwellian distribution and the directed beam [2, 3] or by the sum of two Maxwellian distributions and the directed beam [4, 5].

In the present paper an attempt is made to consider the disturbance by the collector of discharge nonequilibrium plasma in which electron velocity distribution can be presented as the sum of two Maxwellian distributions at different temperatures.

2. Model of gas discharge processes

The circuit of gas discharge and switch of collector is presented in Fig. 1, *a*. For simplicity we shall accept, that the collector is located in the anode plane, their total area is equal to F, the share of the collector in this area being f. The plasma electron component consists of thermal electrons with concentration n_{et} and temperature T_{et} and hot electrons with concentration n_{eh} and temperature T_{eh} ($T_{et}<T_{eh}$). The discharge is considered as homogeneous in cross section. The plasma potential φ exceeds the anode potential U_0 (Fig. 1, *b*), i.e. the anode potential drop is negative.

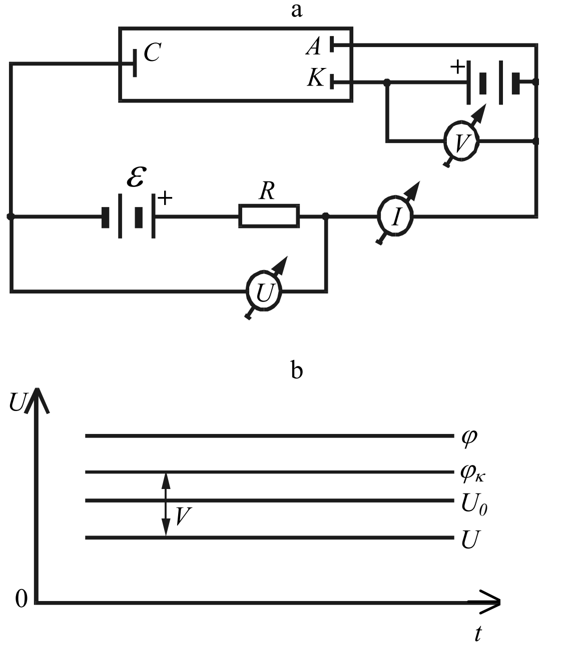

Fig. 1. Electric supply circuit of discharge and electron collector (a) and ratio of different electrode and plasma potentials (b). C is cathode, A is anode, K is collector, ε is discharge emf, R is ballast resistance, I is discharge current, U is potential difference between anode and cathode, U_0 is the same when V=0, V is potential difference between anode and collector, φ_k, φ are collector and plasma potentials in relation to cathode

As shown in [1], one of the key parameters determining the degree of plasma disturbance by the electron collector is parameter G equal to the ratio of chaotic electron current density to discharge current density. In the case under consideration, in view of the chaotic current density of thermal (j_rt) and hot (j_{rh}) electrons and the negative anode potential drop parameter G can be presented as

$$G = \frac{j_{rt} + j_{rh}}{j_{rt}\exp\left(-\frac{e\varphi - eU_0}{kT_{et}}\right) + j_{rh}\exp\left(-\frac{e\varphi - eU_0}{kT_{eh}}\right)}, \quad (1)$$

where

$$j_{rt} = en_{et}\sqrt{\frac{kT_{et}}{2\pi m}}, \qquad j_{rh} = en_{eh}\sqrt{\frac{kT_{eh}}{2\pi m}}, \quad (2)$$

e, m are electron charge and mass, k is Boltzmann's constant. If we introduce the notation

$$\alpha_h = \frac{n_{eh}}{n_{et} + n_{eh}}, \quad \alpha_t = \frac{n_{et}}{n_{et} + n_{eh}}, \quad \beta = \frac{T_{et}}{T_{eh}}, \quad (3)$$

than

$$G = \frac{\alpha_h + \alpha_t\sqrt{\beta}}{\alpha_h \exp\left(\frac{eU_0 - e\varphi}{kT_{eh}}\right) + \alpha_t\sqrt{\beta}\exp\left(\frac{eU_0 - e\varphi}{\beta kT_{eh}}\right)}. \quad (4)$$

Now we shall consider the mechanism of the gas discharge disturbance by the electron collector. At positive displacement V the anode potential U decreases by μV:

$$U = U_0 - \mu V, \quad (5)$$

and the collector potential increases by $(1-\mu)V$ in relation to the initial potential U_0 (Fig. 1, *b*). It results in decreasing anode electron current density $j_a(V)$ and in increasing collector electron current density $j_k(V)$. As this takes place, the total discharge current $I(V)$ increases as V increases:

$$I(V) = \frac{\varepsilon - U_0 + \mu V}{R}. \quad (6)$$

Expression (6) is received from Kirchhoff's second rule for the electric circuit containing both power supplies (Fig. 1, *a*).

From expressions (5) and (6) it follows, that

$$\mu = -\frac{\Delta U}{\Delta V}, \quad \mu = \frac{\Delta IR}{\Delta V}, \quad (7)$$

i.e. the value of μ is numerically equal to the anode potential decrease or to the discharge current increase through unit ballast resistance at unit increase in collector displacement V. Proceeding from such physical sense, we shall name parameter μ as disturbance coefficient. Maximum value of μ cannot exceed 1. Zero value of μ testifies that the collector does not disturb the discharge.

Let's establish the limits of applicability of the disturbance model under consideration and find out, how the disturbance coefficient depends on nonequilibrium plasma parameters. Let's introduce parameter

$$H(V) = \frac{j_a(V)}{j_k(V)}. \quad (8)$$

Proceeding from (8) $H(0)=1$. As V increases parameter $H(V)$ will decrease, remaining positive, i.e.

$$0 < H(V) < 1, \quad (9)$$

if the electron current from plasma to the anode does not change its sign to the opposite.

Based on (8) discharge current at some displacement V can be written down as the sum of the current to collector (the first summand) and the current to the anode (the second summand):

$$I(V) = j_k(V)Ff + H(V)j_k(V)F(1-f). \quad (10)$$

Let's divide (10) by $I(V)=j(V)F$, where $j(V)$ is discharge current density:

$$1 = f\frac{j_k(V)}{j(V)} + (1-f)H(V)\frac{j_k(V)}{j(V)}. \quad (11)$$

At a certain value of $V=V_\varphi$ the collector potential reaches the plasma potential ($\varphi_k=\varphi$). As this takes place, the current density to a collector $j_k(V_\varphi)$ becomes equal to chaotic electron current density $j_r(V_\varphi)$ and if we accept, as it is done in [1], that G does not depend on V,

$$\frac{j_k(V_\varphi)}{j(V_\varphi)} = \frac{j_r(V_\varphi)}{j(V_\varphi)} = G, \quad (12)$$

and equation (12) becomes

$$1 = fG + (1-f)H(V_\varphi)G. \quad (13)$$

From (13) we shall define $H(V_\varphi)$:

$$H(V_\varphi) = \frac{1 - fG}{(1-f)G}. \quad (14)$$

As seen from (14), to satisfy (9) at all values of V up to $V=V_\varphi$, the following condition should be satisfied

$$fG < 1. \quad (15)$$

If $fG \geq 1$, $H(V_\varphi) \leq 0$. It means that at a certain value of $V < V_\varphi$ the electron current to the anode will change its sign, i.e. the anode will pass to the mode of the cathode, and the collector – to a mode of the anode.

Let's express parameter $H(V_\varphi)$ through parameters of nonequilibrium plasma:

$$H(V_\varphi) = \frac{\alpha_h \exp\left(-\frac{eV_\varphi}{kT_h}\right) + \alpha_t\sqrt{\beta}\exp\left(-\frac{eV_\varphi}{\beta kT_h}\right)}{\alpha_h + \alpha_t\sqrt{\beta}}, \quad (16)$$

we shall also copy (4) considering that $\varphi - U_0 = (1-\mu)V_\varphi$:

$$G = \frac{\alpha_h + \alpha_t\sqrt{\beta}}{\alpha_h \exp\left[\frac{e(\mu-1)V_\varphi}{kT_{eh}}\right] + \alpha_t\sqrt{\beta}\exp\left[\frac{e(\mu-1)V_\varphi}{\beta kT_{eh}}\right]}. \quad (17)$$

Using equations (14) and (16) and setting f, G, α_h, α_t, β, it is possible to calculate eV_φ/kT_{eh}, and then, having substituted this value in (17) to receive value of disturbance coefficient μ.

For the collector to work in the mode of a probe and not to disturb a discharge, it is necessary, as well as in [1], to observe condition

$$fG \ll 1. \quad (18)$$

It means, that the share of the current to the collector will be negligible even at $V=V_\varphi$. As this takes place, the increase of V from 0 up to V_φ practically will not lead to changing the discharge current. It means, as it follows from (6), that $\mu=0$ and $\varphi_k=U_0+V$, $U=U_0$, i.e. the anode potential will not change (the discharge not disturbed), and the collector potential will increase by V.

3. Collector current-voltage characteristics

On the basis of the above stated representations it is possible to receive a dimensionless expression for the current to collector $I_k(V)$ which looks as follows:

$$\frac{I_k(V)}{I_k(0)} = \left(1+\frac{\mu V}{\varepsilon - U_0}\right)\frac{1}{f+(1-f)H(V)}, \qquad (19)$$

where

$$I_k(0) = I_k\,|_{V=0} = \frac{\varepsilon - U_0}{R} f, \qquad (20)$$

$H(V)$ parameter which is part of (19) can be expressed through the nonequilibrium plasma parameters. So the current density $j_a(V)$ and $j_k(V)$ in expression (8) can be represented as follows:

$$j_a(V) = j_{rh}\alpha_h \exp\left[\frac{(\mu-1)eV_\varphi}{kT_{eh}}\right]\exp\left(-\frac{\mu eV}{kT_{eh}}\right)+ \\ +j_{rh}\alpha_t\sqrt{\beta}\exp\left[\frac{(\mu-1)eV_\varphi}{\beta kT_{eh}}\right]\exp\left(-\frac{\mu eV}{\beta kT_{eh}}\right), \qquad (21)$$

$$j_k(V) = j_{rh}\alpha_h \exp\left[\frac{(\mu-1)eV_\varphi}{kT_{eh}}\right]\exp\left[\frac{(\mu-1)eV}{kT_{eh}}\right]+ \\ +j_{rh}\alpha_t\sqrt{\beta}\exp\left[\frac{(\mu-1)eV_\varphi}{\beta kT_{eh}}\right]\exp\left[\frac{(\mu-1)eV}{\beta kT_{eh}}\right]. \qquad (22)$$

Taking into account expressions (8, 19–22) one can calculate collector current-voltage characteristics. These expressions are also correct in the case of negative values of V that is why they can be used, for example, in probe diagnosing of nonequilibrium plasma.

The analysis of expressions, determining the current-voltage characteristics of the collector, if it works in the probe mode ($fG<<1$, $\mu=0$) confirms the correctness of the methods of probe characteristic treatment offered in [4, 5]. Using these methods the parameters of nonequilibrium plasma for experimental conditions [5, 6] have been determined, and the current-voltage characteristics were calculated after that. Fig. 2 and 3 show the comparison of calculated and experimental current-voltage characteristics for conditions corresponding to curve 4 in Fig 13 of [6] and in fig. 4 of [5]. The peculiarity of the latter case is that $fG=0{,}48$, i.e. condition (18) is not observed. However the author of [5] artificially kept the discharge current and anode potential constant while measuring the collector current-voltage characteristic, evidently, at the expense of changing the discharge emf and the thermionic cathode heat. This provided the value of disturbance coefficient μ equal to 0.

The satisfactory concurrence of calculated and experimental current-voltage characteristics confirms the correctness of the proposed model of electron collector in nonequilibrium gas discharge plasma.

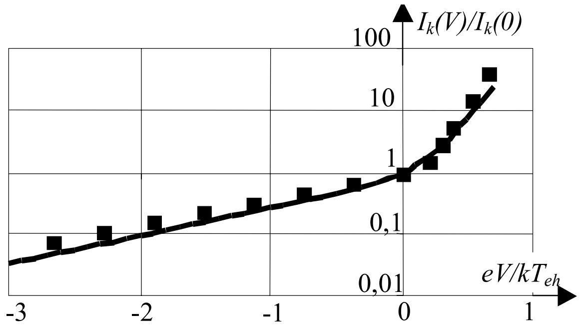

Fig. 2. Comparison of experimental (dots) [6] and calculated (solid line) collector current-voltage characteristics. $G=40$; $f=1{,}33\cdot10^{-3}$; $\alpha_h=0{,}016$; $\alpha_t=0{,}984$; $\beta=0{,}15$; $T_{eh}=13{,}59$ eV; $kT_{eh}/(\varepsilon-U_0)=0{,}03$; $V_\varphi=10{,}7$ V; $\mu=0{,}03$

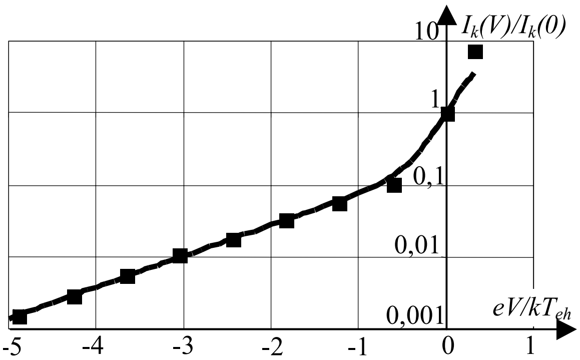

Fig. 3. Comparison of experimental (dots) [5] and calculated (solid line) collector current-voltage characteristics. $G=3{,}7$; $f=0{,}13$; $\alpha_h=0{,}017$; $\alpha_t=0{,}983$; $\beta=0{,}164$; $T_{eh}=8{,}19$ eV; $V_\varphi=2{,}66$ V; $\mu=0$

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