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Effect of electron temperature on the distribution of plasma parameters on the phase planes for thermionic diode with low temperature emitter

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Abstract. Influence of temperature distribution of thermal and fast electrons on the distribution of the ion current density in the electrode gap diode has been studied. Studies on the phase planes, especially in the plane of the plasma density – ion current density have been carried out. It is shown that the generation of ions in the electrode gap is specified by the fast electron temperature.

1. Introduction

To effectively control the surface plasma processing technology products it is necessary to know the distributions of plasma parameters and mechanisms of their formation. One critical parameter of the plasma is the distribution ion current density in the interelectrode gap which occurs due to the mechanism of generation of ions. For plasma processing of the surfaces of products, as a rule, glow discharge is used, rather complex structure on the phenomenon. Probe characteristics this discharge have two extended linear section [1, p. 316]. This is interpreted as the temperature distribution of the two group electrons. The impact of these distribution on ionization processes remains unclear. On the other hand, cesium low-temperature plasma of thermionic diode has similar probe characteristics [2]. But cesium discharge thermionic diode is simpler in structure as compared with the glow discharge and therefore it is easier to study the mechanism of generation of ions.

At a certain combination of parameters thermionic diode, in particular at low temperatures emitter probe semilog cesium plasma arc characteristics have two linear areas. Processing of these characteristics gives two electrons temperature distribution in the interelectrode gap (IEG) [2, 3]: in the low (thermal) energy of the electrons and the electrons in the high energy range. The latter group is associated [2] with the electrons which have major influence on the processes of generation of excited atoms and cesium ions.

With a low temperature plasma model [2] we can obtain the distribution of plasma parameters which are not measured in the experiment: the ion current density, electron energy density, function generating ions in the plasma volume; for spectroscopic measurements – the potential of the space occupied by the plasma. It is interesting to study the influence of two electron temperature distribution in the distribution of unmeasured plasma parameters, especially the function of the ion generation electrode in the diode gap.

As a method of research we used the analysis of experimental distributions and unmeasured plasma parameters on the phase planes [4–8]. Such a representation of distributions allows, among other things, designing qualitative and quantitative criteria for the comparison of distributions of plasma parameters.

In this paper we investigate the effect of the distributions of two electron temperature distribution in the experimental and unmeasured (calculated) cesium plasma parameters for a thermionic diode with a low temperature emitter. On the experimental material checked the results of theoretical research model distributions of plasma parameters on the phase planes [8].

2. The model of calculating the distribution of the ion current density

The equation for the ion current density in the IEG thermionic diode (taking into account the friction forces on the ions, electrons $R_{ie} = J_e/\mu_{ei}$) can be written as [2]:

$$J_i = \left(\frac{1}{\mu_{ea}} + \frac{1}{\mu_{ia}}\right)^{-1} \left[-\frac{J}{\mu_{ea}} - (\beta_e - 3/2)kn\frac{dT_e}{dx} - (\beta_i - 3/2)kn\frac{dT}{dx} - k(T_e + T)\frac{dn}{dx}\right]; \quad (1)$$

continuity equation for the ion current density can be written as:

$$\frac{dJ_i}{dx} = -\Gamma(n, n_a, T_e), \quad (2)$$

$$\Gamma(n, n_a, T_e) = en_a\bar{v}_e(T_e)\sigma(T_e)\left[1 - n^2/n_{sh}^2(n_a, T_e)\right], \; \sigma(T_e) = 1{,}44 \cdot 10^{-12}\exp\left[-3{,}21/(kT_e)\right],$$

where e – the electron charge; k – the Boltzmann constant; n – plasma density; T_e, T – electron temperature plasma and heavy components (atoms and ions) temperature; $\bar{v}_e$ – the thermal velocity of the electrons; μ_{ea}, μ_{ei}, μ_e, μ_{ia} – coefficients of diffusion and mobility of electrons and ions; β_e, β_i – coefficients of proportionality, taking into account the scattering of electrons and ions on atoms; Γ – function of generating ions in the IEG; $\sigma(T_e)$ – step ionization cross section; $n_{sh}(n_a, T_e)$ – Saha density plasma.

The good approximation for the temperature of the heavy component of the plasma in a weakly ionized plasma diode is of a linear variation along the gap from the emitter temperature to the collector temperature. The distribution density of the atoms $n_a = n_a(x)$ in the IEG is determined from the equation of state for the pressure of the saturated cesium vapor:

$$p_{\mathrm{Cs}} = n_a kT. \quad (3)$$

Using characteristics probes, we can obtain distribution $n = n(x)$, $T_e = T_e(x)$, and the potential of the space occupied by the plasma $V = V(x)$, and then evaluated $J_i = J_i(x)$. Spectroscopic measurements make it possible to obtain only the first two distributions. In this case, the distribution $V = V(x)$ also relate to unmeasured plasma parameters.

Thus, the expressions (1)–(3) and for the known distribution $T_e = T_e(x)$ and $n = n(x)$ allow calculating the distribution of ion current density and its derivative.

3. Results and discussion

Experimental distribution of the plasma density and two temperatures of the electrons were obtained [2, 3] for two current density J_1 =0.26 A/cm^2, J_2 =0.33 A/cm^2 and the following parameters of the thermionic diode: temperature emitter T_E = 915 K, pressure of saturated cesium vapors of the reservoir p_{Cs} =0.44 torr, interelectrode spacing d =0.1 cm. The temperature collector is assumed to be T_C = 600 K.

To construct the distribution of plasma parameters on the phase planes we must calculate their spatial derivatives, so the experimental distribution approximated. We used the following

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approximating functions: for $T_{et}=T_{et}(x)$ – exponential; to $n=n(x)$ – sine; for $T_{et}=T_{et}(x)$, $T_{eg}=T_{eg}(x)$, $n=n(x)$ – polynomial.

Figure 1 shows the experimental distribution of the plasma parameters and their best approximation in the phase plane. Red lines denote the temperature distribution of fast electrons $T_{eg}=T_{eg}(x)$, and black lines – the temperature distribution of slow electrons $T_{et}=T_{et}(x)$. The solid lines meet current density J_1=0.26 A/cm^2, the dotted lines – J_2=0.33 A/cm^2.

Experimental data were obtained [3] in the range 0.15≤x≤0.85 cm, x– distance measured from the emitter. The boundaries of the extrapolation from the emitter marked cross (x), while the collector – a circle (o).

In the following figures notations are similar (if not stated otherwise): the red color is used to indicate the distribution of the plasma parameters obtained with the use $T_{eg}=T_{eg}(x)$, the black – with $T_{et}=T_{et}(x)$; solid lines – J_1, dashed lines – J_2.

The final choice of type of approximation was based on four criteria of fitness: the sum of squared errors (SSE), the square of determination (RS), adjusted R-squared (RSA) and the root of the mean squared error for (RSMSE).

The behavior of all four criteria the fitness was the same for selected approximating functions of distributions $T_{eg}=T_{eg}(x)$ and $n=n(x)$. Therefore, it is a quadratic polynomial for the distribution $T_{eg}=T_{eg}(x)$ the best approximation (figure 1 (b)), and for $n=n(x)$ – sinusoidal dependence (figure 1 (a)). When fitting the experimental data $T_{et}=T_{et}(x)$ the best approach to fitness criteria (exponential dependence) was SSE and RSMSE and a linear relationship was for the remaining two criteria of fitness. Perhaps this is a reflection of the fact that on the one hand the fundamental solution of the heat equation is the exponential function and on the other hand because of the smallness of the IEG solution is actually linearized. In further calculations we used the exponential approximation (see, figure 1 (b)).

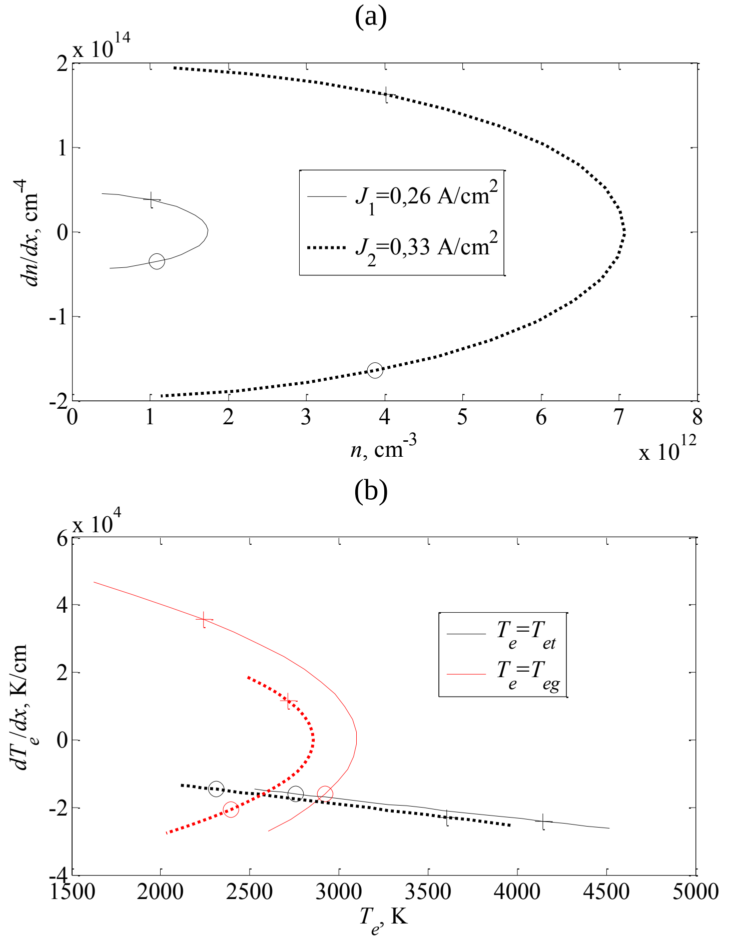

Figure 1. Experimental distribution of the plasma parameters and their best approximation represented in the phase plane. (a) ($n, dn/dx$). (b) ($T_e, dT_e/dx$).

Figure 1 (a) shows that both the density distribution of the plasma current densities are symmetric, their maxima differ by approximately 4 times and they are at the point $x\approx 0.5d$. By increasing the

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current density the temperature distribution $T_{et} = T_{et}(x)$ decreases and the distribution of temperature $T_{eg} = T_{eg}(x)$ increases and these distributions are converging. If the temperature difference is maintained for J_1 (figure 1 (b)) in the range $0.15 \leq x \leq 0.75$ cm then the range is considerably reduced for J_2: $0.15 \leq x \leq 0.35$ cm. Approximation based on both temperatures vary throughout the measuring range (see, figure 1 (b)). By increasing the current density, the plasma density is increased by 3–4 times, respectively, the thermal conductivity of low-energy electron gas increases and the temperature $T_{et} = T_{et}(x)$ decreases.

The size of the electrode sheaths with non-equilibrium plasma is ~ 10^{-3} cm, which it is much less IEG. Relaxation length of the electron energy distribution function for the Maxwell distribution for the electrode of the plasma parameters L_{M1}=0.06 cm is compared with IEG, and it decreases with increasing current density – L_{M2} =0.03 cm. The area of influence of the electron beam from the emitter on the electron energy distribution function takes for J_1 approximately half of the gap, and it decreases almost doubled for J_2. The temperature distribution $T_{et} = T_{et}(x)$ and $T_{eg} = T_{eg}(x)$ differ from each other at the same distances from the emitter (see, figure 1 (a)) for different current densities.

The mean free path of electrons in the atoms Cs l_{ea} varies in the range 0.002 ... 0.006 cm ($l_{ea} \ll d$) and the diffuse arc mode is realized in the gap. The length of the Coulomb scattering of electrons in the Cs ions l_{ei} is to order more l_{ea}, so it does not affect the transport processes in plasma.

The presence of two electron temperature distributions raises the question of their impact on the unmeasured plasma parameters. To answer this question we can use the simulation, but the current models of plasma does not exist. It is possible to evaluate the influence of a distribution on the plasma parameters calculated using experimental data. Using the expression (1), the distribution $J_i = J_i(x)$ is calculated, is constructed and is analyzed the phase curves for the two distributions the temperature electrons $T_{et} = T_{et}(x)$ and $T_{eg} = T_{eg}(x)$.

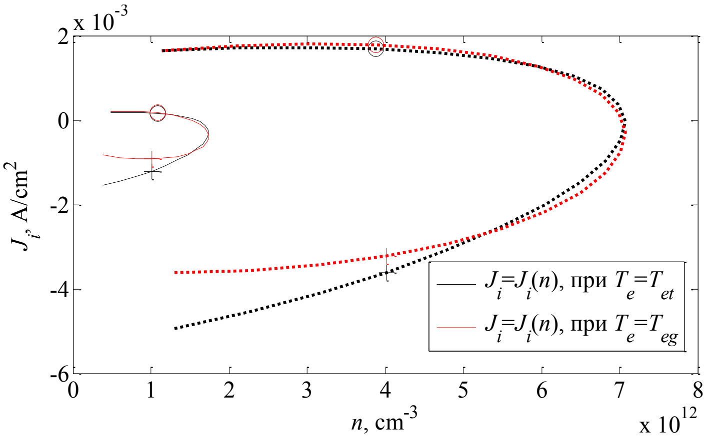

Figure 2. The distribution of plasma parameters are in the phase plane (n, J_i) represented for different densities of the diode current.

Figure 2 shows the distribution of the plasma parameters in the phase plane in the coordinates of the plasma density – the ion current density. The phase curves are of regular and similar for the different densities current of the diode. Constant displacement phase curves $J_i = J_i(n)$ has due to a member of $J\,\mu_{ia}/\mu_{ea} \approx -0.4 \cdot 10^{-3}$ A/cm^2 in the expression (1) for J_i. Thermal diffusion terms in the expression (1) for J_i have little effect on the behavior of the phase curves. The biggest differences for different electron temperature distributions are expressed in the asymmetry of the phase curves $J_i = J_i(n)$ near the electrode sheaths for temperature distribution $T_{et} = T_{et}(x)$.

Analysis of the experimental distributions of plasma parameters showed that the volume recombination is proportional to the square $n/n_{sh}\left(T_{eg}\right)$, around the electrode gap it is small, excepting the area by emitter for J_1.

There is maximum ratio $n/n_{sh}\left(T_{eg}\right)\approx 0.5$ at $x=0$. This behavior is explained by extrapolating $T_{eg}=T_{eg}\left(x\right)$ in this region, where the electron temperature decreases monotonically decreases rapidly and n_{sh}, according to the expression (2) n_{sh} □ $\exp\left(-1/T_{eg}\right)$.

Figure 3 (a) shows the behavior of ion generation functions $\Gamma=\Gamma\left(n,n_a,T_e,x\right)$ on the plane configuration for the two electron temperature distributions. Functions $\Gamma=\Gamma\left(n,n_a,T_{et},x\right)$ in region by emitter are to order more similar functions $\Gamma=\Gamma\left(n,n_a,T_{eg},x\right)$. Furthermore, the function of ion generation for distribution $T_{et}=T_{et}\left(x\right)$ decreases with increasing current density through the diode, but for distribution $T_{eg}=T_{eg}\left(x\right)$ is increasing against. Differentiate depending $J_i=J_i\left(x\right)$ on x (purple curves in figure 3 (b)) also have an increase with the increase J.

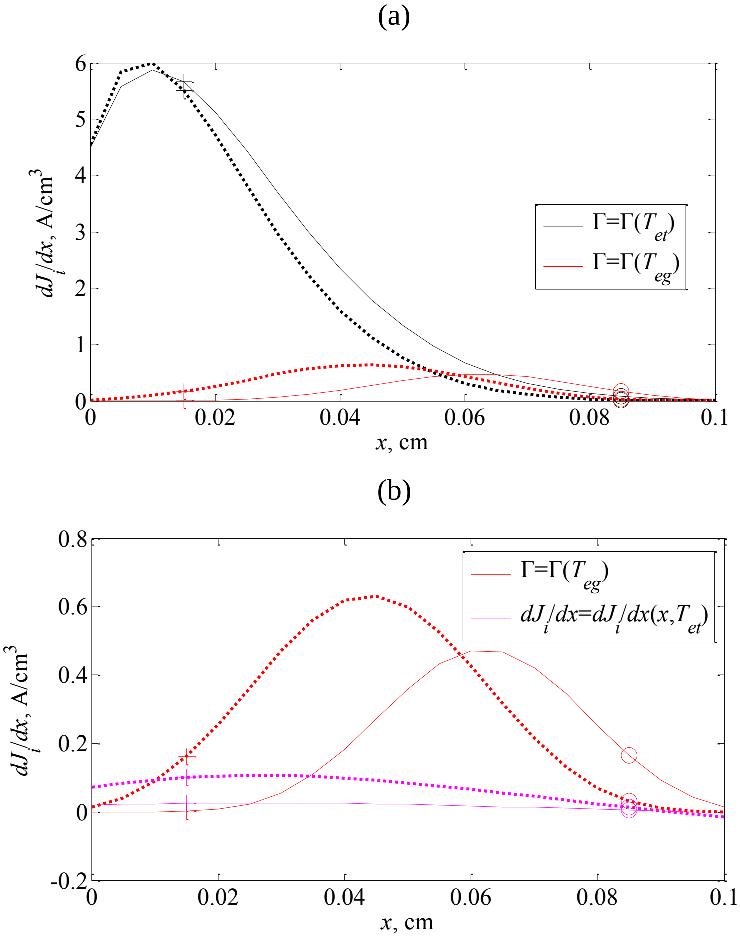

Figure 3. Distribution of ion generation represented in the IEG. (a) for different electron temperature distributions. (b) for the distribution of electron temperature $T_{eg}=T_{eg}\left(x\right)$.

Moreover, the functions $\Gamma=\Gamma\left(n,n_a,T_{eg},x\right)$ and dJ_i/dx are comparable in the value. This difference becomes even less expressed with decreasing cross section of ionization $\sigma=\sigma\left(T_e\right)$, which is typical for the values of the plasma density $n\le 10^{13}\ \text{cm}^{-3}$ [2]. These results confirm the fact that the processes of the volume ionization and recombination are determined by the fast electron temperature $T_{eg}=T_{eg}\left(x\right)$.

4. Conclusion

The results based on the analysis on the phase planes of the influence the two electron temperature distribution types (slow – $T_{et} = T_{et}(x)$ and fast – $T_{eg} = T_{eg}(x)$) on the distribution of unmeasured parameters of the low-temperature plasma cesium thermionic diode allow to draw the following conclusions:

1. Experimental plasma density distributions $n = n(x)$ are almost symmetrical. The maximum $T_{et} = T_{et}(x)$ decreases with increasing current density (increasing the plasma density) distribution and the maximum of the distribution $T_{eg} = T_{eg}(x)$ increases. Thus, the distribution of two types of temperature distributions of electrons converge together.
2. There is significant difference in dependencies $J_i = J_i(n)$ calculated for two types of temperature distributions of electrons in the region close to the emitter.
3. To show the decisive role of the fast electron temperature distributions $T_{eg} = T_{eg}(x)$ by the analysis of the impact on the processes of ion generation in the electrode gap for different types of electron temperature distributions.

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