EFFECT OF SURFACE AND VOLUME IONIZATION ON THE ELECTRODE POTENTIAL DROP

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We consider the change in the potential of the electric field in the "free fall" layer at the electrodes as a function of the characteristics of the surface and the volume ionization. Systematic calculations are made of the electrode potential drop for a tungsten cathode and anode in a lithium and cesium plasma. The potential of the electric field is obtained as a function of the plasma pressure, the degree of volume ionization, the electron temperature, the electrode temperature, and the current density.

The greatest change in potential in a gas discharge occurs near solid surfaces. It is usually assumed that the change in potential is confined to two plasma regions adjacent to the electrodes. In the first zone, immediately adjacent to the metal surface, which has a thickness of the order of the Debye radius (less than the mean free path of the charged particles), there is no quasineutrality, i.e., there is a considerable volume charge. In the second zone, which has a thickness which is considerably greater than the mean free path of the charged particles, quasineutrality is maintained. In the quasineutral region the change in the potential of the electric field can be calculated by solving the usual equations of plasma dynamics of the hydrodynamic type. The change in potential in the free-fall layer immediately adjacent to the electrodes must be calculated taking into account the specific features of the collisionless motion of the particles in the electric field.

Below we investigate the potential drops adjacent to the electrodes in the collisionless layer. The problem of the particle fluxes is solved approximately. The investigation is made for electrodes which have a negative potential with respect to the adjacent plasma volume. The case of electrodes with positive potential requires a more complex consideration in order to obtain the necessary expressions for the electron flux. Moreover, calculations show that a positive value of the electrode potential exists in a comparatively small range of variation of the discharge parameters.

We will assume that the temperature of the heavy particles in the space-charge layer is equal to the temperature of the electrode surface. The potential in the layer adjacent to the electrode must be found from the following equations [1, 2]:

$$j = j_e + j_i$$

$$j_e = \frac{\xi_{es}^-}{4} e n_{es} v_{es} \exp\left[-\frac{e\Delta U_w}{kT_{es}}\right] - j_w, \quad j_i = -\frac{\xi_{is}^-}{4} e n_{is} v_{is} + \frac{\xi_{is}^+}{4} e n_{is} v_{is} \tag{1}$$

$$j_w = A_0 T_w^2 \exp\left[-\frac{e\varphi_w - e\sqrt{eE_w}}{kT_w}\right], \quad p = k n_{es}\left(T_e + \frac{1}{\alpha_s} T_w\right)$$

Here j is the discharge current density (the direction away from the electrode is taken as the positive current direction); j_e and j_i are the densities of the current components due to motion of the electrons and ions respectively; j_w is the thermionic current density; p is the pressure; n_{es} and n_{is} are the particle densities; v_{es} and v_{is} are the thermal velocities of the particles; T_w is the surface temperature; ΔU_w is the potential difference between the plasma of the boundary layer of the space charge (s) and the electrode

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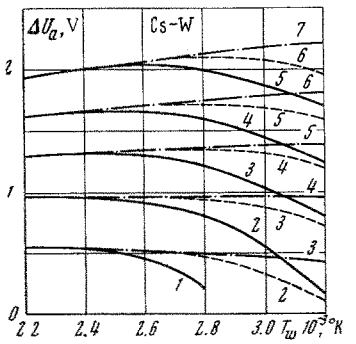

Fig. 1

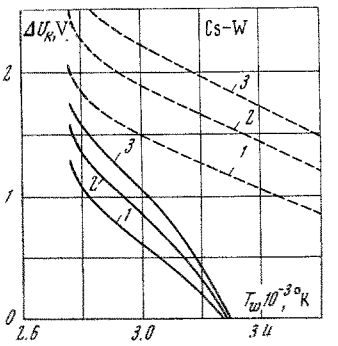

Fig. 2

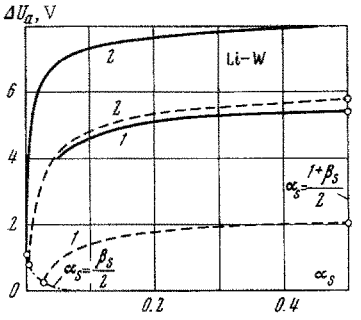

Fig. 3

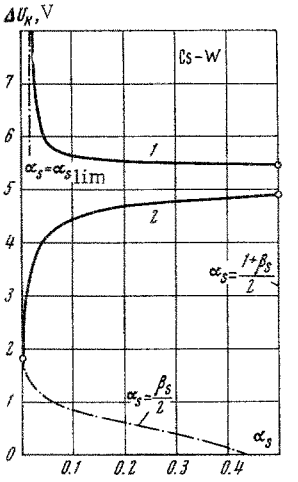

Fig. 4

(w); α_s is the degree of volume ionization; e is the absolute value of the electron charge; E_w is the electric field intensity on the surface; k is Boltzmann's constant; ξ^-_{es}, ξ^-_{is}, ξ^+_{is} are correction factors (the subscript s denotes the value of quantities on the external free fall boundary layer; the minus sign corresponds to particle motion from the plasma to the electrode, and the plus sign denotes motion of the particles from the electrode to the plasma), approximate expressions for which can be obtained by considering the particle balance on the external boundary (s) of the free-fall layer:

$$\xi^-_{es} = \frac{2 - j_w/(1/4\, en_{es}v_{es})}{2 - \exp[-e\Delta U_w/kT_{es}]}, \quad \xi^-_{is} = 2 - \frac{\beta_s}{\alpha_s}, \quad \xi^+_{is} = \frac{\beta_s}{\alpha_s} \tag{2}$$

$$\beta_s = \frac{\exp[-e\Delta U_w/kT_w]}{(1/\beta_w) - 1 + \exp[-e\Delta U_w/kT_w]}, \quad \beta_w = \frac{\alpha^*}{1+\alpha^*}, \quad \alpha^* = A_i \exp\left[\frac{e(\varphi_i - V_i)}{kT_w}\right] \tag{3}$$

In these expressions β_s is the effective surface ionization coefficient, referred to the conditions on the boundary; β_w is the surface ionization coefficient of the atoms on the electrode; α^* is the degree of surface ionization; V_i is the ionization potential of the atoms; A_i and φ_i are the parameters in the Saha-Langmuir formula [1].

In the limiting cases the flux of heavy particles which travels to the electrode through the surface s may consist of either atoms only or ions only, so that the degree of volume ionization α_s varies in the limits

$$1/2\beta_s \leqslant \alpha_s \leqslant 1/2(1+\beta_s) \tag{4}$$

To determine the potential drop adjacent to the electrode the basic formulas, which follow from (1)-(3), are

$$K = \frac{1}{L}\left[2\left(kT_e + \frac{1}{\alpha_s}kT_w\right)\left(\frac{j+j_w}{e}\right) + p\left(1 - \frac{\beta_s}{\alpha_s}\right)\left(\frac{8}{\pi}\frac{kT_w}{m_i}\right)^{1/2}\right]$$
$$L = p\left(\frac{8}{\pi}\frac{kT_e}{m_e}\right)^{1/2} - 2\left(kT_e + \frac{1}{\alpha_s}kT_w\right), \quad \Delta U_w = -kT_e \ln\frac{2K}{1+K} \tag{5}$$

Here T_e is the electron temperature, and m_e and m_i are the electron and ion masses. In the case of an alkali-element plasma and glowing high-melting point electrodes when surface ionization can affect the value of ΔU_W, the calculation is carried out using Eqs. (3) and (5), for example, by iteration.

Figures 1-4 show the values obtained for ΔU_W, using the thermionic emission and surface ionization characteristics taken from [3-9], for tungsten electrodes, ignoring the Schottky effect.

Figure 1 shows potential drop ΔU_a adjacent to the anode as a function of T_W (°K), the pressure of the cesium plasma (curves 1, 2, 3, 4, 5, 6, 7 correspond to $p = 10, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7$ μbars), and the discharge current density j (j = 3, 30, 300 A/cm^2 are for the continuous, dashed, and dot-dash lines, respectively) for an electron temperature $T_e = 5000$°K and $\alpha_s = {}^1/_2\,\beta_s$. For a given temperature T_W the value of ΔU_a increases with p and falls as j increases. It should be noted that the change in the sign of ΔU_a occurs in the region of high T_W, low T_e, and large j. It is easy to show that as α_s increases, the value of ΔU_a will increase.

Figure 2 shows the potential drop adjacent to the cathode ΔU_k as a function of T_W, the pressure of the cesium plasma p (the continuous lines are for $p = 10^2$ μbars, and the dashed lines are for $p = 10^4$ μbars), and T_e (curves 1, 2, 3 correspond to $T_e = 5{,}000$, 10,000, and 20,000°K) for $j = -3$ A/cm^2 and $\alpha_s = {}^1/_2\,\beta_s$. As T_W increases the value of ΔU_k on the graph falls, while an increase in T_e and p produces an increase in ΔU_k. The potential difference ΔU_k adjacent to the electrode changes sign in the region of high electrode temperatures and low plasma pressures.

Figure 3 shows the change in ΔU_a as a function of α_s, the pressure of a lithium plasma p (curves 1 and 2 correspond to $p = 10^2$ and 10^3 μbars), and j (the continuous lines are for j = 3 and the dashed lines are for j = 30 A/cm^2, respectively) for $T_W = 2600$°K. The quantity α_s takes limited values as given by inequality (4). As α_s increases, the value of ΔU_a also increases, in the region of low values of α_s quite strongly, and for $\alpha_s \gtrsim 0.1$ negligibly. An increase in p and a reduction in j lead to an increase in ΔU_a, as in the case of a cesium plasma.

Figure 4 shows ΔU_k as a function of α_s for cesium plasma and T_W, for $p = 10^4$ μbars and $j = -3$ A/cm^2. The temperature $T_W = 2400$°K (curve 1) corresponds to $j_W < |j|$, and $T_W = 3000$°K (curve 2) corresponds to $j_W > |j|$. The nature of the change in ΔU_k as a function of α_s for $T_W = 3000$°K ($j_W > |j|$) is the same as for ΔU_a (Fig. 3). In the first case ($j_W < |j|$) as α_s increases, the potential drop adjacent to the cathode ΔU_k falls. The lower limit of α_s is given by $\lim \alpha_s \approx 1.91 \cdot 10^{-2}$, below which ΔU_k, according to the analytical relationships, increases without limit. For $\alpha_s < \lim \alpha_s$ the number of ions reaching the cathode becomes insufficient to supplement the thermionic emission current up to the given discharge current.

The above investigation has shown the relationship between the potential drop adjacent to the electrodes and the volume and surface ionization. The relations which have been obtained between the potential drop ΔU_W and the degree of volume ionization α_s and the coefficient of surface ionization β_W should be borne in mind when designing and analyzing plasma devices.

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