FIELD EMISSION OF ELECTRONS INTO A PLASMA

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The expressions in [1-3] are normally used to calculate the current density at the cathode in an arc discharge with field emission of electrons. However, these expressions for the field-emission current density into a vacuum assume that the electric field near the cathode is constant. It frequently happens in an arc discharge that there is a layer in front of the cathode where the ion space charge is not balanced out. The potential variation then becomes highly nonlinear and the shape of the potential barrier near the cathode and the transmittance of this barrier are significantly altered. There is a change in the current density of the emitted electrons which pass through this barrier.

The potential distribution in the cathode region of an arc discharge is usually obtained from a solution of Poisson's equation and the use of the Langmuir and McCown assumptions. When the ion density in the layer n_+ is greater than the electron density n_- ($n_+ \gg n_-$), i.e., when the ratio of the ion to the electron current densities (j_+/j_-) is almost equal to unity, the potential distribution is of the form

$$V_1 = -V_c + \left(V_c^{3/4} - \frac{3}{4}\frac{E_c}{V_c^{1/4}}x\right)^{4/3}, \tag{1}$$

where V_c is the cathode potential drop, x is the distance from the cathode, and E_c is the electric field at the cathode.

Using (1), we get the following expression for the potential barrier at a metal—plasma boundary:

$$V_2 = \varphi - e/4x - V_c + \left(V_c^{3/4} - \frac{3}{4}\frac{E_c x}{V_c^{1/4}}\right)^{4/3}.$$

We note that for field emission into a vacuum the potential barrier has the form

$$V_2' = \varphi - e/4x - eE_c x,$$

where φ is the work function.

The potential distributions for $V_c > \varphi$; $V_c = \varphi$; and $V_c < \varphi$ are shown in Fig. 1; the dashed lines give the potential barrier for emission into a vacuum and the continuous lines, the barrier at a metal—plasma boundary.

We will calculate the transmittance of the barrier Q, following [4, 5]. For simplicity, in the first approximation we neglect the term e/4x in order to emphasize more strongly the difference between electron emission into a vacuum and emission into a plasma. When the e/4x term is included, the expressions for the barrier transmittance Q have the following forms for $V_c > \varphi$, $V_c = \varphi$, and $V_c < \varphi$:

$$Q_1 = \frac{2\pi\sqrt{2m}}{h}\frac{4V_c}{3E_c}\sqrt{V_c - \varphi}\,\alpha_1(a_1; b_1),$$

$$Q_2 = \frac{2\pi\sqrt{2m}}{h}\frac{4V_c^{3/2}}{3E_c}\alpha_2(b_2),$$

$$Q_3 = \frac{2\pi\sqrt{2m}}{h}\frac{4V_c}{3E_c}\sqrt{\varphi - V_c}\,\alpha_3(a_1; b_1),$$

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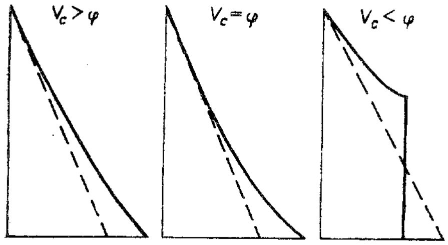

Fig. 1

where

$$\alpha_1 = \int_{t_1}^{t_2} \sqrt{a_1(1-t)^{4/3} - \frac{b_1}{t} - 1}\, dt;$$

$$\alpha_2 = \int_{t_1}^{t_2} \sqrt{(1-t) \quad - \frac{b_2}{t}}\, dt;$$

$$\alpha_3 = \int_{t_1}^{t_2} \sqrt{1 + \frac{b_1}{t} - a_1(1-t)^{4/3}}\, dt;$$

$$a_1 = V_c/V_c - \varphi;\ b_1 = 3eE_c/4V_c\ (V_c - \varphi);\ b_2 = 3eE_c/4V_c^2.$$

Knowing Q, we can find the current density j_{F-P}:

$$Q = \frac{2\pi\sqrt{2m}}{h} \int_0^{x_2} \sqrt{\varphi - V_c + \left(V_c^{3/4} - \frac{3}{4}\frac{E_c x}{V_c^{1/4}}\right)^{4/3}}\, dx, \tag{2}$$

where x_2 is defined by the expression

$$x_2 = \left[V_c - V_c^{1/4}(V_c - \varphi)^{3/4}\right] \frac{4}{3E_c} \quad \text{for} \quad V_c > \varphi$$

or $x_2 = (4/3)V_c/E_c$ for $V_c \leqslant \varphi$.

We consider three cases in the evaluation of (2).

1. $V_c > \varphi$; then

$$Q = \frac{2\pi\sqrt{2m}}{h}\frac{V_c^{1/4}}{E_c}(V_c - \varphi)^{5/4} \int_0^{\frac{\varphi}{V_c - \varphi}} t^{1/2}(1+t)^{-1/4} dt = \frac{V_c^{1/4}}{E_c}(V_c - \varphi)^{5/4} \frac{2\pi\sqrt{2m}}{h}\left(\frac{\varphi}{V_c - \varphi}\right)^{3/2} \frac{2}{3}\, {}_2F_1\left(1/4;\ 3/2;\ 5/2;\ -\frac{\varphi}{V_c - \varphi}\right),$$

where ${}_2F_1[{}^1/_4,\ {}^3/_2,\ {}^5/_2,\ -\varphi/(V_c - \varphi)]$ is the Gauss hypergeometric function. Knowing the transmittance of the potential barrier, we can determine the current density of the field emission into the plasma j_{F-P}. Figure 2a shows how j_{F-P} varies with E_c for φ = 4.5 V and V_c = 10, 15, 20, and 30 V; Fig. 2b gives the results for φ = 4 V and V_c = 10, 15, 20, and 30 V.

2. $V_c = \varphi$. In this case (2) simplifies to

$$Q = \frac{4}{5}\frac{2\pi\sqrt{2m}}{h}\frac{\varphi^{3/2}}{eE_c}.$$

The expression for the current density j_{F-P} is now:

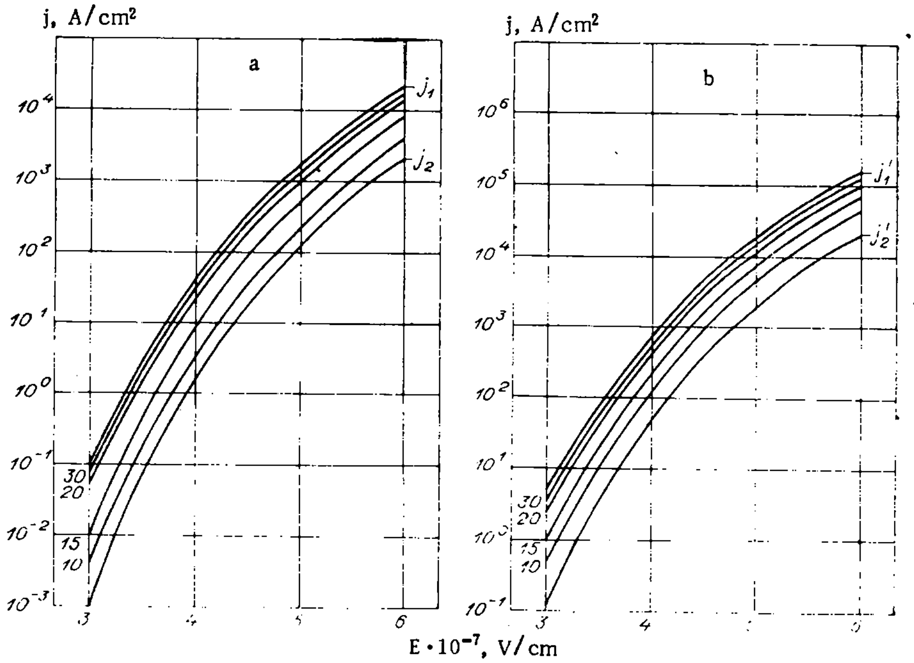

Fig. 2

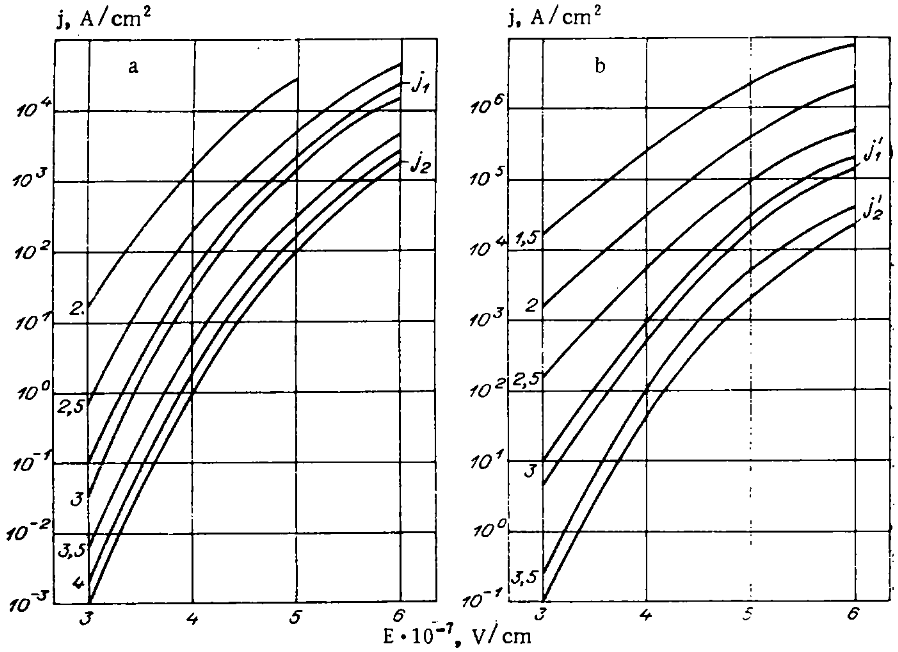

Fig. 3

$$j_{F-P} = \frac{1.55 \cdot 10^{-6} E^2}{\varphi} \exp\left[-1.2 \frac{6.85 \cdot 10^7 \varphi^{3/2}}{E_c}\right], \tag{3}$$

whereas the expression for the current density of the field emission into a vacuum j_F is

$$j_F = \frac{1.55 \cdot 10^{-6} E^2}{\varphi} \exp\left[-\frac{6.85 \cdot 10^7 \varphi^{3/2}}{E_c}\right]. \tag{4}$$

Graphs of (3) and (4) are given in Fig. 2a and b (the curves j_2 and j_2', j_1 and j_1'). It can be seen that the current densities j_{F-P} and j_F can differ by more than an order of magnitude for the same values of φ and E_c.

3. $V_c < \varphi$; then

$$Q = \frac{2\pi\sqrt{2m}}{h}\frac{(\varphi - V_c)^{5/4}V_c^{1/4}}{E_c}\int\limits_0^{\frac{V_c}{\varphi - V_c}}\frac{\sqrt{1+t}}{t^{1/4}}\,dt =$$

$$= \frac{2\pi\sqrt{2m}}{h}\frac{(\varphi - V_c)^{5/4}V_c^{1/4}}{E_c}\,{}_2F_1\left(-1/2;\,3/4;\,7/4;\,-\frac{V_c}{\varphi - V_c}\right).$$

As in case 1, knowing Q, we can determine the current density of the field emission into a plasma j_{F-P}.

Figure 3a shows how the current density j_{F-P} varies with E_c for φ = 4.5 V and V_c = 4, 3.5, 3, 2.5, and 2 V; Fig. 3b gives the results for φ = 4 V and V_c = 3.5, 3, 2.5, 2, and 1.5 V.

We note, in conclusion, that when $V_c \geqslant \varphi$, the current density of the field emission into a plasma j_{F-P} must be smaller than the current density into a vacuum, and it approaches its minimum value defined by (3) as V_c tends to φ. When $V_c < \varphi$, the current density j_{F-P} can be either smaller or greater than j_F.

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EXPERIMENTAL INVESTIGATION OF THE PLASMA IN A MULTICHANNEL CATHODE

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In electroplasma accelerators and plasma sources, hollow cathodes are finding applications [1, 2]. One of the possible variations of their application is the multichannel cathode [3, 4]. Although at the present time there are a considerable number of papers on the single-channel hollow cathode [3-6], the physical conditions in a multichannel cathode remain unstudied; this is due to the difficulties in determining the plasma parameters in channels of small cross section, the high temperature of the working surface, and the high density of the plasma. The problem concerning the magnitudes of the pressure, concentrations, and temperature, degree of ionization of the plasma, and the dependence of these parameters on the discharge current remains unexplained. While the existing experimental data on the single-channel cathode are attributed predominantly to a plasma of different gases, the alkali metals also offer practical interest as working substances.

In this paper the parameter of a plasma in the hollow multichannel cathode of a coaxial plasma source with a power of 7 kW, operating on lithium, are studied. An experimental investigation is carried out, based on the use of a special optical system of observation behind the plasma in the discharge section of the channel.

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