PROPERTIES OF A METAL–PLASMA CONTACT

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It is shown from an analysis of experimental data that the effective work function of a metal in the presence of a plasma is lower than the value in vacuo.

A study of electrode processes in a distributed (noncontracted) arc discharge in various media (inert gases, alkali metals) [1-7] shows that in the presence of a plasma the effective work function of a metal is reduced by a significant amount (in comparison with the vacuum value φ_w). The same conclusion is reached from an analysis of the balance relations on an electrode surface.

The current balance equation at an electrode surface (cathode and anode) can be written as

$$j_w = j_e^e + j^i - j^e \exp\left[-eU / kT\right] \tag{1}$$

Here j_w is the experimentally measured current density at the electrode, j_e^e is the electron current density emitted from a heated electrode, j^i and j^e are the random electron and ion current densities from the plasma as calculated from the plasma parameters at the boundary of the electrode potential-drop layer (whose thickness is of the order of the Debye length r_D), U is the change in potential across this layer, T is the plasma electron temperature, and e is the electron charge. We consider the case where the plasma potential is higher than the electrode potential by an amount U, so the ions move freely to the electrode but the electrons are partially decelerated. This effect is shown in the last term of (1).

The energy balance at the electrode surface can be represented as

$$q_w + j_e^e \varphi = j^i \left(U + U_i - \varphi + 2\frac{k}{e}\Delta T_i\right) + j^e \exp\left(-\frac{eU}{kT}\right)\left(\varphi + 2\frac{k}{e}\Delta T_e\right) + q \tag{2}$$

Here q_w is the thermal flux from the electrode due to cooling, U_i is the ionization energy of the working substance, ΔT_i and ΔT_e are the differences between the ion and electron temperature and the electrode temperature, φ is the work function, q is the thermal flux which flows from the plasma to the electrode as a result of radiation and the presence of a neutral component, and k is Boltzmann's constant.

In the experiments, the current j_e^e is caused entirely by thermionic emission, i.e.,

$$j_e^e = AT_w^2 \exp\left(-\frac{e\varphi}{kT_w}\right) \tag{3}$$

Here A is the Richardson constant and T_w is the electrode temperature.

An analysis of experimental data on cathodes [1-4] shows that if (3) is used with the value of φ taken as the vacuum work function φ_w, then the left side of (1) is one or two orders of magnitude (and sometimes even more) greater than the right side. A similar effect is observed with anodes [5-7] except that the right side is now greater than the left. The situation is similar for (2).

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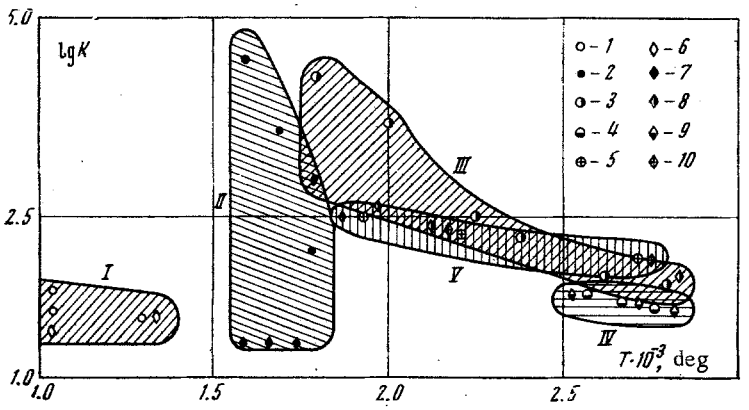

Fig. 1

This lack of balance in (1) and (2) is eliminated if φ is reduced by about 1 eV (the plasma temperatures in the various experiments were at the level T ~ 1 eV and the pressures p ~ 1-10^2 mm Hg). The anomalously high thermal emission cannot be explained by the formation of films on the electrode surfaces reducing the work function because the effect is observed not only with alkali metals; but also with inert gases; moreover, at electrode temperatures T_W ~ 3000°K and pressures of 1-10^2 mm Hg the probability of effective films occurring is small. It has also proved impossible to explain the lack of agreement by the hollow-cathode effect or experimental errors.

It is assumed that the electron work function from a metal to vacuum φ_W is the sum of two terms, each of which can be considered separately [8, 9]. The first term φ_{W_1}, is determined by processes which take place in the volume of the metal and the second term φ_{W_2}, by surface effects. The potential outside the metal in the vacuum is taken to fall off as 1/r (image forces [10]).

By analogy with a metal we can define the work function of a plasma φ_P, i.e., the work which must be done in taking an electron from the plasma into a vacuum $\varphi_P = \varphi_{P_1} + \varphi_{P_2}$.

The quantity φ_{P_1} can be represented in the form [11] $\varphi_{P_1} = \gamma kT/e$, where T is the plasma temperature, and γ is the 'imperfection' coefficient $\gamma = e^2/r_D kT$.

It is difficult to determine the quantity φ_{P_2} since it depends on the nature and properties of the surface which bounds the plasma. In the particular case where the plasma is confined by a magnetic field, we have [12] $\varphi_{P_2} = kT/e$. The value of φ_{P_2} depends on the polarizing forces acting on the plasma surface. We can show from energy considerations that φ_{P_2} ~ kT/e. So to a first approximation we can write

$$\varphi_P = (\gamma + 1) T \frac{k}{e} \tag{4}$$

The potential distribution at a plasma–vacuum boundary will be the same as for a metal–vacuum boundary.

We consider the potential distribution at a metal–plasma contact by analogy with metal–metal, metal–semiconductor, and semiconductor–semiconductor contacts. Two cases are possible [13]: a) the zero levels in the potential distribution coincide when the contacting bodies are at a distance d from each other; b) the chemical potential levels coincide when the contacting bodies are sufficiently close to each other ('close' contact).

In case a) an electron passing from the metal to the plasma must overcome a potential barrier whose height (effective work function) is

$$\varphi = \varphi_w - e/d \tag{5}$$

For a b) contact the potential barrier (or work function) is equal to

$$\varphi = \varphi_w - \varphi_P \tag{6}$$

Figure 1 shows the results of a comparison between thermionic current-density data obtained experimentally and values calculated from (3) and (6); K (the anomaly coefficient) is the ratio of the current density (experimental or calculated) to the values derived from (3) with $\varphi = \varphi_W$.

The shaded region I is a comparison between the experimental results 1 and calculated values 2 from [1]. Region II is for 3 and 4 from [3]; III for 5 and 6 from [2]; IV for 7 and 8 from [4]; V for 9 and 10 from [5, 7]. It can be seen that for low electrode temperatures there is a large discrepancy between theory and experiment. This is because surface films have a strong effect on the potential barrier at low temperatures. At high temperatures ($T_w > 2000°K$), when there is little probability of films being formed, the values calculated from (3) and (6) are in satisfactory agreement with the experimental results.

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