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Modeling of the effect of temperature and field-induced electron emission from the cathode with a thin insulating film on the Townsend discharge ignition voltage in argon–mercury mixture

G.G. Bondarenko [a], M.R. Fisher [b], V.I. Kristya [b, *]

[a] National Research University Higher School of Economics (HSE), Myasnitskaya St. 20, Moscow, 101000, Russia
[b] Bauman Moscow State Technical University, Kaluga Branch, Bazhenov St. 2, Kaluga, 248000, Russia

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ABSTRACT

A model of the low-current (Townsend) discharge in argon–mercury mixture in the presence of a thin insulating oxide film on the cathode is developed. It takes into account the cathode ion-electron emission and the electron emission from the cathode metal substrate under the strong electric field generated in the film by the ion surface charge. An influence of the mixture temperature and the oxide film on the discharge ignition voltage is estimated and it is shown that formation of a thin insulating film on the cathode surface can facilitate the discharge ignition in mercury-containing gas discharge devices at low temperatures.

1. Introduction

An important characteristic of gas discharge devices, such as arc illuminating lamps, is their ignition voltage V_b equal to the minimum voltage between the electrodes, ensuring the gas breakdown in the inter-electrode gap and initiation of the low-current (Townsend) discharge, which can then transit into the glow and arc modes [1,2]. The discharge ignition voltage is determined by the processes of electron emission from the cathode and ionization of the background gas atoms in the discharge volume. They are characterized by the cathode effective secondary electron emission yield γ_{eff} equal to the average number of emitted electrons per an incident ion and the ionization coefficient α equal to the average number of gas atom ionizations per an electron per a unit discharge length, respectively.

In many types of illuminating lamps the argon–mercury mixture is used as the background gas with the constant argon density n_{Ar} and the mercury vapor density n_{Hg} increasing with the mixture temperature T [3–7]. When the current flows in it, ionization of mercury atoms in collisions with argon metastable excited atoms occurs (the Penning reaction) in addition to the direct ionization of atoms of the both gases by electrons [3,4]. This results in an increase of the gas ionization coefficient and a decrease of the discharge ignition voltage in comparison with that in pure argon. However, when the temperature T is decreased, a substantial reduction of the mercury density and, consequently, the ionization coefficient value takes place, followed by an increase of the discharge ignition voltage, complicating the lamp turning on [8,9]. Such reduction of the ionization coefficient α may be compensated by an increase of the effective secondary electron emission yield γ_{eff} of the cathode, which can be achieved by formation of a thin insulating film on its surface. When the current flows in the inter-electrode gap, positive charges are accumulated on the film and generate the electric field in it, sufficient for the electron emission from the cathode metal substrate [10–12]. Emitted electrons are accelerated by the field to the film outer surface and, reaching it, neutralize the positive surface charges, so that the steady discharge mode is established. A fraction of the electrons overcomes the potential barrier at the film boundary and goes out into the discharge volume, increasing γ_{eff}. It was shown by many authors that field electron emission is important for discharge ignition and sustaining in micrometer-size gaps between the metal electrodes [13–17], and the presence of dielectric inclusions on the cathode surface facilitates transition of glow discharge into arc due to enhanced electron emission from them [18,19]. However, an

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* Corresponding author.
E-mail address: kristya@bmstu-kaluga.ru (V.I. Kristya).

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influence of this factor on the gas breakdown and the low-current discharge characteristics was not studied yet.

In this work, a model of the low-current discharge in argon–mercury mixture in the presence of a thin insulating film on the cathode surface is developed, and the effect of temperature and electron emission from the cathode metal substrate on the discharge ignition voltage is estimated.

2. Mathematical model

Let the low-current discharge is initiated in the gap between the anode surface $z = 0$ and the cathode surface $z = d$, filled with the argon–mercury mixture of density $n = n_{\mathrm{Ar}} + n_{\mathrm{Hg}}$, and a thin insulating film of thickness H_f exists on the cathode (see Fig. 1). Due to rather small current density, the electric field strength is constant along the gap [1] and equals to $E = V_d/d$, where V_d is the discharge voltage drop across the gap.

Under bombardment of the cathode by ions, accelerated in the discharge, with the current density j_i, the electron emission from the film surface occurs with the current density $j_{ei} = \gamma_i j_i$, where γ_i is the cathode ion-induced secondary electron emission yield. As a result, positive charges are accumulated on the film, generating the electric field of strength E_f in it. When E_f reaches value of the order of 10^8–10^9 V $\cdot \mathrm{m}^{-1}$, the field-induced electron emission from the metal substrate into the film starts. Contributions in it, depending on the E_f magnitude, can make different mechanisms (trap-assisted tunneling, Frenkel–Poole hopping and Fowler–Nordheim tunneling) [20–25], and its macroscopic current density grows rapidly with E_f, so that $j_f = s_f f(\beta E_f)$, where s_f is the fraction of the film-substrate boundary, which emits electrons due to local enhancement of the electric field strength on it, β is the field enhancement factor.

The emitted electrons move to the film outer boundary and neutralize the positive surface charges on it, whereas a fraction δ_f of them goes out of the film, producing an additional electron current with the current density $j_{ef} = \delta_f j_f$. Therefore, the electron current density from the cathode surface equals to $j_e = j_{ei} + j_{ef} = \gamma_{eff} j_i$, where $\gamma_{eff} = \gamma_i + \gamma_f$, $\gamma_f = j_{ef}/j_i$, the total discharge current density is:

$$j = j_i + j_e = \left(1 + \gamma_{eff}\right) j_i \tag{1}$$

From expressions for γ_{eff}, γ_f, j_{ef} and j the formula follows:

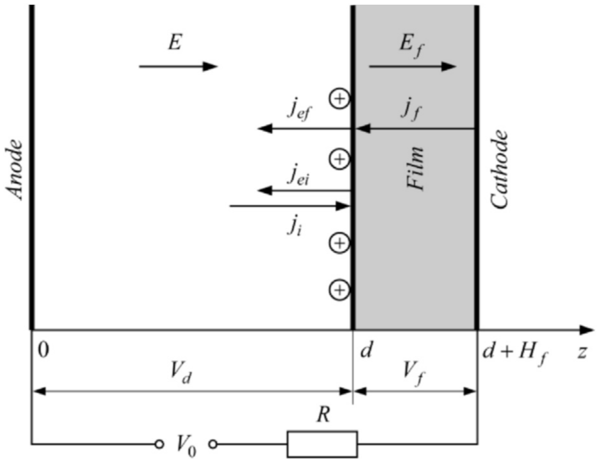

Fig. 1. Schematic of the discharge geometry.

$$\gamma_{eff} = \left(\gamma_i + \delta_f\right) / \left(1 - \delta_f\right), \tag{2}$$

which shows that the influence of the field-induced electron emission from the substrate on the cathode effective secondary electron emission yield and, consequently, on the discharge characteristics is determined completely by parameter δ_f, which value can depend on the film material and structure, as well as on H_f and E_f.

For calculation of the mixture ionization coefficient α in the discharge gap, a hybrid model of the low-current discharge, described in Refs. [26], [27], is used. In this model, simulation of the electron motion is carried out on the basis of the Monte Carlo method, whereas the ion and metastable excited atom motion is described by their transport equations. As a result, the electron velocity distribution function $f_e(z,v,v_z)$ is found, where v and v_z are the electron velocity and its z − component. Then the mixture ionization coefficient α in the gap is calculated as the sum of the ionization coefficients of argon atoms and mercury atoms by electrons and the ionization coefficient of mercury atoms by argon metastables:

$$\alpha(z) = \alpha_{Ar}(z) + \alpha_{Hg}(z) + \alpha_{Pen}(z), \tag{3}$$

where

$$\alpha_{Ar}(z) = \iint n_{Ar} \sigma_{iAr}(v) f_e(z, v, v_z) v \, \mathrm{d}v \, \mathrm{d}v_z / J_e(z),$$

$$\alpha_{Hg}(z) = \iint n_{Hg} \sigma_{iHg}(v) f_e(z, v, v_z) v \, \mathrm{d}v \, \mathrm{d}v_z / J_e(z),$$

$$\alpha_{Pen}(z) = k_{Pen} n_{Hg} n_{Ar^*} / J_e(z),$$

$$J_e(z) = -\iint f_e(z, v, v_z) v_z \, \mathrm{d}v \, \mathrm{d}v_z,$$

$\sigma_{iAr}(v)$ and $\sigma_{iHg}(v)$ are the cross sections of argon and mercury atom electron ionization, respectively, n_{Ar^*} is the argon metastable excited atom density, k_{Pen} is the constant of the Penning ionization reaction [4,26].

The condition of low-current discharge self-sustaining in the inter-electrode gap has the form [1]:

$$\int_0^d \alpha(z) dz = \ln\left(1 + 1/\gamma_{eff}\right), \tag{4}$$

and the discharge current density can be found from equation

$$V_b + RjS = V_0, \tag{5}$$

where $V_b = V_d + V_f$, $V_f = E_f H_f$ is the voltage drop across the film, S is the cathode surface area occupied by the discharge, V_0 is the applied external voltage, R is the ballast resistor, which value is chosen such as to ensure sufficiently low discharge current density [1].

Eqs. (1)–(5) form a system, from which the low-current discharge characteristics can be found.

3. Results and discussion

Calculations have been performed for the discharges in pure argon and in argon–mercury mixture in cases of the aluminum cathode with a monolayer of aluminum oxide on its surface (i.e. in the absence of the insulating film) and the aluminum cathode with an aluminum oxide film of thickness $H_f = 10$ nm. The following