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Modeling of the effect of field electron emission from the cathode with a thin insulating film on its emission efficiency in gas discharge plasma

G.G. Bondarenko [a], V.I. Kristya [b,*], D.O. Savichkin [b]

[a] National Research University Higher School of Economics, 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 field electron emission from the metal cathode with a thin insulating film under the strong electric field, generated in the film by ions bombarding its surface in gas discharge, is developed. It takes into account tunneling of electrons from the electrode metal substrate into the insulating film, their motion in the film and going out of it into the discharge volume. An analytical solution of the one-dimensional kinetic equation for the energy distribution function of emitted electrons in the film conduction band is found and an expression for the film emission efficiency equal to the fraction of emitted electrons, which escapes from the film and increases the cathode effective secondary electron emission yield, is obtained. It is demonstrated that calculated dependence of the emission efficiency on the electric field strength in the aluminum oxide film is in an agreement with experimental data for metal-insulator-metal tunneling cathodes. The proposed model can be used for investigation of an influence of the field electron emission from the cathode with a thin insulating film on its emission characteristics in gas discharge devices.

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1. Introduction

An important characteristic of gas discharge devices, such as arc illuminating lamps and gas lasers, is the ignition voltage. Its reduction results in a decrease of power consumption by the device and in an increase of its service time due to less intensive sputtering of the electrodes. The ignition voltage depends considerably on the cathode effective secondary electron emission yield γ_{eff} equal to the average number of emitted electrons per an ion falling on the cathode from the discharge plasma [1–3]. If a thin insulating film exists on the cathode, then due to its bombardment by ions the electron emission from the film surface occurs, characterized by the cathode ion-induced secondary electron emission yield γ_i. As a result, positive charges are accumulated on the film surface, which generate the electric field in the insulator, sufficient for the field electron emission from the cathode metal substrate into the film [4,5]. Emitted electrons are accelerated by the field in the direction of the film outer surface and, reaching it, neutralize positive surface charges, preventing their further accumulation. A fraction δ_f of them can go out of the film, producing an additional electron current. This results in an increase of γ_{eff}, which in this case is determined by formula $\gamma_{eff} = (j_{ei} + j_{ef})/j_i = (\gamma_i + \delta_f)/(1 - \delta_f)$ [6], where j_{ei}, j_{ef} and j_i are the ion-induced electron current density, the additional electron current density, caused by field electron emission from the cathode metal substrate, and the ion current density at the cathode, respectively. It follows from this formula that an influence of the field 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 is called the film electron emission efficiency [7]. Its magnitude depends on the electric field strength in the film, as well as on film material and structure.

The electron emission efficiency of thin insulating films was studied experimentally [7–10] and theoretically (without taking into account energy losses of electrons in the film) [11] for metal-insulator-metal structures used in microelectronics. However, simulations of the electron transport in thin insulating films on the cathodes of gas discharge devices, in which the function of one of the electrodes is performed by the discharge plasma, were not fulfilled yet.

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

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In this work, a model describing the field emission of electrons from the electrode metal substrate into the insulating film, their motion in the film and escaping from it into the discharge volume is developed. An analytical expression for the film emission efficiency is obtained, taking into account its dependence on the film parameters and discharge conditions.

2. Mathematical model

Let a thin insulating film of thickness H_f exists on the flat cathode. Under its bombardment by ions, positive charges are accumulated on the film surface and the electric field of strength E_f is generated in the film. We assume that coordinate z is directed perpendicular to the cathode surface, the boundary between the cathode metal substrate and the film is located in plane $z = 0$ and the outer film boundary coincides with plane $z = H_f$. Then the potential energy of an electron in the insulator relative to the bottom of the metal conduction band with due account of the image force is described by expression [12]:

$$V(z) = \varepsilon_F + (\varphi_m - \chi_d) - e\varphi(z), \tag{1}$$

where $\varphi(z) = E_f z + ke/4z$ is the electric potential in the film, $k = 1/4\pi\varepsilon_0\varepsilon_f$, ε_F and φ_m are the metal substrate Fermi energy and work function, respectively, χ_d and ε_f are the film material electron affinity and high frequency dielectric constant [8], respectively, e is the electron charge magnitude, ε_0 is the permittivity of free space. The energy band diagram of the metal-insulator-plasma system is presented in Fig. 1.

Under an increase of the surface charge density on the film in the process of its ion bombardment in the discharge, the electric field strength E_f in it is also increased. When E_f reaches value of the order of 10^8 V m^{-1}, width of the potential barrier at the substrate surface becomes sufficiently small for tunneling of electrons, i.e. for field electron emission from the metal into the insulator conduction band. At low temperatures, the longitudinal component ε_z of energy of almost all electrons in the metal does not exceed the Fermi energy ε_F [12]. As it is seen in Fig. 1, the potential barrier width is increased practically linearly and hence the probability of electron tunneling through the barrier is decreased exponentially with a reduction of ε_z [13]. Therefore, the main contributions to the field electron emission into the insulator make electrons with energies ε_z near the Fermi level. The barrier width H_t for them can be found from expression (1) under substitution of $z = H_t$ and $V(H_t) = \varepsilon_F$ in it, which results in

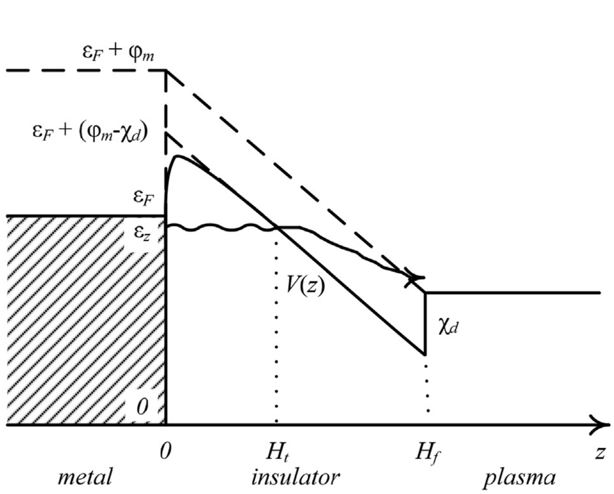

Fig. 1. Energy band diagram of the metal-insulator-plasma system.

$$H_t = \frac{\varphi_m - \chi_d}{2eE_f}\left(1 + \sqrt{1 - y_0^2}\right), \tag{2}$$

where $y_0 = c\sqrt{E_f}/(\varphi_m - \chi_d)$, $c = 3.795 \cdot 10^{-5}$ eV$\cdot$m$^{1/2}\cdot$V$^{-1/2}$.

Distribution of the flow density of tunneled electrons in the longitudinal component ε_z of their energy is described by expression [12]:

$$f_t(\varepsilon_z) = \frac{4\pi m^*}{h^3}(\varepsilon_F - \varepsilon_z)\exp\left[-d + \frac{\varepsilon_z - \varepsilon_F}{\varepsilon_d}\right], \tag{3}$$

where $d = (4\sqrt{2m^*}/3\hbar eE_f)(\varphi_m - \chi_d)^{3/2}v(y_0)$, $\varepsilon_d = \hbar eE_f/2\sqrt{2m^*(\varphi_m - \chi_d)}t(y_0)$, m^* is the effective electron mass in the insulator [14], $\hbar = h/2\pi$, h is the Planck's constant, $v(y_0) = 0.95 - y_0^2$, $t^2(y_0) = 1.1$ [15].

Under calculation of the field emission electron current density from the metal substrate into the insulating film one must take into account that usually some relief exists at their interface, resulting in an increase of the electric field strength on its tops, characterized by the field enhancement factor β [16–21]. And as according to (3) the field emission current density depends exponentially on E_f, electrons are emitted only from a small fraction s_f of the film-substrate boundary near the relief tops. For insulating oxide films of nanometer thickness the characteristic lateral dimension of the relief elements is usually much more than the film thickness [10,22]. Therefore, distribution of the electric field strength across the film near the relief tops can be considered as uniform and equal to $E_f = \beta U_f/\varepsilon_f H_f$ [23], where U_f is the voltage drop on the film. Then the macroscopic (averaged over the substrate surface) density of the field emission current from the substrate into the film is determined by expression

$$j_f(H_t) = es_f\int_0^{\varepsilon_F} f_t(\varepsilon_z)d\varepsilon_z. \tag{4}$$

Substitution of (3) in it and calculation of the integral with taking into account that $\varepsilon_F >> \varepsilon_d$ give the Fowler-Nordheim formula [15,24]:

$$j_f(H_t) = \frac{as_f E_f^2}{t^2(y_0)(\varphi_m - \chi_d)} \times \exp\left(-\frac{bv(y_0)(m^*/m)^{1/2}}{E_f}(\varphi_m - \chi_d)^{3/2}\right), \tag{5}$$

where $a = 1.541 \cdot 10^{-6}$A$\cdot$eV$\cdot$V^{-2}, $b = 6.831 \cdot 10^9$ V$\cdot$m$^{-1}\cdot$eV$^{-3/2}$, m is the free electron mass.

Electrons emitted from the substrate into the conduction band of the film are accelerated by the electric field to its outer surface and decelerated in collisions with phonons [8,10]. Under the assumption that the energy loss of an electron in each collision with phonon is equal to $\Delta\varepsilon$ and its mean path length along z-axis between collisions is λ_e, the electron energy distribution function in the film $f_e(z, \varepsilon_z)$ fulfills the kinetic equation [25]:

$$\frac{\partial f_e(z,\varepsilon_z)}{\partial z} + e\frac{d\varphi}{dz}\frac{\partial f_e(z,\varepsilon_z)}{\partial \varepsilon_z} = \frac{1}{\lambda_e}f_e(z,\varepsilon_z + \Delta\varepsilon) - \frac{1}{\lambda_e}f_e(z,\varepsilon_z) \tag{6}$$

with boundary condition $f_e(H_t, \varepsilon_z) = f_t(\varepsilon_z)$.

Replacing in (6) ε_z by a new variable $s = \varepsilon_z - e\varphi(z)$, we obtain an

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