Journal of Optoelectronics and Advanced Materials Vol. 7, No. 5, October 2005, p. 2435 - 2441

TEMPORARY THERMAL FLUCTUATIONS ON THE CATHODE SURFACE AND THEIR INFLUENCE ON SWITCHING OF THE CATHODE WORKING MODE

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The aim of this paper is to investigate the effect of a thermal fluctuation on the emissive active cathode zone. Function of various external conditions, like current intensity, electrodes shapes and surface electrode non-homogeneities, the electrode functioning mode can be diffuse or hot-spot. The two modes are extremely different from the evaporation and sputtering of the emissive layer point of view. In the diffuse mode, the surface temperature distribution is relatively constant and low. The vaporization rate of the barium layer is small. Contrary, in the hot-spot case, the local core temperature of the spot can be higher than of the tungsten melting point temperature (3663 K) and the activator layer is rapidly destroyed. This allows to the lamp lifetime reduction. From this point of view is more convenient to have an electrode operating in diffuse mode. In this work are analyzed what happens with a local thermal fluctuation due to the current discharge pulse superposed on the current injected by the source supply. Are found the conditions when the cathode operation mode passes from diffuse to hot-spot mode and also the conditions when the fluctuations are dumped in time.

(Received January 12, 2005; accepted September 21, 2005)

Keywords: Field-enhanced thermionic emission, Diffuse and hot-spot mode, Switching process

1. Introduction

The lifetime of high-intensity discharge lamp is strongly influenced by the lamp ignition and also by the cathode functioning mode. During the lamp ignition the cathode is heavily stressed by the high voltage and also by the ionic impact. This makes a strong vaporization and sputtering of the electrode activator. Big damage of the emissive cathode layer is produced also by a high local temperature, which leads to a greater vaporisation rate of the activator element. In the diffuse mode functioning the temperature distribution in the cathode active zone is almost constant and around 1500 K. If the cathode mode functioning is hot-spot, the local temperature in the spot zone reaches the tungsten melting point and more. Consequently, the vaporisation rate of the activator element increase dramatically and the emissive layer is destroyed. The electron work function increase from 2.61 eV (for barium-oxide activator layer) to 4.55 eV (for tungsten). The high-emissivity current request is not satisfied and the high-pressure discharge is stopped. For a better understanding of the electron emission process and of the electrode design is necessary to know the conditions, which determine the appearance of one of the cathode working modes.

2. Theory

In high-pressure mercury and sodium lamps, the electron emission is generally due to the field-enhanced thermionic emission process. This is described by Richardson-Duschman equation

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corrected with the Schottky's charge image effect [1]. In addition, a secondary emission due to the ionic impact (γ-Townsend process) appears. Using the β-Waymouth coefficient which gives a relation between ionic j_i and electronic j_e current density in the cathode neighbourhood [2] we set the equation [3, 4] which allows us to obtain the dependence between the electrode temperature in the emissive area T, discharge current density j, β-Waymouth and γ-Townsend coefficients, work function φ_0 and electric field intensity at the cathode surface E_k:

$$\frac{h^3(1-\beta\gamma)jT^{-2}}{4\pi e m_e k_B^2(1+\beta)}\exp\left(\frac{e\varphi_0}{k_BT}\right)=\exp\left[\frac{e^{3/2}E_k^{1/2}}{(4\pi\varepsilon_0)^{1/2}k_BT}\right] \tag{1}$$

where, h is the Planck constant, k_B is the Boltzmann constant, e is the electron charge, m_e is the electron mass and ε_0 is the free space dielectric constant.

The cathode fall field, E_k, is related to the potential drop over the free fall sheath, V_k, by MacKeon equation [5]:

$$E_k^2 \approx \frac{4j_i}{\varepsilon_0}\left(m_i V_k /(2e)\right)^{1/2} \tag{2}$$

where m_i is the ion mass.

Sometimes, the lamp power supply can have two-step rectangular pulse where the value of the high pulse current has different amplitude and temporal size (Fig. 1 a), or can be a superposition of a d.c. and a.c. current (Fig. 1 b).

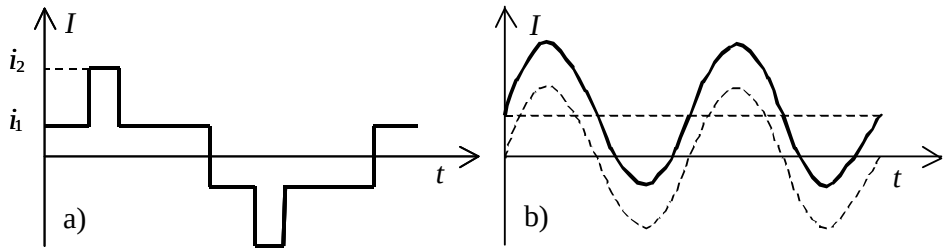

Fig. 1. Periodic current supply.

This means that the lamp has a low temperature ignition followed by a high temperature. The low temperature is calculated in diffuse mode when the discharge covers the entire active surface. The supplementary pulse determines a supplementary cathode heating. This supplementary heating can be seen like an adiabatic heating if the processes are rapid (the temporal size of the high pulse is small). This allows a surface temperature high local increase. By contrary, if the high pulse duration is long, the thermal conduction is important. In this situation the active electrode surface reach the same value in all points and the cathode mode functioning is not changed.

In our model we are starting from a temperature distribution in the active cathode area over which we superpose a high temperature local pulse. Than we observe what happens in time with the emissive zone. In each moment the total current discharge must be constant:

$$I = 2\pi \int_0^{\text{all emissive surface}} j(T) r \cdot \mathrm{d}r \tag{3}$$

The spot size r_0 is calculated through the energetic flux conservation equation [6]:

$$\frac{I}{\pi r_0^2(1+\beta)}\left[\beta(V_k+V_i)-\varphi_0(1+\beta)-\frac{2k_BT_{hs}}{e}\right]-\sigma\varepsilon_W(T_{hs})\left[T_{hs}^4-T_{plasma}^4\right]=k_W(T_{hs})\left(\frac{\partial T}{\partial z}\right)_{z=z_{spot}} \tag{4}$$

which is solved together with the heat transport equation [3]:

$$\rho c \frac{\partial T}{\partial t} = \nabla\left[-k_W(T)\nabla T\right] + S \tag{5}$$

In the two previous equations, $k_W(T_{hs})$ is the tungsten thermal conductivity at the hot-spot temperature, V_i is the ionisation potential (10.434 V), σ is Stefan-Boltzmann constant, $\varepsilon_W(T_{hs})$ is the total tungsten emissivity, ρ is the tungsten density, c is the tungsten heat capacity, T_{plasma} is plasma temperature far from electrode surface. S is the source term given by Joule effect $S(r,z) = \rho_W(T) j^2 = \rho_{0W}\{1+\alpha_W[T-T_0]\}j^2$, with ρ_W is the electric resistivity of the electrode.

In our model we set the following tungsten characteristics: density $\rho = 19300\ kg/m^3$, heat capacity $c = 133\ Jkg^{-1}K^{-1}$, thermal resistivity coefficient $\alpha_W = 6.76\times10^{-3}\ \mathrm{deg}ree^{-1}$, electric resistivity $\rho_{0W} = 5.28\times10^{-8}\ \Omega m$ and plasma temperature $T_{plasma} = 6000\ K$.

Tungsten thermal conductivity and emisivity dependencies on the temperature are introduced as functions which fit the experimental results (see Fig. 2). So, we obtain :

$$k_W(T) = \frac{776}{T^{0.256}} \tag{6}$$

$$\varepsilon_W(T) = -5.6148\times10^{-2} + 1.6019\times10^{-4}\cdot T - 1.3685\times10^{-8}\cdot T^2 \tag{7}$$

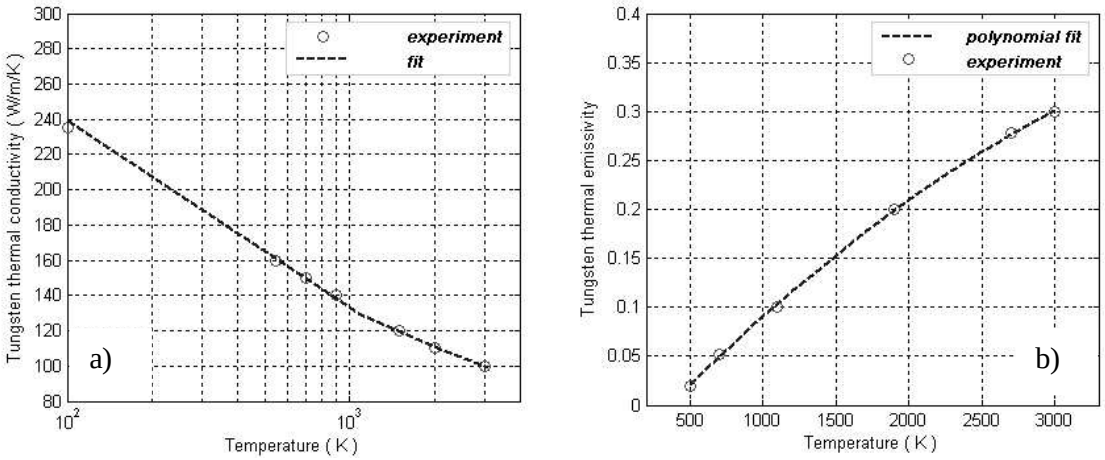

Fig. 2. Tungsten thermal conductivity (a) and emissivity (b) temperature dependencies.

The current density distribution in the cathode bulk is obtained by solving the electric conductive media equation

$$-\nabla\left(\frac{1}{\rho_W(T)}\cdot\nabla V - \vec{j}^{\,e}\right) = Q_j \tag{8}$$

where V is the electric potential, $\vec{j}^{\,e}$ is the externally generated current density and Q_j is the source term (zero in our model).

So in function of the electrode dimension, of the active surface temperature in the diffuse mode (determined by the discharge current), of the thermal fluctuation size, amplitude and duration, the functioning mode of the cathode is switched from the diffuse to hot-spot mode. From the lifetime and wall blackening point of view this switch is more inconvenient.

3. Results and discussion

A self-consistent model able to calculate the densities current and electrode temperature distributions was created by solving simultaneously the equations (1), (4), (5) and (8). Some results of the model are presented as follows.

In Fig. 3 the total, electronic and ionic current densities distributions on the electrode surface for 1.5 A 1 discharge current intensity value are presented. The restrictive condition (3) of the self-consistent model is satisfied taking the value 1.5022 A for the external imposed current $I = 1.5$ for a pure diffuse mode functioning. On the electrode axis the temperature of the spot takes the value $T_{sp} = 2420$ K.

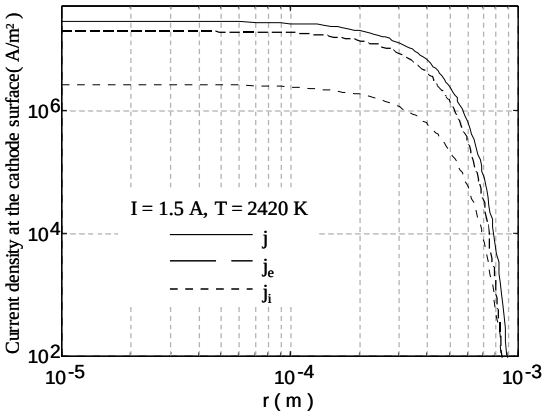

Fig. 3. Total, electronic and ionic current densities at the cathode surface in the case of diffuse mode functioning.

In the case of hot-spot mode functioning, the condition (3) is modified in the form

$$I = 2\pi \int_0^{r_0} j_{spot}(T(r)) \cdot r \cdot dr + 2\pi \int_{r_0}^{R} j(T(r)) \cdot r \cdot dr \tag{9}$$

where r_0 and R are the spot radius and active electrode surface radius.

In Fig. 4 the electrode surface temperature and current densities distributions are presented at various current discharge (various modes functioning). In the figure legend are marked the maximal surface temperature of the hot-spot T_{hs} (on the symmetry axis) and the spot size r_0 obtained from energetic flux conservation equation (4).

The condition (9) applied for the hot-spot mode functioning presented in Fig. 4, gives the values $0.5065, 1.0049$ and 1.5002 A for the external current intensities $0.5, 1$ and 1.5 A respectively.

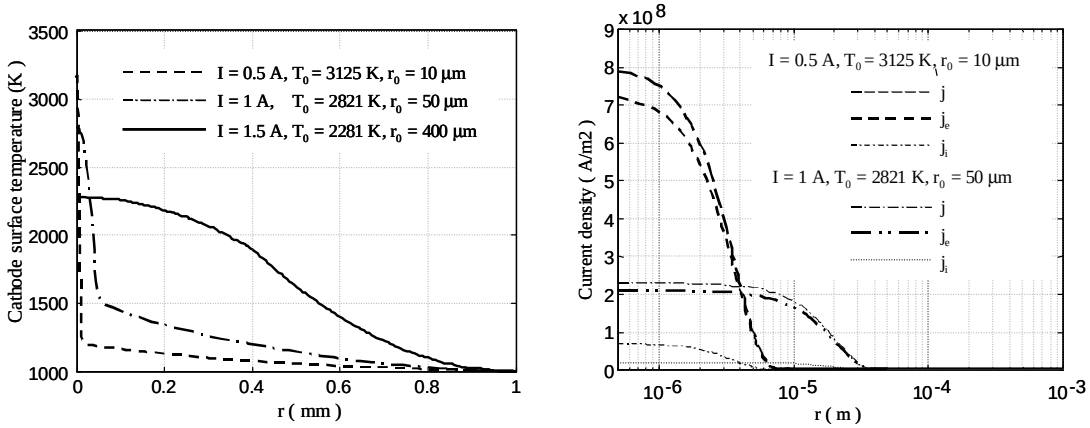

Fig. 4. Cathode surface temperature and current density distributions at various current Discharge for different cathode modes functioning.

A diagnostic of the energetic flux at the electrode surface are made in the case of the stationary regime of the electrode for both of the two mode functioning. It was calculated all the energetic flux quantities which interfere in the flux continuity equation. These are presented in Table 1.

Table 1. Electrode diagnostic in the stationary state of the a) hot-spot mode ($I = 0.5A$, $r_0 = 10\,\mu m$, $T_{hs} = 3125\,K$) and b) diffuse mode functioning ($I = 1.5A$, $r_{spot} = 400\,\mu m$, $T_{sp} = 2281\,K$).

Quantity	Expression	Integral expression	Value	
			a). Hot-spot	b). Diffuse
Ionic flux density	$\phi_{ionic} = j_i(V_k + V_i - \varphi)$	$\Phi_i = \int_0^R \int_0^{2\pi} \phi_{ionic} r dr d\varphi$	0.81 W	2.43 W
Electronic flux density	$\phi_{elec} = j_e(\varphi + 2k_B T / e)$	$\Phi_e = \int_0^R \int_0^{2\pi} \phi_{elec} r dr d\varphi$	1.39 W	4.06 W
Thermal conduction flux density	$\phi_{ther} = k_W(T)\left(\frac{\partial T}{\partial z}\right)_{z=0.005}$	$\Phi_{th} = \int_0^R \int_0^{2\pi} \phi_{ter} r dr d\varphi$	13.43 W	30.32 W
Radiant flux density	$\phi_{rad} = \varepsilon_W(T)\sigma T^4$	$\Phi_r = \int_0^R \int_0^{2\pi} \phi_{rad} r dr d\varphi$	12.86 W	28.69 W

Can be easy verified that summing the integral flux transported by the ions and integral flux coming by thermal conduction from plasma is equal with the flux loss through electron and thermal radiation emission:

$$\Phi_i + \Phi_{th} = \Phi_e + \Phi_r \tag{10}$$

The derivative which appear in the thermal conduction flux was approximated by the following expression:

$$\left(\frac{\partial T}{\partial z}\right)_{z=0.005} = \frac{T_{plasma} - T}{\delta} \tag{11}$$

where $\delta = 10^{-6}\ m$ is the cathode free fall sheath.

To find what happens with thermal fluctuation we suppose the following:

- the discharge core is located on the symmetry axis. This allows for a one dimensional model with the distance from symmetry axis as model variable;
- for the case represented in Fig. 1 a) at each value of the current i_1 and i_2 a stationary model is used in order to find the temperature distribution along the electrode radius; the same path is followed for the current represented in Fig. 1b (a superposition of a d.c. current i_1 and a.c current $i_2(t) = I_{02}\sin(2\pi\nu t)$);
- 1D dynamic problem is posed as a 2D static problem. Here the time variable is represented by x, distance from symmetry axis by y and the temperature by $T(x, y)$. So, the transient 1D problem is solved as 2D static problem described as follows:

$$\rho c_p \frac{\partial T}{\partial x} = \frac{1}{y} \cdot \frac{\partial}{\partial y}\left[k_W(T) \cdot y \frac{\partial T}{\partial y}\right] + S \tag{12}$$

where ρ, c and S have the significations presented above and $k_W(T)$ is given by the formula (6);

- we specify the initial value of $T(0, y)$ along $x = 0$, also the time history along the sides $y = 0$ (on the electrode center) and $y = R$ (the border of the electrode emissive area).

- the of the temperature value T is assigned everywhere on the boundary excepting along the segment $y = \tau$, $0 < x < R$. Along this segment, we use the Neumann boundary condition. This corresponds to the case where there is no boundary source. This implies a free segment for the boundary $(\tau, 0)$ to (τ, R). In this model we assume that τ (and hence $t = \tau$) is sufficiently large in order to reach the stationary regime. The magnitude of τ is equal with few current periods.

By changing the initial conditions, the history on the electrode points $r = 0$ and $r = R$ and the electrode source term given by Joule effect, one checks what happens with the perturbation for various value of τ.

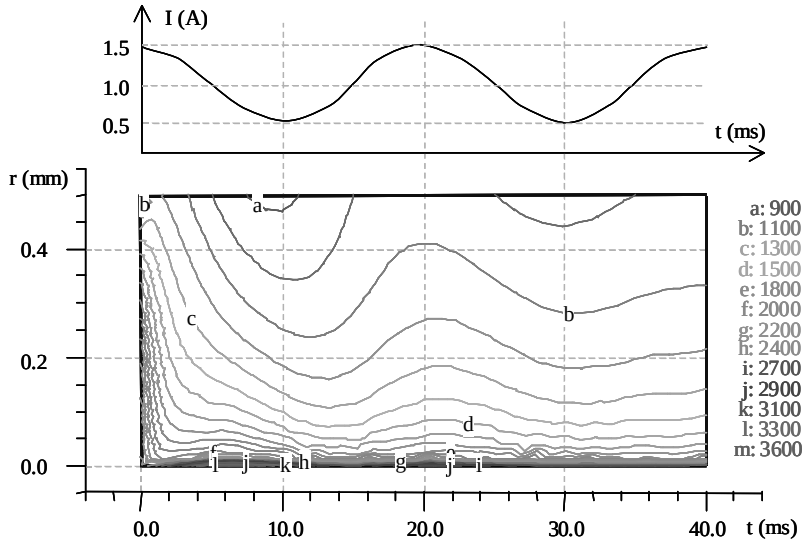

Fig. 4. Results of the 1-D transient heat flow at the cathode surface (solved at 2D static problem).

For example, in Fig. 4 are presented the results obtained for a superposition of a d.c. with a.c currents. The frequency is $\nu = 50\ Hz$ and the time of simulation is equal with two current periods $\tau = 2/\nu$. The cathode is supposed to work in diffuse mode.

The current decrease according with a co-sinusoidal law. Also, the source term inside of the cathode have a square co-sinusoidal variation. The equation (12) results show that around $t \cong 10\ ms$ the mode functioning passes in hot-spot mode, with central temperature equal with the tungsten melting point. Can be observed (from Fig. 4) that the core temperature determine the active surface frontier cooling. This is a result of restrictive conditions (3) respectively (9). The electrode is cooled at the border and heated on the symmetry axis, in order to assure the required discharge current. For short time, the tendency is to pass in hot-spot mode. But, for the case of our simulation – with very thin electrode ($r = 0.5\ mm$) – this tendency is dumped in time. After approximately two periods the temperature becomes quasi-stationary in all surface of electrode and this remains in diffuse mode functioning. Also, the mode remains diffuse if the high pulse duration (see Fig. 1.a) is sufficiently large. For a big electrode radius, the thermal inertia is not reached and the mode functioning is quickly changed. The dynamic changes of the arc attachment modes to the cathode surface have the flickering character described by Fromm and Hohlfeld [7].

Must be noted that this calculus are made for the symmetry cylindrical discharge. We assumed that even in hot-spot mode this is attached to the cathode on the symmetry axis. In reality, the hot-spot mode is attached usually on the rod end. Sometime, in the case of high-pressure sodium lamps, the spot is attached on the first layer of coils wrapped on the tungsten rod. In future a time depending 3D model must be elaborated.

4. Conclusions

In this work are analyzed the time evolutions of the thermal fluctuations induced at the cathode surface trough the power supply intensity. The cathode can function in two modes: diffuse and hot-spot. The diffuse cathode working mode is favored by the uniform temperature distribution and by the high heat conduction in the bulk electrode material. In the diffuse mode the plasma covers the whole top of the cathode and parts of the rod. This mode is preferred at low pressure and small cathode diameter (weak cooling, high thermal conduction).

The hot-spot mode functioning appears at low current intensity, at poor heat conduction and at non-homogenous surface material. This mode is preferred at large cathode radius, smaller length and lower support temperature. The spot temperature determines a very important sputtering and damage of the activator layer.

The highest stress of the electrode appears at the lamp ignition. It is preferable to power on the lamp directly in the cathode diffuse working mode by a supplementary cathode heating.

Even the start is in diffuse mode (high value of i_1 current intensity in Fig. 1 a), the supplementary pulse determines a supplementary cathode heating. This heating can be seen like an adiabatic heating if the processes are rapid (the temporal size of the high pulse is small). This allows a high local surface temperature increase and the changing of the working mode for the case of large electrode radii.

By contrary, if the high pulse duration is long, the thermal conduction is important and the active electrode surface temperature reach a stationary value in all points. Consequently the cathode working mode remains diffuse.

For technical purpose it is relevant to take predictions on the type of arc attachment mode to the cathode surface and under what circumstances the changes occur.

Mode changes can be enforced by current or pressure variation. Investigations have shown that most spots do not change continuously into diffuse mode. In terms of time, the change between modes can be distinctly faster that the electrode-temperature changes [8].

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