Paper

Study of the Glow Discharge Mode in High-frequency Instant-start Fluorescent Lamps

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ABSTRACT

Steady-state glow discharge operation has been studied on model fluorescent lamps equipped with bare tungsten electrode filaments. Energy transfer mechanisms were measured by electrode temperatures as a function of electric driving parameters and fill gas pressure. The measurements were evaluated and discussed by application of plasma models of the cathode dark space region.

KEYWORDS: fluorescent lamp, glow discharge, cathode fall, cathode dark space, electrode, instant start, sputtering, rapid cycling

1. Introduction

Glow discharge is present in hot-cathode fluorescent lamps in the initial few tens of milliseconds of ignition with instant start ballasts, and has important life limiting effect as the particle bombardment from the plasma can result in the destructive sputtering of the electrodes. We investigated the energy transport mechanisms between the glow discharge and the electrodes and found that by modifying the fill pressure and filament geometry the efficiency of heat transferred to the electrodes can be increased.

2. Measurement method

In this work our experimental lamps were kept in constant glow discharge mode. This stable operation with lamp currents and voltages typical for glow mode periods after instant-starting ignitions was achieved by using bare tungsten electrodes without electron emissive coating. Due to the high work function of tungsten the energy input to the electrodes is not enough to maintain thermionic electron emission temperatures that would be sufficient for the cathode to transition into arc mode. In this manner, these lamps could be operated in continuous AC glow discharge mode for a prolonged time sufficient for making steady-state measurements.

The lamps studied in this paper have the following design parameters: Glass tube diameter 12.7 mm discharge length: 190 mm. The cold spot temperature of the tube was kept at 25°C, resulting in a mercury vapor pressure of 0.26 Pa. The lamp fill gas was argon, and fill pressure was varied between 3 and 8 mbars.

The operating conditions of the lamps in the following experiments were the following: Lamps were driven with an AC power supply at constant current between I_RMS=0.7 mA and 26 mA. In this range the operation of the lamp is stable, and the damage rate is low enough to avoid blackening of the tube during the measurements. Driving current was a 15 kHz sine wave, the current was limited by a series 1 kOhm resistance. All values of current and voltage referred to hereinafter are considered as root mean squares of alternating current.

In case of an instant-start lamp the role of the glow discharge is to heat-up the electron emission material coated on the middle part of the tungsten filament. This is done by the power deposited by the cathode fall region of the discharge, P_{cathode fall}. Since only a part of P_{cathode fall} can be considered useful which heats up the coated part of the filament, let the rest of the power dissipated be P_{loss}. Thus, the useful P_{filament} power deposited to heat up the filament is:

\[ P_{\text{filament}} = P_{\text{cathode fall}} - P_{\text{loss}} \]

To determine P_{filament}, we have measured the steady state temperature distribution of the filament, which have been measured by near-infrared thermal camera. By re-creating the filament temperatures measured during the stabilized glow discharge mode by applying an external resistive DC heating to an electrode with no discharge we can calculate the power dissipated in the filament during glow mode. We get \( P_{\text{filament}} \) (glow, \( T \))=\( P_{\text{filament}} \) (resistive, \( T \))=\( U_{\text{filament}} \) (resistive)*\( I_{\text{filament}} \) (resistive), when the mean temperature of the resistively
heated filament is equal to the temperature of the electrode in glow discharge. Two exemplary matching temperature distributions are shown in Figure 1.

The temperature-to-filament power calibration curve is shown on Figure 2.

To determine $P_{\text{cathode fall}}$ we have measured the cathode fall of glow discharge in front of the electrode by a metal probe inserted into the discharge near the filament. The cathode fall voltage of the glow discharge can be determined from measuring the potential between the probe and the electrode. The measured function of cathode fall voltage vs. lamp current can be seen on Figure 3 for three different fill pressures. The power dissipated at the cathode region can now be calculated by multiplying the cathode fall voltage by the glow current flowing through the lamp: $P_{\text{cathode fall}} = U_{\text{cathode fall}} I_{\text{lamp}}$.

Although the previous method resulted in more reliable and repeatable results, we can also calculate the cathode fall by subtracting the positive column voltage from the total lamp voltage. The total power dissipated at one cathode is thus: $P_{\text{cathode fall}} = (P_{\text{lamp}} - P_{\text{positive column}})/2$. The power dissipated in the positive column ($P_{\text{positive column}}$) is calculated from the voltage-current characteristics measured on lamps with the same construction but having emissive coatings on their electrodes. These lamps were operated in arc mode, and the surplus of the cathode fall at low discharge currents were eliminated by applying auxiliary electrode heating.

The final result of the measured glow mode heating efficiencies at different driving currents and fill pressures are shown in Figure 4 and Figure 5.

Because of the rapid sputtering of filament material, the inner surface of the discharge tube chamber gets progressively covered by a thin layer of tungsten which is not transparent in the infrared range. This can be solved by repeatedly calibrating the resistive and-glow heated filament thermographs through a wide range of tungsten film deposition, continuously re-measuring the power needed to heat up the filament to match the heating effect of glow discharge each time the transparency of the lamp bulb changes.

Limitations of the measurement method to predict
3. Discussion

The $P_{\text{filament}}$ power transferred from the discharge to the filament is the sum of ion, atom and electron bombardment powers. The charged particles gain their kinetic energies in the cathode fall region while they are accelerated by the high electric field. Some part of their energy is turned into the generation of new charge carriers needed for a self-sustaining glow discharge, but a significant portion of the energy is transferred to neutral atoms by symmetric charge transfer in the cathode fall region\textsuperscript{4}, as the typical length of the cathode fall region is several times longer than the $\lambda$ mean free path of the reaction. The third energy transfer mechanism is the heating of the electrode via the kinetic energy of charged particles impacting the electrode surface. The electron heating in anode cycle, the cooling of electron emission in cathode cycle and the energy taken by the atoms sputtered from the electrode can be neglected.

The electrode heating is of special importance in instant-start fluorescent lamps, as this mechanism heats up the emissive coating on electrodes needed for thermionic electron emission. However, not only charged particles can contribute to the heating process. There are a large number of fast neutral atoms generated during symmetrical charge transfer collisions that are not attracted by the electric field towards to electrode, but they still reach the electrode surface with a certain probability. This probability is reduced by elastic scattering in the cathode fall. The average probability is determined by the relative sizes of the cathode fall region, electrode surface and the mean free path of symmetrical charge transfer collision.

The cathode dark space length $d$ can be calculated from the self-sustainment condition of the discharge following the deductions of Haverlag et al.\textsuperscript{3}

$$d = \frac{\ln((1+\gamma)/\gamma)}{AB \frac{dp^2}{U_C} S \left( \frac{2}{B \frac{dp}{dp}} \right)}$$

where the $S(u)$ function is the following:

$$S(u) = u e^{-\frac{u}{\lambda}} + E_i \left( -\frac{1}{u} \right)$$

$A$ and $B$ are the Townsend ionization coefficients of the gas, $\gamma$ is the secondary electron yield\textsuperscript{5} characteristic for the cathode material and the bombarding ions, $p$ is the pressure of the gas and $E_i(x)$ is the complex exponential integral function:

$$E_i(x) = -\int_x^\infty \frac{e^{-t}}{t} dt$$

For a given discharge gas and cathode material $d$ is the function of pressure and cathode fall voltage. $d$ has the same pressure dependence as mean free path, consequently $d/\lambda$ depends only on $U_C$. Figure 5 shows

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**Figure 4** Power dissipated in the cathode fall and heating up the filament. Fill pressure is 5 mbars of Argon

**Figure 5** Ratio of power dissipated in the cathode fall and heating up the filament as a function of the lamp current for different fill pressures. Fitted ratios are written on the dotted lines

the behavior of CFL lamps during rapid cycling use include neglecting some aspects of the real glow mode state after ignitions. For example, our model lamps did not have emission mix on them, while it is known that the surface of the emission mixture has a higher secondary electron yield than bare tungsten surface. Also, the stabilized glow discharge is followed by a glow-to-arc transition when the glow current is concentrated into a small surface while the cathode fall voltage remains very high, resulting in very intensive heating and sputtering that we could not reproduce with this measurement method. Lastly, our method neglects glow discharge power dissipated in the lead wires. This is because resistive heating by external power supply heats up only the filament, while glow discharge forms around the entire electrode assembly.
calculated $d$ functions for Argon gas and tungsten electrode.

The width of the cathode dark space (CDS) is comparable to the size of electrode filaments used in fluorescent lamps. For the coil used in our experiments the size of the cathode dark space is comparable to the size of the tertiary windings (see Figure 6). As the probability that neutrals generated in the CDS reach the electrode surface is the function of (electrode size)/(CDS width) ratio, the strong dependence of the impact probability is expected when the electrode surface and the CDS width are of similar sizes.

The heat transferred to the electrode by the neutrals is the product of their impact probability and their energy. The energy of the neutrals can be calculated from the energy balance of the CDS:

$$ P_{\text{neutrals}} = I_{\text{lamp}} - P_{\text{ionization}} - P_{\text{ion bombardment}} $$

where $P_{\text{neutrals}}$ and $P_{\text{ion bombardment}}$ are the power transferred into the kinetic energy of neutrals, the power needed to ionize the gas atoms and the power deposited to the electrode by impacting ions. $E_{\text{Ar ionization}}$ is the ionization energy of Argon in eV units.

As typical values of the $U_{\text{cathode fall}}$ voltage drop in the CDS are in the several hundred volts range, the energy turned to ionization is only a few percent of the energy dissipated in the CDS ($E_{\text{Ar ionization}} = 15.76$ eV).

Several studies have been carried out to calculate the energy distribution of ions and atoms in the cathode fall region of glow discharges either by analytical or by computer simulation techniques. Davis derived the below formula for the energy distribution of ions at the surface of the cathode in a DC discharge.

$$ f(x) = \frac{1}{U_c} \frac{d}{\lambda} \frac{1}{1-\exp\left(\frac{-d}{\lambda}\right)} \frac{1}{2} \frac{1}{U_c} \exp\left(\frac{-d}{\lambda \left(1-\frac{1-x}{U_c}\right)}\right) $$

where $\lambda$ is the mean free path for symmetrical charge transfer.

Since there is a difference of two orders of magnitude between the collision frequency of fill gas particles and the frequency of the driving current, the energy distribution corresponding to the instantaneous cathode fall voltage can develop, and the above expression can be used when integrated as a time-dependent function for the AC driving currents used in the experiments.

Substituting $d/\lambda = 20$ the equation yields $0.095U_{\text{cathode fall}}$ for the average energy of impacting ions for argon gas and tungsten electrode. As all the ions are collected by the electrode, it follows that the minimum efficiency of electrode heating is $0.95/(1+\gamma) \times 100% \approx 10.5\%$. This minimum value corresponds to the case when (electrode size)/(CDS width)<1, consequently fast neutrals reach the electrode with low probability.

In our experiments the values of $P_{\text{filament}}/P_{\text{cathode}}$ are higher than 0.105 (Figure 5), indicating that fast neu-
trials transfer significant power to the electrode. The pressure dependence of the heating efficiency can be explained as the result of the pressure dependence of the dark space thickness. With increasing pressure the dark space size decreases, consequently more fast neutrals transfer their energies to the electrode, the heating becomes more efficient.

4. Summary
Our work has pointed out that due to the similar sizes of CDS width and electrode coil in fluorescent lamps the probability that fast neutrals reach the electrode surface strongly depends on the CDS width. As most of the energy dissipated in the CDS is turned to the energy of fast neutrals and pressure is the most important factor determining the width of CDS, it concludes that the efficiency of electrode heating is strongly influenced by the fill gas pressure.

References