Measurements of Distributions of Ba Atom Density and Electrode Temperature in Low-pressure Fluorescent Lamp

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The lifetime of a fluorescent lamp mainly depends on the loss of Ba atoms from its electrode, i.e. the rate of Ba atoms loss controls the lifetime of the lamp. The mechanism of the loss has not been clarified yet sufficiently. We have investigated relationship between electrode temperature distributions and characteristics of Ba atom emission in a fluorescent lamp which are measured by using black-body radiation method and laser-induced fluorescence (LIF) method, respectively. The lamp was operated at AC 100V-60 Hz. The experimental results of electrode temperature measurement are consistent with our previous report that the lifetime of the lamp depends on thermal evaporation from a hot spot at an anode half-cycle.

Keywords: laser induced fluorescence, black-body radiation method, fluorescent lamp lifetime, barium emission, electrode temperature

1. Introduction

Barium oxide as an emitter material is usually coated onto electrodes of low-pressure fluorescent lamp (FL) to emit thermal electrons at low temperature. Because existence of Ba atoms in the surface substantially lowers the work function of bare tungsten of approx. 4 eV to approx. 1.38 eV [1], a low discharge voltage (sheath potential) resulting high efficiency operation of the FL can be achieved. However, Ba atoms are evaporated and sputtered from the electrodes during lamp operation, which shortens the life time. Misono *et al.* mentioned that Ba atoms are consumed by sputtering when the electrode is working as cathode (cathode half-cycle) [2]. On the other hand, Bhattacharya reported that Ba atoms are evaporated during anode half-cycle, although the mechanism of Ba atom loss is not clarified yet in detail [3]. We have clarified the mechanism of Ba atom loss in part, in which Ba atom loss is mainly due to thermal evaporation from a hot spot [4]. Thermal evaporation of Ba atoms and emission of thermionic electron depend largely on the electrode temperature. Watanabe reported on the spatiotemporal distributions of electrode temperature in a FL that worked at various frequencies in detail [5]. However the results are not consistent with Misono's paper that reports the electrode temperature and Ba atom loss mechanism using optical emission spectroscopy [2]. Even in a FL worked under a typical discharge condition, relationship between the electrode temperature and the Ba atom loss mechanism has not been clarified yet. Therefore, systematical solution on how emissions of emitter materials and electrode temperature influence to form or sustain the discharge plasma is strongly desired.

We have investigated relationship between loss mechanism of Ba atom from the electrode and its temperature. Ba atom was measured by Laser-induced fluorescence (LIF) technique and electrode temperature was measured by black-body radiation method. In this paper, experimental results of distributions of the Ba atom density and the electrode temperature in FL are described.

2. Experimental Procedure

The studied lamp in this work was a commercially based fluorescent lamp with 26 mm diameter and 600 mm length, and was operated by AC (60 Hz) power supply. An additional heating current was used to change

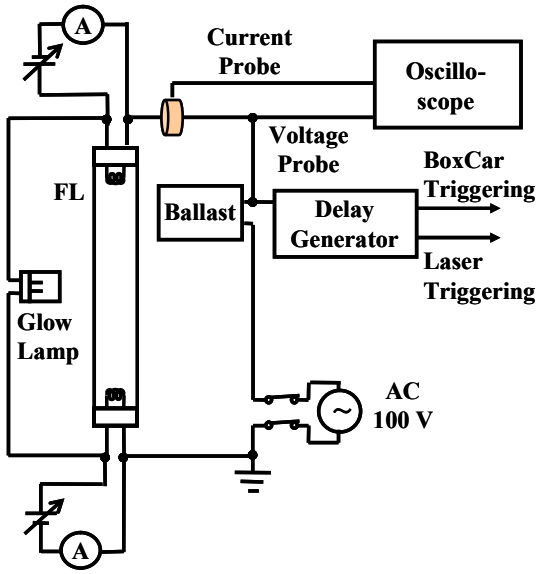

Fig. 1 Fluorescent lamp discharge circuit.

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the temperature of the electrode filament independent of the discharge current heating, as shown in Fig. 1. The lamp consisted of a clear glass tube without any coating of fluorescent materials on the inner wall was specially designed to transmit the UV laser beam. The lamp current was measured with a current probe (Yokohama, CTL-35-S162-5F-1R10), and the voltage across the lamp was measured with a voltage probe (Tektronix, P6139A). The current and voltage waveforms were recorded using a digital oscilloscope (Sony Tektronics, TDS5054B).

The experimental arrangement for LIF is schematically shown in Fig. 2(a). In the present work, the "three-level" scheme of Ba atom was used, in which Ba atoms in the ground state (6^1S_0) are excited to the 5^1P_1 state (350.1 nm) and the fluorescence due to the 5^1P_1 – 5^1D_2 transition (582.6 nm) is detected. The second harmonic (532 nm) of a pulsed Nd-YAG laser (Continuum, PL8000) was used to pump a dye laser (Continuum, ND-6000) to generate a 700.2 nm radiation. The second harmonic radiation (350.1 nm) of the dye laser beam was generated using an angle-tuned KDP crystal. A beam separator (BS) was used to separate the fundamental and the second harmonic radiations. Using a spherical lens with a focal length of 200 mm, the laser beam of 350.1 nm was irradiated through the lamp along with the axis parallel to the filament electrode just in front of it. The effect of glass tube of the lamp on the focusing of the laser beam was neglected because of too long focal length of the glass tube. The laser pulse (7 ns duration) with a repetition rate of 10 Hz was synchronized and varied with respect to the lamp current using a (DG-535) delay generator. The spot size of the beam was about 0.2 mm. The LIF emission at 582.6 nm was focused on the entrance slit of a monochromator (Nikon G-500 III) by a collecting lens perpendicular to the axes of the laser beam and the fluorescent lamp, and detected by a photomultiplier (Hamamatsu, R1333). The distortion of the image on the entrance slit by the lamp tube is negligibly small for the observation area of this measurement. A HP filter was used to cut the scattered laser beams. In order to increase the signal to noise ratio, the LIF signal was averaged over 600 laser pulses by a boxcar integrator and recorded by a computer based data acquisition system (PC).

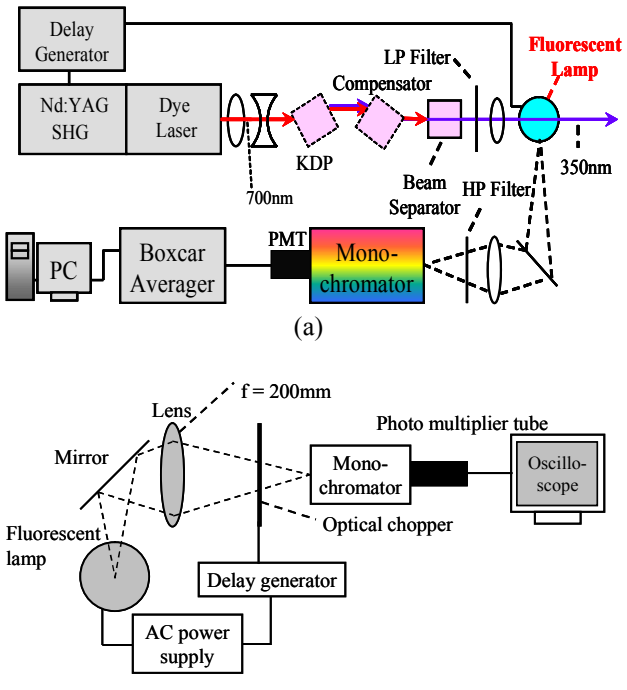

Fig. 2 Schematic illustrations of (a) Ba atom density measurement using LIF technique, and (b) electrode temperature measurement using black-body radiation method for a FL.

Fig. 2(b) shows an experimental setup for temperature measurement. Emission light from electrode (700-900nm) is incidented to monochromator, and converted to electrical signal by PMT (Hamamatsu, R943-2). Then wavelength distribution of emission intensity is obtained. Electrode temperature is estimated by fitting a measured spectrum with a theoretical curve of black-body. The optical emission detection system was calibrated by using a standard lamp.

3. Results and Discussion

The lamp was operated at two discharge currents (I_d) of 0.005 A and 0.29 A. Measurements of the current-voltage characteristic curve of the lamp showed that at I_d = 0.005 A the lamp is operated by glow discharge mode and at I_d = 0.29 A the lamp is operated by arc discharge mode. The glow-to-arc transition occurs at high discharge current due to the change of electron emission mechanism. At low discharge current the secondly electrons are emitted from a cathode electrode by an ion bombardment. As the discharge current is increased to enough high value, the electrode temperature increases and the electron emission mechanism changes to be due to thermionic emission. Glow-to-arc transition affects also the mechanism of the loss of Ba atom.

Figure 3 shows the temporal distribution of the LIF intensity from Ba atoms at three cases of (1) I_d = 0.005 A, I_f = 0, (2) at I_d = 0.005 A, I_f = 0.27 A, and (3) I_d = 0.29, I_f = 0. Also the current and voltage waveforms at low (case (1)) and high (case (3)) discharge currents are shown. In these measurements, the LIF signal was observed from very close to the surface of the filament electrode (x = 0) with a spatial resolution of 50 μm (x) × 16 mm (z), which covered the entire length of the electrode. It is obviously noticed that the temporal distribution of Ba atom density in the three cases is completely different. In case (1), Ba atoms are mainly emitted during the cathode half-cycle with very high rate. At this low discharge current, the filament electrode is cold and the discharge is sustained on glow discharge mode. Misono showed that the glow discharge generation in such a low discharge current (high discharge voltage) causes the short lifetime of FL

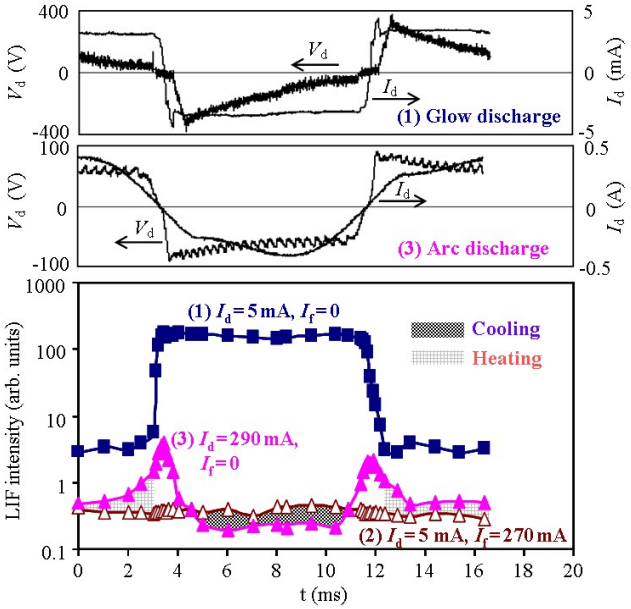

Fig. 3 Temporal distribution of Ba-LIF intensity at three cases of (1) I_d = 0.005 A, I_f = 0, (2) at I_d = 0.005 A, I_f = 0.27 A, and (3) I_d = 0.29A, I_f = 0, together with the current and voltage waveforms at case (1) in glow discharge and case (3) in arc discharge.

[6]. In the glow discharge, the positive ions bombard the electrode acting as a cathode, which are accelerated by the large cathode sheath potential. As the result, large amount of Ba atoms are sputtered from the electrode surface during a cathode half-cycle. In case (2), the electrode temperature is raised by I_f. The temperature increase causes remarked decrement of the Ba atom loss due to the decrease of the energy of the bombarding ion. At this high temperature the thermionic electrons are emitted from the cathode, and a mode transition occurs from glow to arc discharges.

In case (3), the lamp is operated by arc discharge but this time the cathode is heated only by I_d. The remarkable difference between cases (2) and (3) in the cathode and anode half-cycles can be referred to the fact that; in the anode half-cycle the electrode temperature is raised by electron collection and then more thermal evaporation and Ba atom loss occurs. On the other hand, in the cathode half-cycle there is some cooling of the electrode due to thermionic cooling, which is mainly electron cooling caused by thermal electron emission with an energy of $e\varphi$ (φ: work function) [7] from the cathode electrode. In fact, using a black-body radiation measurement Misono *et al* [2] have clarified that the electrode temperature increases during the anode half-cycle and decreases during the cathode half-cycle as a FL is operated at 6 Hz. In case (3), the electrode temperature is dominated only by the I_d (AC 0.29 A). It is conjectured that the electrode temperature during anode half-cycle is higher than that during cathode half-cycle. In case (2), on the contrary, the electrode temperature is dominated by I_f (DC 0.27 A) and kept constant, because the fluctuation due to the heating/cooling by I_d (AC 0.005 A) is negligibly small. This is suggested by the fact that during the anode half-cycle the LIF intensity for case (3) is larger than that for case (2), while it is smaller oppositely during the cathode half-cycle, as can be seen in Fig. 3. It is concluded that in arc discharge heat evaporation is the dominant factor of Ba atom loss from the electrode but not sputtering by ion bombardment. It is consistent with our previous considerations [4, 8].

Electrode temperature is the parameter that causes discharge mode transition; also plays an important role in the loss process in both glow and arc discharge modes. The electrode temperature, in the present work, was changed using additional filament current I_f of 0 – 0.3 A. Figure 4 shows the rms values of the discharge voltage (V_d) as a function of I_f at I_d = 0.005 A. It is clearly shown that V_d decreases with increasing of I_f. As the electrode temperature is raised by I_f, the rate of electron emission from the cathode electrode increases, and the cathode sheath potential reduces consequently, which appears as a decrease of V_d. At the same conditions the LIF signal was measured in the geometry as same as in Fig. 3. and integrated over entire period of one cycle of discharge. The integrated values of LIF are shown in Fig. 4. It can be noticed that as I_f increases to 0.2 A the Ba atom loss decreases to about 6 % of its value at I_f = 0. This behavior can be referred to the fact that; as the cathode temperature is increased the cathode sheath potential decreases due to the emission of electrons from the cathode. This decrease of cathode sheath potential causes a decrease in the energy of the bombarding ions and hence reduces sputtering yield of Ba atoms. As I_f reaches a value of 0.25 A, the Ba atom loss goes to be very low (two orders of magnitude less than for I_f = 0). Further increase in I_f (0.3 A) causes an increase of the Ba atom loss due to thermal evaporation. This change of the effect of I_f on the loss rate can be referred to the discharge mode transition from

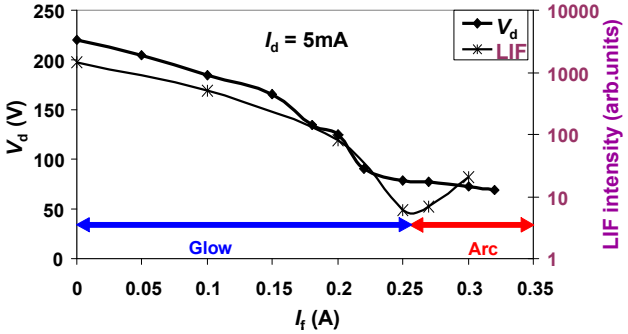

Fig. 4 LIF intensity and discharge voltage versus filament current I_f at a low discharge current (I_d=5 mA).

glow to arc, where it was found that at I_f = 0.25 A the electrode temperature is high enough to make thermionic emission [4]. These opposite effects of the electrode temperature on Ba atom loss in glow and arc discharges play an important role in the improvement of the lamp lifetime. If the lamp is operated by glow discharge (*ex.* dimming mode operation) it will be better to raise its temperature by an auxiliary current.

Figure 5(a) and 5(b) shows the spatial distribution of Ba atoms in front of the electrode in glow and arc discharge modes, respectively. Figure 5(a) was measured at the cathode half-cycle in glow discharge, and Fig. 5(b) at the first peak seen in case (3) in Fig. 3 (in arc discharge). The spatial resolution of these types of measurement was chosen to be 50 μm (x) × 2 mm (z). As can be seen in Fig. 5, the transition from glow to arc discharge affects the distribution of Ba atoms in front of the electrode. In glow discharge the Ba atoms are emitted homogeneously from all parts of the electrode. Ba atoms are sputtered due to the bombardment of ions which are accelerated in the large voltage of cathode sheath. In arc discharge the Ba atoms are mainly emitted from the hot spot of the electrode. The hot spot is the nearest point of the electrode connected to the discharge circuit. The high temperature of the hot spot results in a maximum evaporation of Ba atom from it. The emitted Ba atoms diffuse randomly as shown in Fig. 5(b). The shapes of spatial distribution in both discharge modes, confirm the change of the mechanism of Ba atom loss due to the glow-to-arc transition.

Figure 6 shows temporal distributions of Ba-LIF and electrode temperature over one cycle of 60Hz. The LIF signal was observed at (x = 0) with the same spatial resolution as Fig. 3 and 4. The spatial resolution of

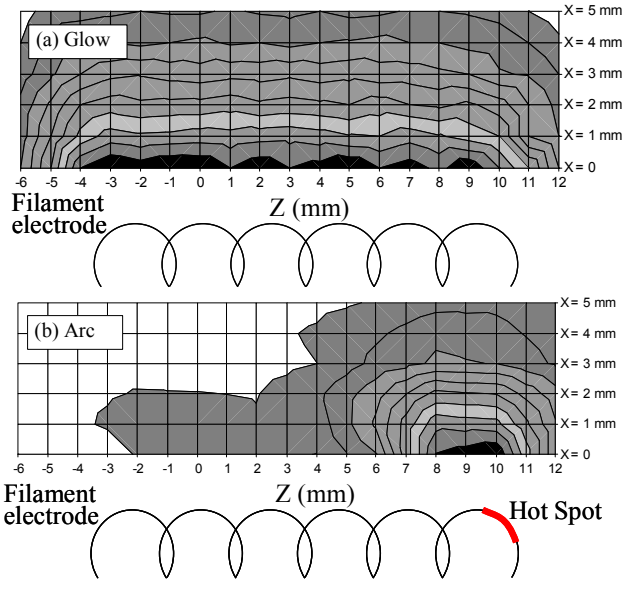

Fig. 5 Spatial distribution of Ba atoms in front of the electrode in (a) glow and (b) arc discharge modes.

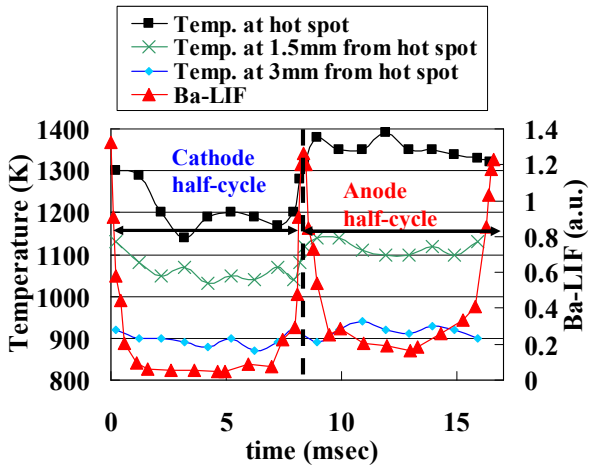

Fig. 6 Temporal distributions of Ba-LIF and electrode temperature.

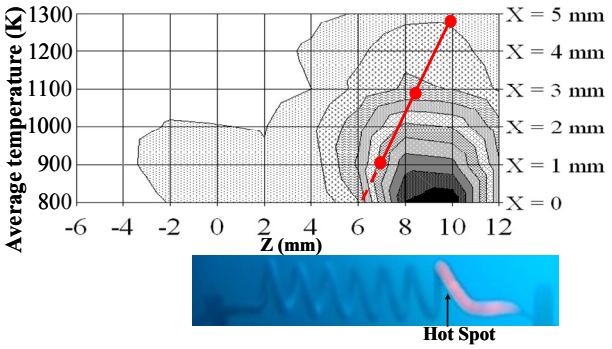

Fig. 7 Spatial distributions of Ba-LIF and temporally averaged electrode temperature. Closed circles indicate the average temperature.

temperature measurement was set to 300 μm (z) × 2 mm (x). Electrode temperature (especially at hot spot) changes following 60Hz cycle. Temperature is higher in anode half-cycle and lower in cathode half-cycle. It is mainly caused by heating due to electron incidence in anode half-cycle and by cooling due to electron emission in cathode half-cycle, as mentioned above. From these results it is considered that Ba atom loss is larger by thermal evaporation in anode half-cycle and lower by few sputtering in cathode half-cycle. It is shown that the hot spot is the most active point of electron incidence and emission and is significant to form or sustain the plasma, although it is the largest emission spot of Ba atoms.

Figure 7 shows spatial distributions of Ba-LIF and electrode temperature. This graph is plotted electrode average temperature (over one cycle) on Ba emission distributions. Temperature at hot spot is the peak, and it is also recognized Ba atom loss is mainly due to thermal evaporation from hot spot.

4. Conclusion

The LIF technique has been applied to study the

effect of glow-to-arc transition on the Ba atom loss in a low-pressure fluorescent lamp, and shown to be a powerful tool for discussing the loss mechanism. The present measurements show that in the glow discharge the Ba atoms are mainly emitted in the cathode half-cycle, while in the arc discharge an amount of Ba atoms emitted in the anode half-cycle is larger than that emitted in the cathode half-cycle. The electrode temperature has been found to play an important role in the control of the loss rate of Ba atoms, and hence the lifetime of the lamp. In glow discharge the Ba atom loss is mainly caused by the sputtering, while in arc discharge by the thermal evaporation. As the electrode temperature is raised to a high value, the discharge mode transition occurs from glow to arc even at low discharge current, also this transition causes a change in the loss mechanism.

Black-body radiation was applied to measure the electrode temperature and to study relationship between loss mechanism of Ba atom from the electrode and the temperature. Electrode temperature changes following 60Hz cycle especially at hot spot. The Ba atom loss is mainly due to thermal evaporation from hot spot, which is consistent with our previous discussion.

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