Paper

Pulsed Discharge Mercury-Free Xenon Fluorescent Lamps with Multi-Pairs of Electrodes

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ABSTRACT

The characteristics of xenon fluorescent lamp with two pairs of anode and cathode in pulsed discharge are demonstrated. By increasing the number of electrodes from one pair to two pairs, luminance is improved by 13 % and achieves 9500 cd/m^2 but estimated efficacy at a positive column is decreased from 68.0 lm/W to 45.6 lm/W . The narrow pulse width is preferred for higher luminance because a higher current density can be attained. It is also shown that there is the critical value of the energy consumed from the time when the current is turned on to the time when the current value reaches maximum and that when the energy excess this limit the discharge state changes from diffused to contracted one.

KEYWORDS: Environment, Mercury-less, Fluorescent lamp, Pulsed discharge, Diffused positive column, Contracted positive column

1. Introduction

Environmental awareness has directed the research effort into finding an alternative chemical element to directly replace the toxic mercury used in fluorescent lamps¹⁻⁵⁾. Xenon emits radiation in the ultra-violet (UV) region therefore it is one of the most promising candidates as an alternative to mercury. Nevertheless, the efficiency with which UV radiation is emitted from a xenon discharge is generally lower than that of mercury. Besides, the positive column of a xenon discharge tends to contract at high current densities and the intensity of the phosphor-converted emissions from a contracted discharge is very low. In this study, the relation between the contraction process and the pulse width used in the pulsed discharge is discussed. Moreover, two pairs of

electrodes are placed in a xenon fluorescent lamp so that the positive column in a diffused state occupies a larger volume for improving the luminance and the efficiency.

2. Experimental setup

The schematic illustration of the lamp used in this study is shown in Figure 1. Two pairs of anodes and cathodes were placed in the lamp. The dimensions are as follows: inner diameter was 26 mm and the length between anode and cathode was 50 mm. Xenon is introduced into the lamp at a pressure of 6.7 kPa, 10.7 kPa or 13.3 kPa. The lamp inner wall is coated with white phosphor, which is mixture of three

Figure 1 The schematic illustration of the lamp used in this study. Two types of the lamps were prepared: with phosphor and without phosphor

Figure 2 The circuit diagram to operate the lamps by pulsed discharge

colors. They are products of Nichia Co. Ltd. and their code numbers are NP-107(Blue), NP-220(Green) and NP-360(Red). The lamps were sustained by pulsed discharge using the circuit shown in Figure 2. In this circuit, anodes are earthed through resistances and the cathodes are connected to the power supply and negative voltage pulse is applied on the cathodes. The frequency and the pulse width were controlled by the pulse waveform input to the FET. Resistors R_1 and R_1' were used to make the current flowing the two paths equal and to limit the total value of the current flowing through the lamp. The resistance was adjusted at 50 k Ω for 6.7 kPa, 70 k Ω for 10.7 kPa and 100 k Ω for 13.3 kPa, respectively⁶⁾. Resistors R_2 and R_2' were added for measurement of the current.

For measurement of luminance of phosphor-converted emission, other lamps whose inner walls were coated by white phosphor were prepared. The other conditions such as dimensions were identical to that without phosphor. A luminance meter (TOPCON, BM-7) was placed at a 50 cm distance from the lamp. The field angle was 2 degrees.

3. Results and Discussion

3.1 State of Positive Column

Two characteristic states of positive column appeared in the xenon lamps operated by pulsed discharge: diffused and contracted positive columns. Pictures of each state are shown in Figures 3(a) and 4(a), respectively. In this experiment to observe and understand the state of positive column, a lamp with a pair of anode and cathode was used. Voltage and current waveforms corresponding to each state are also shown in Figures 3(b) and 4(b), respectively. In general, when the current is small, the positive column tends to diffuse. In this case, the current increases gradually after pulse is turned on. If the current is increased, the slope of the current waveform from turned on to the peak becomes larger, and the positive column becomes brighter and enlarged towards the glass wall. However, if the current is further increased, the positive column suddenly contracts towards the center of the lamp. In this case, the current waveform rises quickly after a little delay from the time of turn on of voltage, and voltage decreases as shown in Figure 4(b). Although the brightness of the positive column itself is high in the contracted state compared with the diffused state, the luminance of phosphor-converted emission is very low in the contracted state because its volume is small and the efficiency of vacuum ultraviolet (VUV) radiation of xenon that excites the phosphor is low. Therefore, in this study, we measured the parameters of the lamps in the brightest state, just prior to transition of the discharge state from diffused to contracted one, and we discuss the properties of the lamps with two pairs of anode and cathode.

Figure 3 (a) Picture of the positive column and (b) voltage and current waveform in the diffused state. The lamp had a pair of electrodes

Figure 4 (a) Picture of the positive column and (b) voltage and current waveform in the contracted state. The lamp had a pair of electrodes

Figure 5 shows appearances of diffused positive columns of lamps with two pairs of anodes and cathodes filled with xenon at (a) 6.7 kPa, (b) 10.7 kPa and (c) 13.3 kPa. Even in the diffused condition, especially at higher pressure, the

Figure 5 Pictures of the diffused positive column in the lamps with two pairs of electrodes. Pressure was (a) 6.7 kPa, (b) 10.7 kPa and (c) 13.3 kPa, respectively

positive column was concentrated between each anode and cathode. However, by comparing Figures 3(a) and 5(a), it becomes clear that it is possible to expand the positive column by using two pairs of electrodes

3.2 Electrical Characteristics of the Lamps

First, the luminous intensity of the phosphor-converted emission was measured under the following conditions: the pulse repetition frequency was varied from 15 kHz to 40 kHz, and pulse width was changed from 1 μ s to 5 μ s. The maximum luminance in this frequency range was achieved at 20 kHz for 6.7 kPa and 30 kHz for 10.7 kPa and 13.3 kPa.

Figure 6 The peak value of voltage waveform measured just prior to transition of the discharge state from diffused to contracted one

Figure 7 The peak value of current waveform measured just prior to transition of the discharge state from diffused to contracted one

The narrow pulse width was favorable for higher luminance. Therefore, we investigated the electrical and luminance properties just prior to transition of the discharge state from diffused to contracted one, at that frequency and pulse width.

Figure 6 shows the peak value of the voltage waveform measured just prior to transition of the discharge state from diffused to contracted one. The voltage peak was higher at higher pressure and narrower pulse width, whereas it was not so different between the lamps with a pair and two pairs of electrodes. The peak value of the current waveform is shown in Figure 7.

In the lamp with one pair of electrodes, the current peak at 10.7 kPa was abnormally small. In this case, the current tended to be more concentrated and the current density became high between anode and cathode and the positive column easily contracted. The trend was however that the

Figure 8 The peak current per one discharge path at the mode change boundary when pulse width and frequency are varied

Figure 9 The energy consumed from the time when the current turn on to the time when the current reach maximum in a pulse as functions of pulse width

current peak decreased when the pressure or the number of electrodes was increased. In the lamps with two pairs of electrodes, the positive column tends to contract easily because the current flowing the two paths attract each other. Thus the measured current peak in the lamps with two pairs of electrodes is lower than that with a pair of electrodes.

3.3 Positive Column Contraction Mechanism in the Pulsed Discharge

To clarify the mechanism of transition of the discharge state from diffused to contracted, in the pulsed discharge, we measured the energy consumed from the time when the current turned on to the time when the current reached maximum in a pulse. An example of this period is shown in Figure 8. At the state just prior to the transition from diffused to contracted positive column, this value did not vary with varying pulse width, as shown in Figure 9. This fact indicates that narrow pulse width is preferred for improving the luminance because a higher current density can be attained, as the positive column remains in the diffused state. In general, the contraction of the positive column in rare gas discharges at higher current density is caused by non-linear

Figure 10 Luminous intensities of phosphor-converted emission measured just prior to transition of the discharge state from diffused to contracted one

Figure 11 The input power to the lamp measured just prior to transition of the discharge state from diffused to contracted one

processes in the plasma such as step-wise ionization⁷⁾⁸⁾. The results show that the energy consumption mentioned above limits the excitation and ionization processes in the lamps. More detailed measurements and analysis are now in progress.

3.4 Luminance and Efficacy

Luminous intensities of phosphor-converted emission (luminance) and input power under to the lamp the conditions mentioned in the section 3.2 are shown in Figures 10 and 11, respectively. The input power W is calculated from the traces of lamp current and voltage measured by using an oscilloscope. The luminous flux F is calculated from luminance L . The flux F was calculated from the luminance L as follows:

$$F = 2 \times 9.3 \times rLL, \quad (1)$$

Figure 12 The efficacy measured just prior to transition of the discharge state from diffused to contracted one

where r and l stands for radius and length of the lamp, respectively. Here r is 13 mm and l is 50 mm. From these luminance and input power, estimated luminous efficacy at the positive column $\eta = P/W$ is obtained, and it is shown in Figure 12. This result shows that higher luminance is obtained at higher pressure. For example in the case of a pair of electrodes maximum luminance is 7028 cd/m² at 1 μ s pulse width with 10.7 kPa of pressure, and luminous flux is calculated as 85.0 lm from the equation (1). At this condition the input power is 1.25 W, therefore the luminous efficacy is calculated as 85.0 / 1.25 = 68.0 lm/W. On the other hand in the case of two pairs of electrodes case maximum luminance is 9500 cd/m² at 1 μ s pulse width with 13.3 kPa of pressure, and luminous flux is obtained as 114.9 lm. Since the input power is 2.52 W, the luminous efficacy is obtained as 114.9 / 2.52 = 45.6 lm/W.

As shown in figure 10 at 13.3 kPa, with 2 μ s pulse width by increasing the number of electrodes, luminance is improved about 13 %. In the case of 1 μ s pulse width at 13.3 kPa by using two pairs of electrodes luminance reaches 9500 cd/m². On the other hand as shown in figure 12 the efficacy decreases by increasing the number of electrodes.

Further studies will focus on the optimization of dimension and arrangement of the electrodes in order to improve the efficacy and luminance.

4. Conclusion

The characteristics of xenon fluorescent lamp with two pairs of anodes and cathodes in pulsed discharge were demonstrated. By increasing the number of electrodes from one pair to two pairs, luminance was improved by 13 % and achieved 9500 cd/m² but the efficacy was decreased from 68.0 lm/W to 45.6 lm/W. The narrow pulse width was preferred for higher luminance; it is indicated from the result that the energy consumed from the time when the current is turned

on to the time when the current reaches maximum in a pulse, did not vary as the pulse width was varied, so a higher current density can be attained by narrower pulse widths. This result also shows that this energy consumption could improve efficacy and luminance by limiting the excitation and ionization processes, which cause decrease of efficacy by energy loss by visible emission or collisions in the lamps.

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