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Radiation Characteristics of Discharge Lamps Filled with Xenon†

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This paper deals with the results obtained by recent researches aimed at developing novel xenon-filled fluorescent lamps. The critical issue of xenon-filled lamps is to prevent the contraction of its positive column, as a contracted positive column tends to emit intense infrared radiation instead of the resonance radiation required for exciting the phosphor. Many methods were attempted in order to increase the discharge current while maintaining a diffuse positive column. The multi-channel positive column is one of the most useful methods to gain high luminance with a diffuse positive column. The pulsed discharge is also an effective operating method because of the contribution from the afterglow. Further, high pressure and high voltage are required to obtain high luminance with a diffuse positive column. It is expected that the results obtained in this study are used to realize xenon-filled fluorescent lamps with high efficacy.

Key Words: Fluorescent Lamp, Xenon, Positive Column, Afterglow, Excimer Radiation

1 Introduction

The fluorescent lamp that was invented by Inman in 1938 has been actively investigated and developed especially in our country because of its high efficacy and long life, and in recent years it amounts to about 70% of all illuminating lamps manufactured in our country. The studies for realizing the fluorescent lamps with higher efficacy, longer life and high functionality are now in progress. The authors are attempting to study and develop a new type of fluorescent lamp. Conventional fluorescent lamps are filled with mercury and argon, but only mercury contributes to the emission of light from the fluorescent lamps. However, argon is also excited and emits ultraviolet radiation by pulsed discharge. Originally, this technique was first developed by the authors to control the luminous color of discharge lamps[1]. Firstly, we tried to improve the efficacy of fluorescent lamps by employing this control technique. However, the wavelength of the ultraviolet radiation from argon is too short to excite the phosphor, hence a mixture of mercury and xenon was used in the experiments. Secondly, out of concern on the environmental issue we attempted to remove the poisonous mercury from the fluorescent lamps. Extensive valuable results have been obtained by these experiments.

2 Experimental Discharge Lamps and Fill in Gases

Three types of lamp configurations were investigated in this study. The first lamp (discharge lamp I) has a single pair or multi pairs of electrodes constructed in the tube as illustrated in Fig. 1, the second lamp (discharge lamp II) has two ring electrodes twisted outside the tube apart in the direction of tube axis as shown in Fig. 2. The third lamp

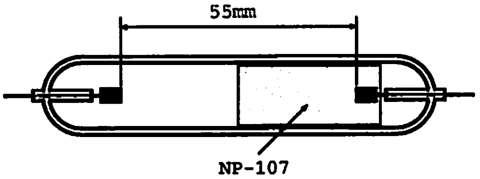

Fig. 1 Discharge lamp with inner electrodes (Discharge lamp I).

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(discharge lamp III) has two sheets of plate electrodes pasted on the opposite sides of the tube in the radial direction as shown in Fig. 3. Xenon gas was filled in all these discharge lamps. A mixture of mercury and xenon was investigated in discharge lamp I. The file xenon fill pressure is given in parenthesis in kPa, such as Xe (aa). The phosphor NP-107 is coated on the inner half surface of the tube.

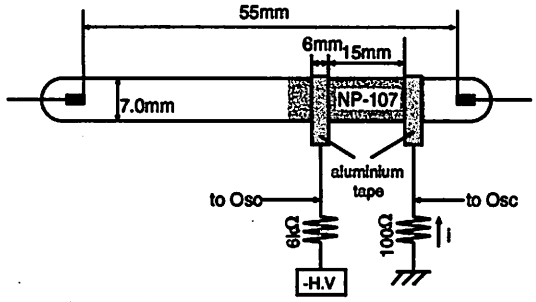


Fig. 2 Discharge lamp with external ring electrodes (Discharge lamp II).

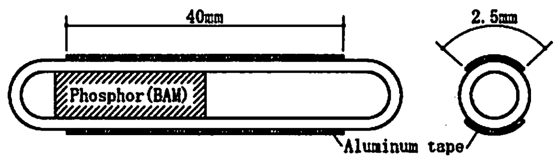


Fig. 3 Discharge lamp with external sheet electrodes (Discharge lamp III).

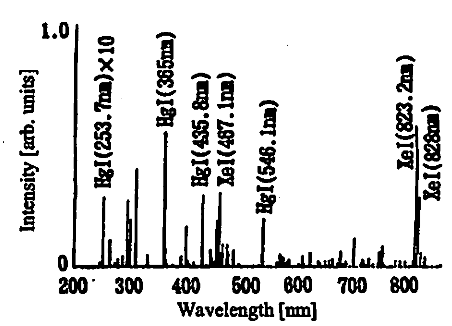
3 Experimental Results and Discussion

3.1 Discharge Lamp I: Hg-Xe Lamp with Inner Electrodes

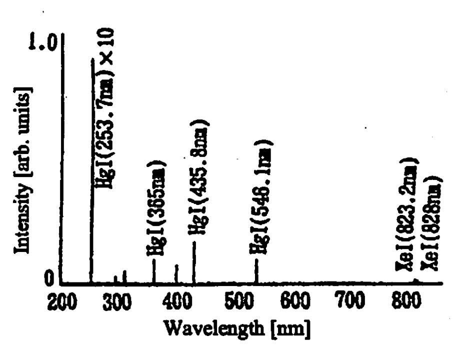
Since the excitation wavelength of phosphor is wide, it can be excited by the ultraviolet radiations from both mercury and argon. The high efficacy of fluorescent lamps may be obtained by controlling the excitation of argon by means of the technique discussed above. However, the wavelength of the resonance radiation of argon is too short for exciting the phosphor. Hence a mixture of mercury and xenon, which has the longest resonance wavelength among all rare gases, was investigated. The wavelength of the resonance radiation of atomic xenon is 147 nm and that of molecular xenon is centered at 172 nm. The discharge lamps with two or three pairs of electrodes were also investigated.

3.1.1 The Luminous States of Positive Column

The spectral distributions of the Hg-Xe (1.33) lamp with the inner diameter of 14 mm and the distance between the electrodes of 150 mm are shown in Fig. 4[2], when they were operated by a rectangular voltage with a pulse width of 15 μs at 50 Hz and a sinusoidal voltage at 28.8 kHz, respectively. The room temperature was 25 °C giving rise to a wall temperature of about 50 °C. In the case of sinusoidal discharge, the spectrum is formed predominantly by mercury emissions, while xenon emissions dominate in pulsed discharge. Neon emissions were not observed in the sinusoidal discharge of mercury-neon mixture, because the energies of the neon excited states are higher than the ionization energy of mercury, as shown in



(a) Pulsed discharge



(b) Sinusoidal discharge

Fig. 4 Emission spectra from Hg-Xe discharge lamp.

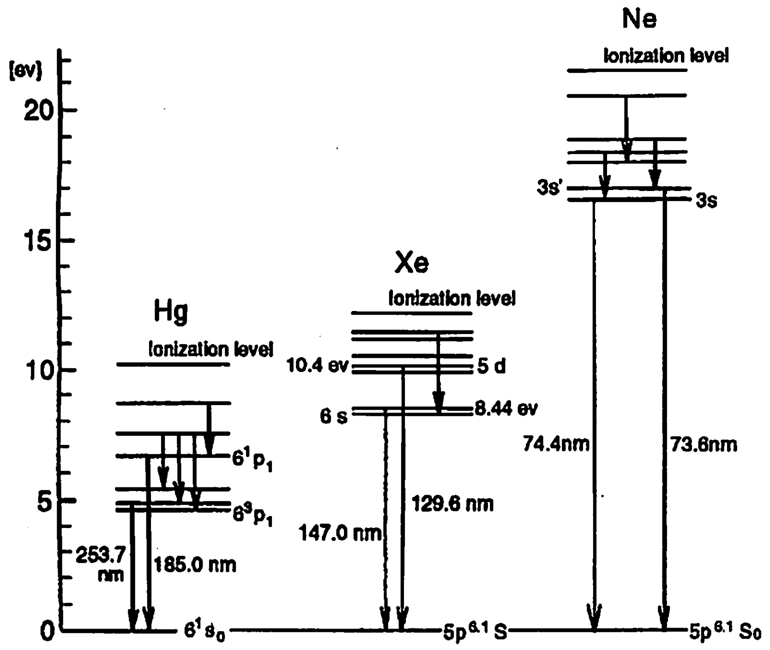


Fig. 5 Simplified energy levels of Hg, Xe and Ne.

Fig. 5[3]. In the mercury-xenon discharge, while mercury is ionized to maintain the discharge, a small amount of xenon is excited and radiates, as some excited states of xenon have lower energies than the ionization energy of mercury. On the other hand, in the case of pulsed discharge, xenon is excited in the rising edge of the current and emits the strong spectra. As shown in Fig. 6[4], mercury mainly emits during the discharge period and xenon emits more intensely during the afterglow period. This is because during the afterglow period, the electron temperature is low and xenon molecules (excimer) are formed by three-body-collisions between two ground state xenon atoms and a metastable xenon atom according to:

$$Xe^m + 2Xe \rightarrow Xe_2^* + Xe. \qquad (1)$$

The excimer emits radiation when it transfers to the ground state through the radiation process:

$$Xe_2^* \rightarrow Xe_2 + h\nu, \qquad (2)$$

where Xe and Xe^m denote the ground state and the metastable state of atomic xenon respectively, Xe_2 and Xe_2^* denote the ground state and the excited state of molecular xenon respectively, and $h\nu$ denotes the radiation. Since the molecular xenon at the ground state is unstable, it instantly dissociates into two ground state atoms. The three-body-collision process of mercury atoms does not take place because of its low pressure.

The luminous state of a positive column changes by varying the discharge current, the frequency and the pulse width. Fig. 7[5] shows the three kinds of positive columns obtained from an Hg-Xe (20) discharge lamp. In Fig. 7 (a), the luminous part of a positive column completely diffuses. This is the diffuse positive column. Fig. 7 (b) shows a narrow and bright filamentary positive column. This is the contracted positive column. The positive column shown in Fig. 7 (c) shows a partially contracted positive column surrounded by a diffuse positive column. This is known as the coexistence positive column. The conditions of the current, the frequency and the pulse width where the diffuse, the contracted and the coexistence positive columns occur are changed as the xenon pressure.

Fig. 8[5] shows the luminous states of the Hg-Xe lamps with an inner diameter of 7 mm and a distance between electrodes of 55 mm, when they were operated at various discharge currents and the frequencies. The xenon pressures studied are (a) 6.7 kPa, (b) 11 kPa, (c) 14.6 kPa and (d) 20 kPa. At the constant frequency, as the discharge current increases, the positive column changes from the diffuse state to

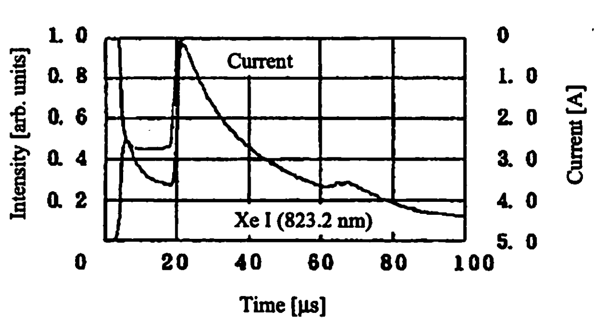
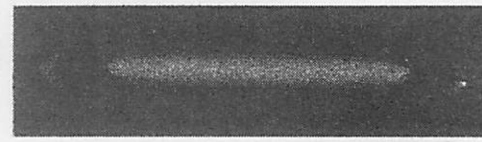


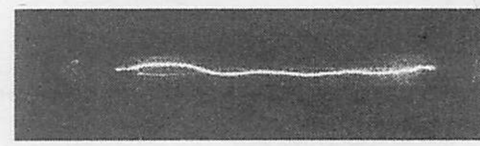
Fig. 6 Xenon radiation waveform in the pulsed discharge.

the contracted state by passing through the coexistence state. As the frequency is increased from 1 kHz, the discharge current required for maintaining a diffuse positive column gradually increases to a maximum value and then starts to decrease. The maximum discharge current required for maintaining a diffuse positive column increases as the xenon pressure increases. The maximum current is obtained at the frequency of 10 kHz for the Hg-Xe (6.7) lamp and at the frequency of 30 kHz for the Hg-Xe (20) lamp. Below 10 kHz, the maximum discharge current for maintaining a diffuse positive column decreases as the xenon pressure increases.

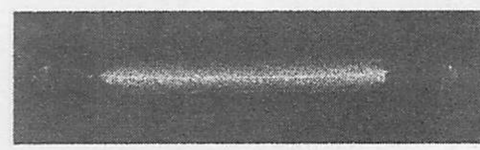
Fig. 9[5] shows how the luminous state of the Hg-Xe lamp changes when the xenon pressure and the operating frequency are varied. When the operating frequency is increased at a constant xenon pressure, the positive column changes from the contracted state to the co-existence state, then to the diffuse state, and later returns to the co-existence state,



(a) Diffuse positive column

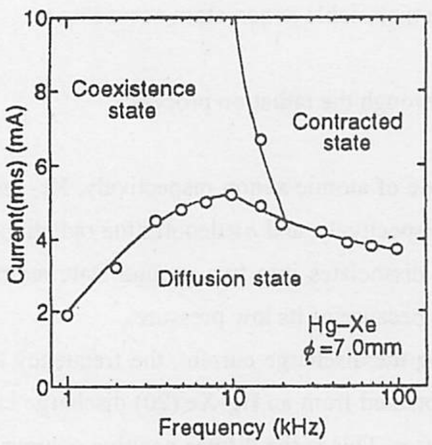


(b) Contracted positive column

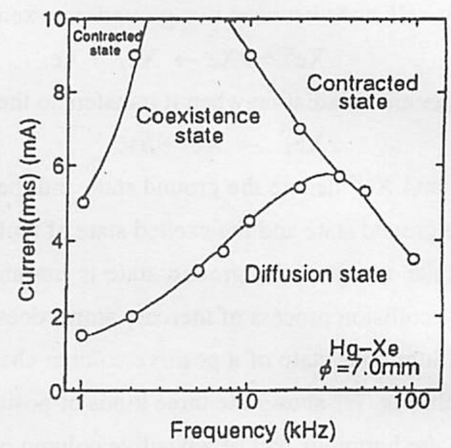


(c) Co-existence positive column

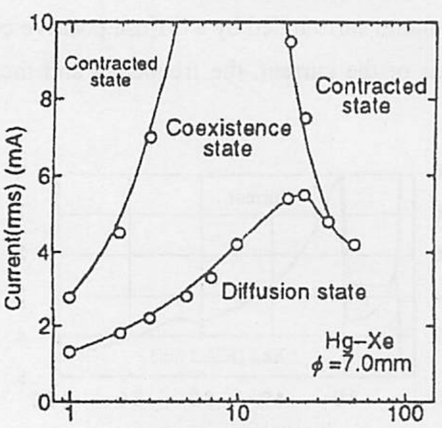
Fig. 7 Three different states of positive column.



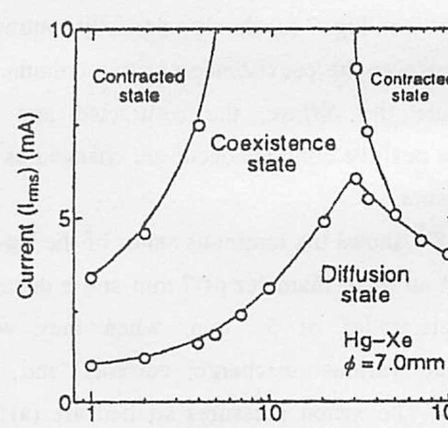
(a) 6.7 kPa



(b) 11 kPa



(c) 17 kPa



(d) 20 kPa

Fig. 8 Luminous states of the Hg-Xe lamps as a function of current and frequency.

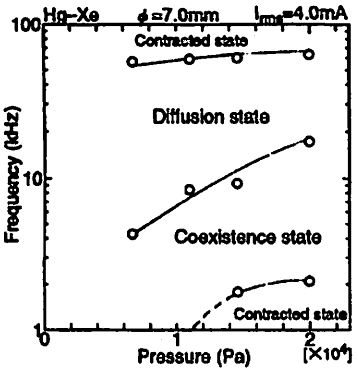


Fig. 9 Luminous states of the Hg-Xe lamps as a function of frequency and pressure.

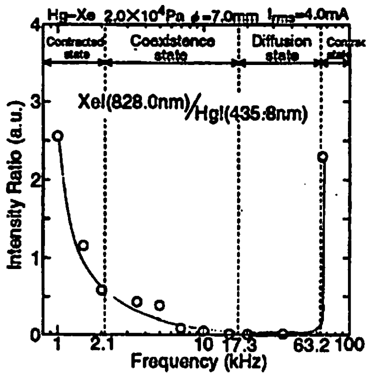
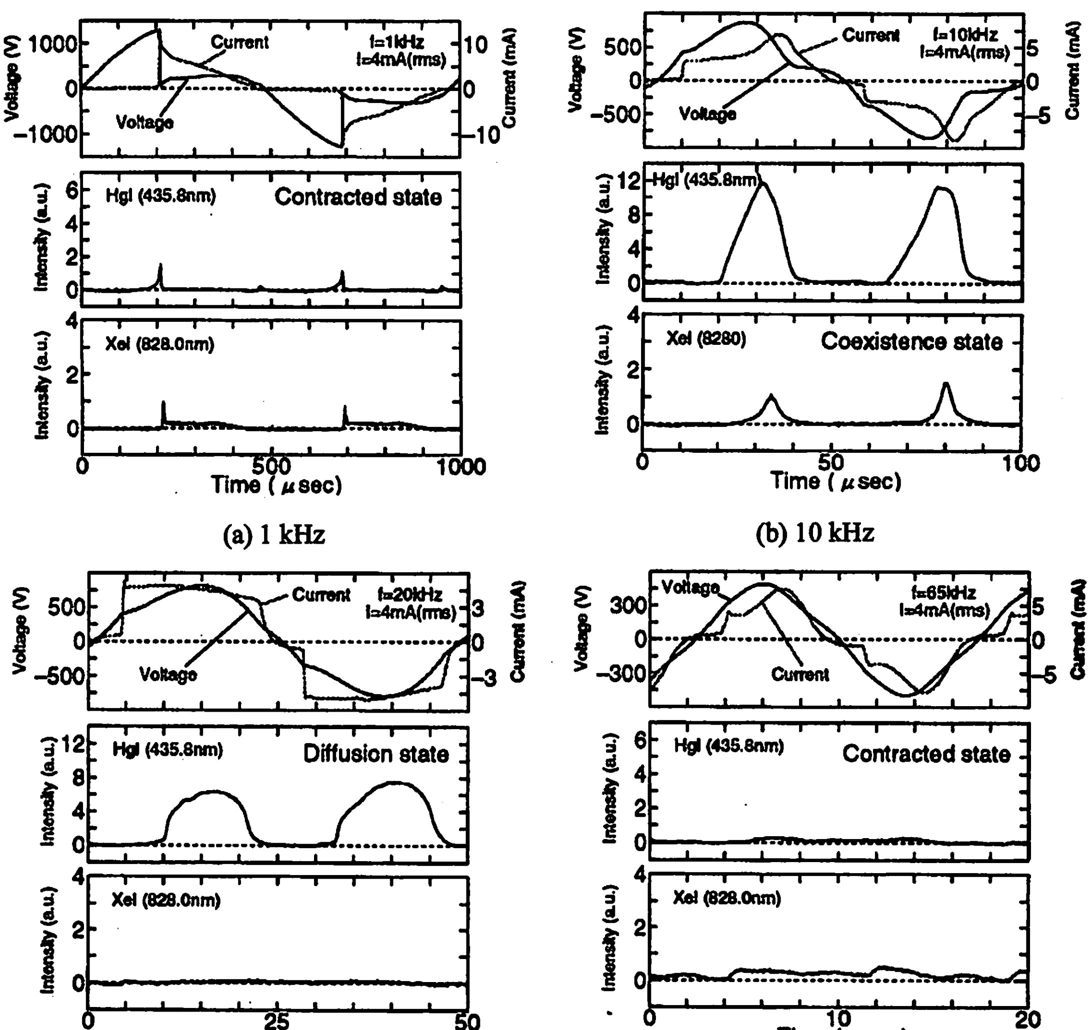


Fig. 10 The emission intensity ratio of Xe I (8280) to Hg I (4358) as a function of frequency.

and finally to the contracted state. At high xenon pressures, the frequency range in which a diffuse positive column can be maintained becomes narrower. The ratio of the intensity of Xe I (8280) to the intensity of Hg I (4358) is shown in Fig. 10[5]. The numerical values in the parenthesis denote the wavelengths in Å unit. Hg I and Xe I indicate the neutral atoms of mercury and xenon respectively. The mercury emissions are more intense with the diffuse positive column; on the other hand, the xenon emissions are more intense with the contracted positive column. The spectral intensities of mercury and xenon with the coexistence positive column lie between these two extreme conditions.



(a) 1 kHz (b) 10 kHz

(c) 20 kHz (d) 65 kHz

Fig. 11 The voltage, the current and the Hg and Xe radiation waveforms.

3.1.2 Atomic Processes in Sinusoidal Discharge

The voltage, current and radiation waveforms of Hg I (4358) and Xe I (8280) of the Hg-Xe (20) lamps are shown in Fig. 11[5], when it is operated by a sinusoidal voltage at a constant discharge current of 4 mA (rms).

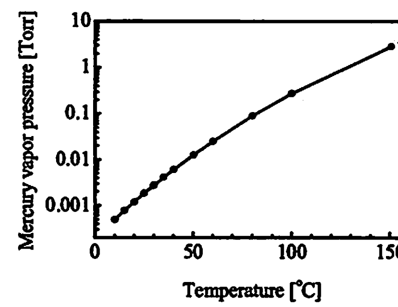
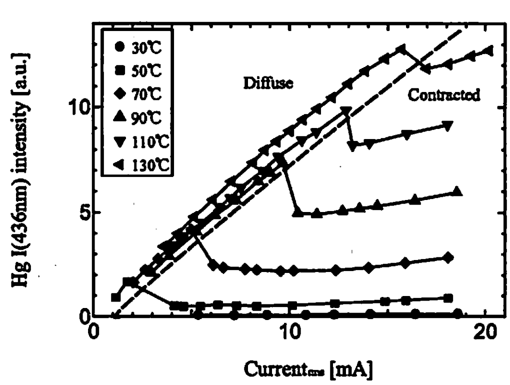


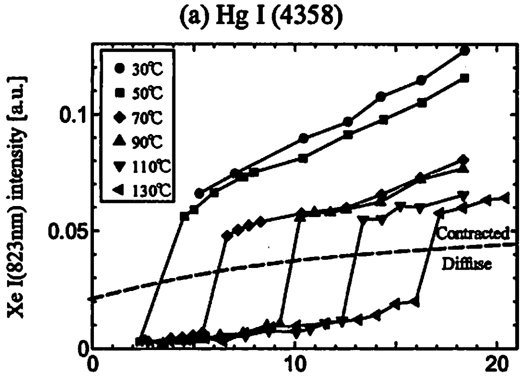
Fig. 12 The mercury vapor pressure as a function of temperature.

(1) The case of 1 kHz (Fig. 11 (a))

When the applied voltage reaches 1260 V, the lamp re-ignites and immediately an arc discharge is initiated. The tube voltage decreases sharply to about 250 V and remains at that value while the arc discharge continues. The discharge current increases rapidly to 12.9 mA and then decreases gradually. A high electron temperature is obtained during the high rate of increase of discharge current. Hg I (4358) is emitted at the same time as the discharge starts and becomes weak while the tube voltage is low. On the other hand, Xe I (8280) is emitted after the discharge current reaches to its peak and continues to emit throughout discharge. This phenomenon is explained as the follows. Since mercury has lower excitation energies compared to xenon, as the electron temperature rises after re-ignition, the mercury is first excited and is later followed by the excitation of xenon.



(a) Hg I (4358)



(b) Xe I (8232)

Fig. 13 The relations of the emissions Hg I (4358) and Xe I (8232) to the discharge current at various temperatures.

The vapor pressure of mercury is 1.7 Pa at 50 °C hence the xenon pressure is more than three orders of magnitude of the mercury vapor pressure. Therefore appreciable formation of Xe^m occurs during the high electron temperature. These atoms are related to the excitation and the ionization of xenon for maintaining the discharge, as given by the following:

$$e\,(high) + Xe^m \rightarrow e\,(low) + Xe^*, \quad (3)$$

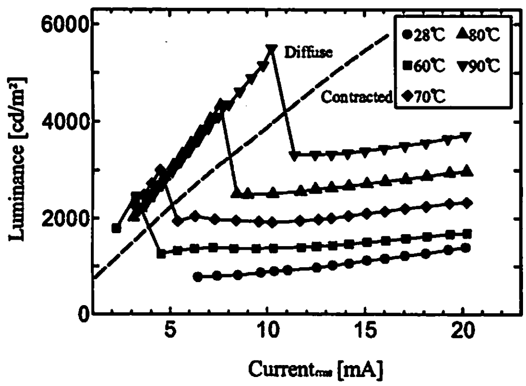
$$e\,(high) + Xe^m \rightarrow 2e\,(low) + Xe^+, \quad (4)$$

where Xe^* and Xe^+ denote an excited xenon atom and a xenon ion respectively, and e (high) and e (low) denote electrons of high speed and of low speed respectively.

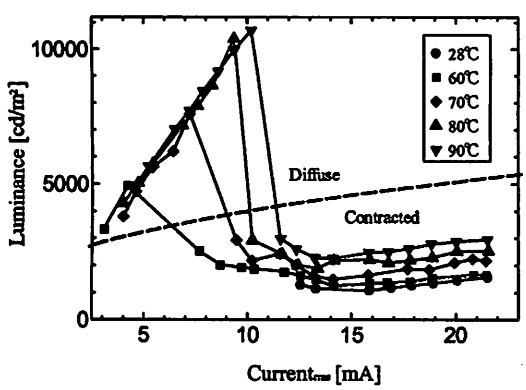
The contracted positive column is formed in the discharge in which xenon emits strong radiation.

(2) The case of 10 kHz (Fig. 11 (b))

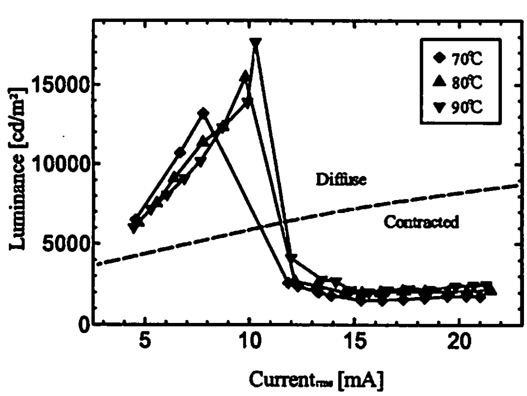
In this case, the glow discharge starts at the applied voltage of about 540 V, which is lower than the re-ignition voltage at 1 kHz, because many metastable xenon atoms and xenon ions are left behind from the previous discharge cycle due to the short non-discharge period. When the discharge current increases slowly in the beginning and reaches about 4 mA, arc discharge begins and the current rises sharply. Mercury emits strongly in the period of glow discharge because the potential difference in the positive



(a) 6.7 kPa



(b) 26.7 kPa



(c) 39.9 kPa

Fig. 14 Relations of the luminance to the discharge current at various temperatures.

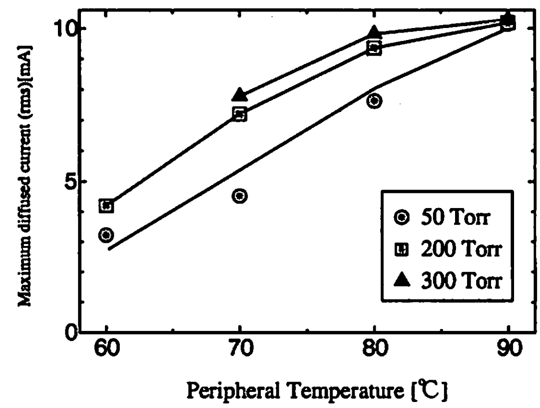


Fig. 15 The maximum current capable of maintaining a diffuse positive column as a function of temperature at three different pressures.

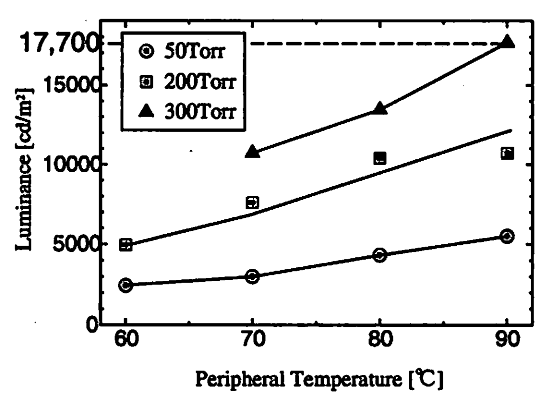


Fig. 16 The luminance as a function of temperature at three different pressures.

column is small as a result of the large cathode drop. In the period of arc discharge, xenon is excited by the large potential difference in the positive column due to the small cathode drop and emits intensely. The luminous state appears diffuse during the glow discharge and contracted on the arc discharge. On average, the positive column appears as a coexistence column.

(3) The case of 20 kHz (Fig. 11 (c))

The re-ignition occurs at about 410 V and the glow discharge starts with high densities of residual ions and metastable atoms. The discharge remains at the diffuse state and does not enter into the contracted state, since the applied voltage increases slowly and remains low. In this case, only mercury is excited and ionized under the low electron temperature. The positive column is at the diffuse state.

(4) The case of 65 kHz (Fig. 11 (d))

The re-ignition starts at 220 V due to the high density of residual Xe^m. The cumulative excitation and ionization of xenon given by eqs. (3) and (4) take place actively. These processes require a low electron energy less than 4 eV, which is below the resonance energy of mercury. Therefore mercury contributes weakly to the discharge and the positive column appears as the contracted state.

3.1.3 Influence of Tube Temperature

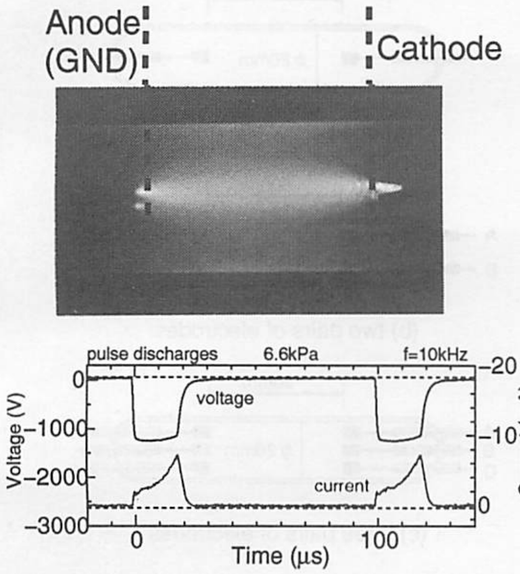
The relations of the emissions Hg I (4358) and Xe I (8232) to the discharge current for the Hg-Xe (13.3) discharge lamp with the inner diameter of 3.8 mm and the distance between the electrodes of 80 mm are shown in Fig. 13[6], when this lamp was set inside an electric oven capable of a temperature control from 30 °C to 130 °C and the discharge was running. The intensity of Hg I (4358) increases in proportion to the discharge current up to certain current value and then falls down abruptly, and after that increases slowly. The higher the tube temperature is, the larger the discharge current is at the point where the Hg I (4358) intensity falls. On the other hand, as the discharge current increases, the intensity of Xe I (8232) increases gradually, rises sharply at a certain current value, and after that increases slowly again. The higher the tube temperature is, the larger the discharge current is at the point where the Xe I (8232) intensity rises. The point at which the Hg I (4358) intensity falls coincides with the point at which the Xe I (8232) intensity rises sharply. At this point, the diffuse positive column transforms into the contracted column.

As the tube temperature rises, mercury vapor pressure increases almost exponentially as shown in Fig. 12, but the increase of xenon pressure is small. The positive column keeps the diffuse state during the discharge under small current is maintained by mercury. For the discharge requiring large current, xenon participates in the discharge, and the contracted positive column is formed.

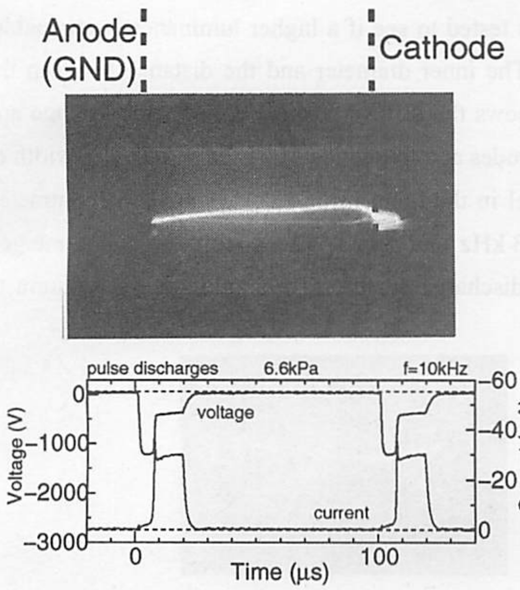
Fig. 14[6] shows the relations of the luminance of phosphor to the discharge current for the Hg-Xe lamp with the inner diameter of 3.8 mm and the distance between electrodes of 80 mm. Xenon pressures are 6.7 kPa, 26.6 kPa and 39.9 kPa and the temperature inside the oven was varied from 28 °C to 90 °C. The luminance of phosphor increases in proportion to the discharge current in the region of diffuse positive column, but it decreases to low value in the contracted region. The same tendency was observed for the intensity of mercury radiation. As shown in Fig. 15[6], the discharge current at the dropping point of luminance, that is, the maximum current capable of maintaining a diffuse positive column, becomes large at high tube temperature and high xenon pressure. At the same tube temperature, a higher luminance may be obtained from the discharge at higher xenon pressure as shown in Fig. 16[6]. This phenomenon is explained by the following. The low electron temperature appropriate for exciting mercury to the resonance level is achieved by the increase of elastic collisions with xenon atoms at high xenon pressure. The maximum luminance of 17700 cd/m^2 was obtained from the Hg-Xe (39.9) discharge lamp at the tube temperature of 90 °C and the discharge current of 10.4 mA.

3.2 Discharge Lamp I: Xe Lamp with Inner Electrode

The voltage and the current waveforms and the photographs of the positive column for a diffuse and a contracted discharge are shown in Fig. 17[7], when a Xe (6.6) lamp with the inner diameter of 26 mm and the distance between the electrodes of 50 mm was operated by a pulse voltage with a pulse width of 18 μs and a repetition frequency of 18 kHz. Fig. 17 (a) shows the voltage and the current waveforms and the luminous state of a diffuse positive column. The discharge current increases slowly to 9 mA at the end of the pulse. Fig. 17 (b)

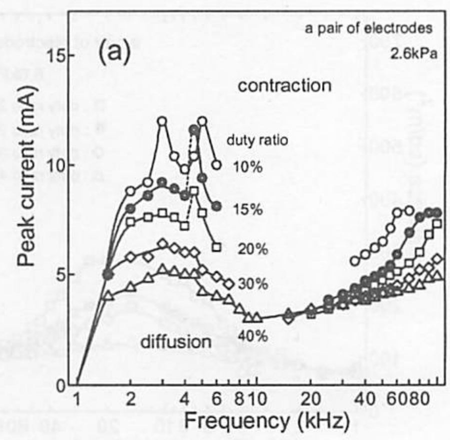


(a) diffuse positive column

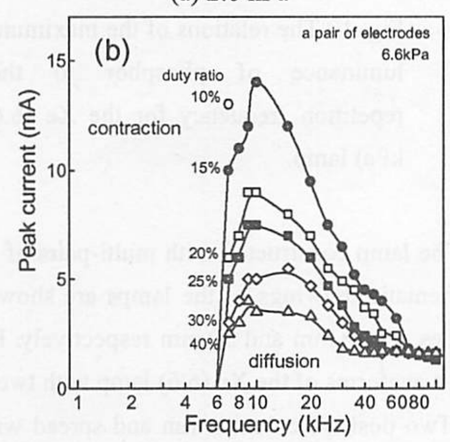


(b) contracted positive column

Fig. 17 The voltage and the current waveforms and the photographs of the positive column in a diffuse and a contracted state.



(a) 2.6 kPa



(b) 6.6 kPa

Fig. 18 The relations of the maximum current required to maintain diffuse positive columns to the repetition frequency with the duty ratios as a parameter.

shows waveforms and the luminous state of the contracted positive column. The discharge current rises to 25 mA immediately after the pulse voltage is applied, and its value remains during a pulse. The diffuse and the contracted positive columns may be formed in a Xe lamp as in an Hg-Xe lamp. Fig. 18[8] shows the relations of the maximum current required to maintain a diffuse discharge before it is transformed into a contracted discharge to the repetition frequency with the duty ratios as a parameter. Fig. 18 (a) and (b) show the relations at the xenon pressure of 2.7 kPa and 6.6 kPa respectively. The region of diffuse positive column occupies the area below these curves. As the duty ratio decreases, the discharge current required for maintaining a diffuse positive column increases. The diffuse positive column does not appear below the frequencies of 1 kHz at 2.6 kPa, and 6 kHz at 6.6 kPa. The maximum current reaches 14 mA at 10 kHz.

Fig. 19[8] shows the relations of the maximum luminance of phosphor to the repetition frequency for the Xe (6.6) lamp. The maximum luminance of 290 cd/m^2 is obtained at about 20 kHz. A high luminance cannot be obtained by this type of lamp, because the current capable of maintaining a diffuse positive column is small.

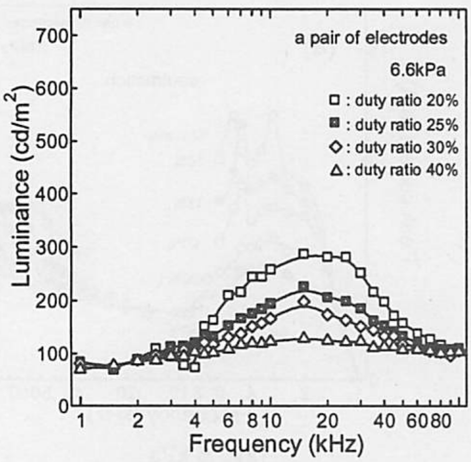


Fig. 19 The relations of the maximum luminance of phosphor to the repetition frequency for the Xe (6.6 kPa) lamp.

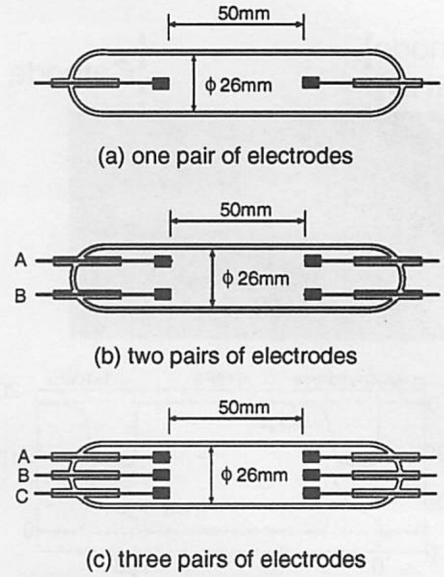


Fig. 20 The schematic drawings of the lamps with multi-pairs of electrodes.

The lamp constructed with multi-pairs of electrodes was tested to see if a higher luminance is attainable. The schematic drawings of the lamps are shown in Fig. 20. The inner diameter and the distance between the electrodes are 26 mm and 50 mm respectively. Fig. 21 (a)[8] shows the diffuse positive column and voltage and current waveforms of the Xe (6.6) lamp with two pairs of electrodes at a frequency of 7 kHz and a pulse width of 27 μs. Two positive columns run and spread widely in parallel in the tube. Fig. 21 (b)[8] shows the contracted positive column and the voltage and current waveforms at 3 kHz and 50 μs. The positive columns merged closely into each other. Fig. 22[8] shows the relations of the discharge current of a single positive column to

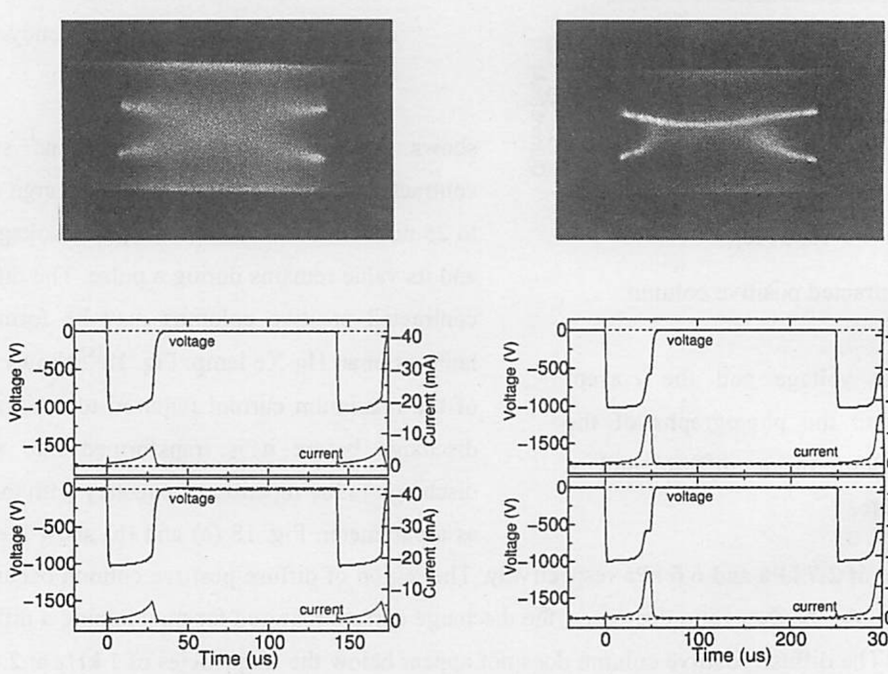
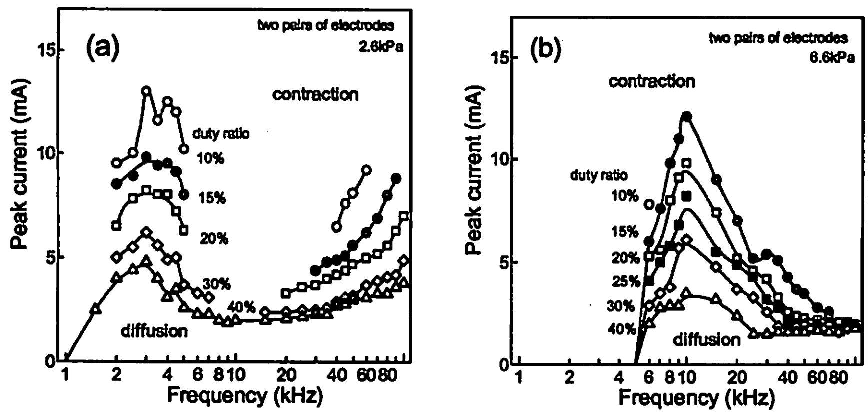
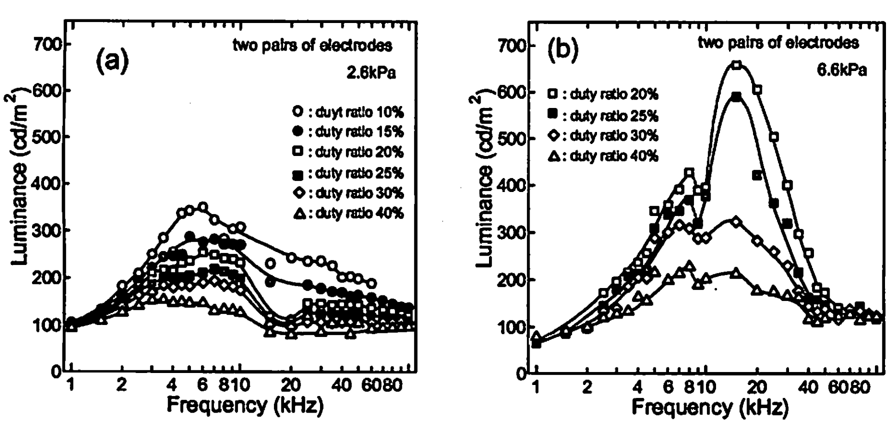


Fig. 21 Photographs of positive column and voltage and current waveforms of the Xe (6.6 kPa) lamp with two pairs of electrodes.



(a) 2.6 kPa (b) 6.6 kPa

Fig. 22 The relations between the peak current and the frequency with two pairs of electrodes.



(a) 2.6 kPa (b) 6.6 kPa

Fig. 23 The relations between the luminance of phosphor and the frequency with two pairs of electrodes.

frequency at the xenon pressures of 2.6 kPa and 6.6 kPa with duty ratios as a parameter. These relations are similar to those of the discharge lamp with a single pair of electrodes. Therefore the total current of a lamp with two pairs of electrodes is twice of that of a lamp with a single pair of electrodes. Fig. 23[8] shows the relations between the luminance of phosphor and the frequency. The maximum luminance of the Xe (6.6) lamp with two pairs of electrodes is 660 cd/m^2 at 15 kHz. This luminance value is more than twice of that of the Xe (6.6) lamp with a single pair of electrodes.

Fig. 24[8] illustrates the picture of a diffuse positive column and the voltage and the current waveforms when the Xe (2.6) lamp with three pairs of electrodes is operated at 10 kHz and 10 μs. Three diffuse positive columns run abreast and spread in the tube. When the discharge current or the pulse width is increased, three positive columns have merged into one another to form a single contracted positive column. Fig. 25[9] indicates the relations between the frequency and the maximum current per diffuse positive column of a lamp with three pairs of electrodes. The diffuse state cannot be realized below 2 kHz. The maximum current of diffuse positive column is obtained at 3 kHz and its value is nearly equal to that of the lamp with a single pair or two pairs of electrodes. Therefore, the total maximum current capable of maintaining a diffuse discharge for a lamp with three pairs of electrodes is about three times of that of the lamp with a single pair of electrodes. Fig. 26[10] shows the relations of the phosphor luminance of the Xe (2.6) lamp with three pairs of electrodes to the repetition frequency. The maximum luminance of 420 cd/m^2 is obtained at the frequency of 9 kHz and the duty ratio of

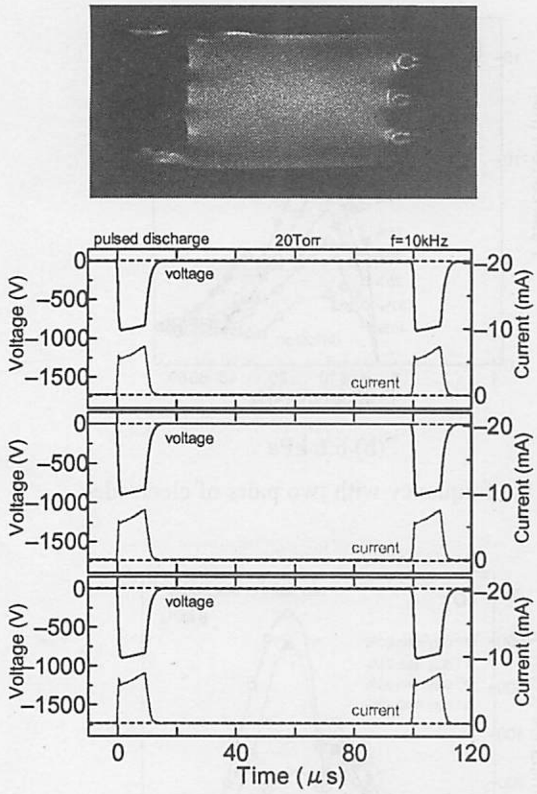


Fig. 24 Photograph of a diffuse positive column and the voltage and the current waveforms of the Xe (2.6 kPa) lamp with three pairs of electrodes

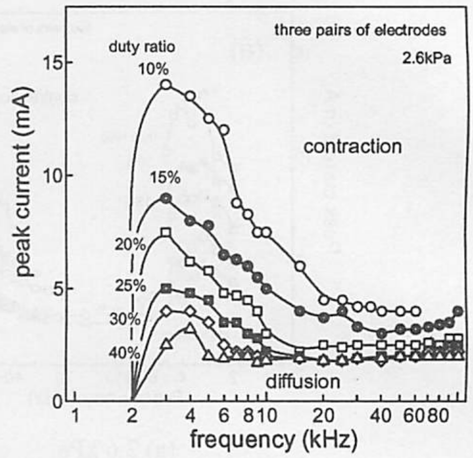


Fig. 25 The relations between the frequency and the maximum current per diffuse positive column of a lamp with three pairs of electrodes.

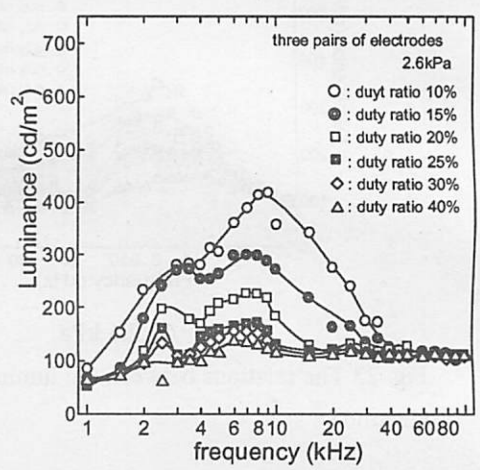


Fig. 26 The relations of the phosphor luminance with three pairs of electrodes to the repetition frequency

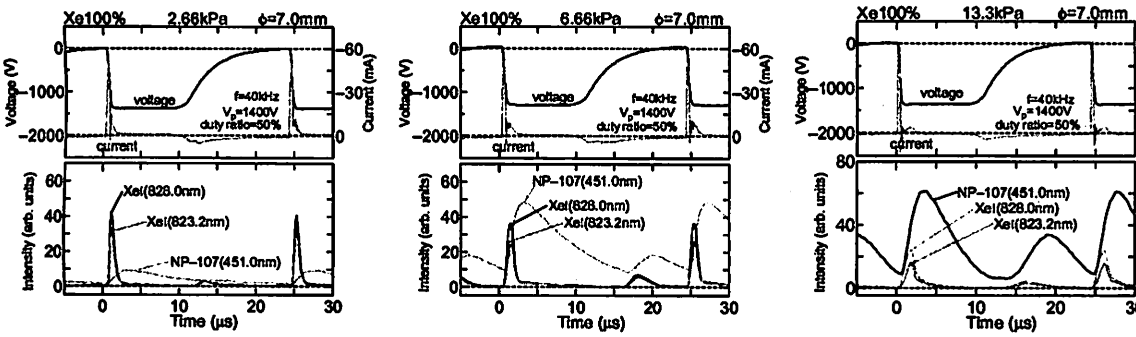
10%.

Higher luminance may be obtained by using discharge lamps with larger number of electrode pairs, because the maximum current per positive column maintains a nearly equal value regardless of the number of electrode pairs.

3.3 Discharge Lamp II: Xe Lamp with External Ring Electrodes

The discharge lamp with external electrodes is often called the electrode-free discharge lamp. Since external electrodes are not in direct contact with the plasma inside a lamp, the life of electrodes may be extended and a wide range of materials may be used as electrodes. Glass layer, acting as a dielectric barrier, between the electrodes and the plasma prevents excessive current from flowing into the plasma. Since glass works as a barrier to the current flow, this type of discharge is often called a barrier discharge. Because the excessive current is prevented by the glass layer, the positive column does not contract easily with a barrier discharge even if a current limiting gear known as ballast is not equipped.

The voltage, current and the radiation waveforms of Xe I (8232), Xe I (8280) and the phosphor NP-107 are shown in Fig. 27[11], when the lamp which has two ring electrodes of 6 mm width that are 15 mm apart and has the inner diameter of 7 mm, is operated by pulse voltage with a magnitude of 1400 V, repetition frequency of 40 kHz and duty ratio of 50%. Xenon fill pressures are 2.6 kPa, 6.7 kPa and 13.3 kPa. Large current spike flows



(a) 2.6 kPa (b) 6.6 kPa (c) 13.3 kPa

Fig. 27 The voltage, current and the radiation waveforms of Xe I (8232), Xe I (8280) and the phosphor NP-107.

immediately after the application of voltage. The current spike flows again at the cut-out of the voltage. The radiation from phosphor continues to emit throughout the discharge and non-discharge period. Three-body-collisions occur actively in a low electron temperature condition after the end of the pulse. Xenon excimer radiation centered at 172 nm increases as xenon pressure increases as shown in Fig. 28[12]. Therefore, more intense radiation from phosphor is obtained at higher xenon pressures.

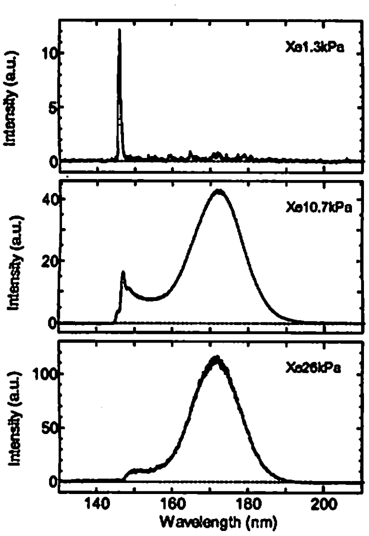
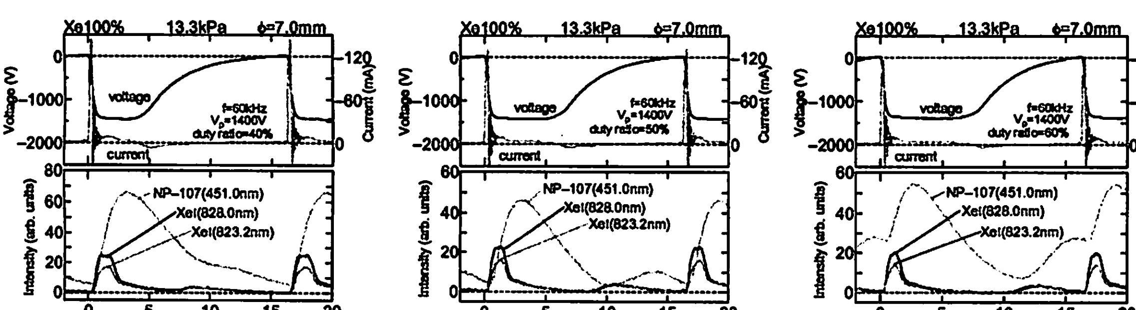


Fig. 28 Change of xenon VUV emission spectra attributed to the change of pressure.

Fig. 29[11] shows the voltage, current and radiation waveforms of Xe I (8232), Xe I (8280) and the phosphor NP-107, when the Xe (13.3) lamp is operated by pulse voltage at various duty ratios. Figs. 29 (a), (b) and (c) represent waveforms at the duty ratios of 40%, 50% and 60% respectively. Since the three-body-collisions are active with the abundant metastable xenon atoms generated in the discharge with long pulse, the larger the duty ratio is, the more intense the afterglow becomes.

3.4 Discharge Lamp III: Xe Lamp with External Sheet Electrodes

The relations between the input power and the luminance of phosphor for the Xe (13.3) lamp are shown in Fig. 30[12], when the



(a) 40% (b) 50% (c) 60%

Fig. 29 The voltage, current and the radiation waveforms of Xe I (8232), Xe I (8280) and the phosphor NP-107 at various duty ratios.

lamp is operated by pulse voltage at various frequencies and pulse width of 1.5 μs. Two sheet electrodes of 5 mm × 80 mm in size are attached on the opposite sides of tube surface. The input power per pulse to the lamp is limited by the electrostatic capacity of the glass immediately under an electrode. The high luminance may be obtained at high frequency because the input power increases in proportion to the frequency independently of the pulse width. As the frequency increases at a constant input power, the power during the pulse on period becomes shorter and the luminance decreases. As the xenon pressure increases, three-body-collisions take place more frequently and the luminance increases. The luminance of 4900 cd/m^2 is obtained at the xenon pressure of 26 kPa, the frequency of 90 kHz and the input power of 3.6 W.

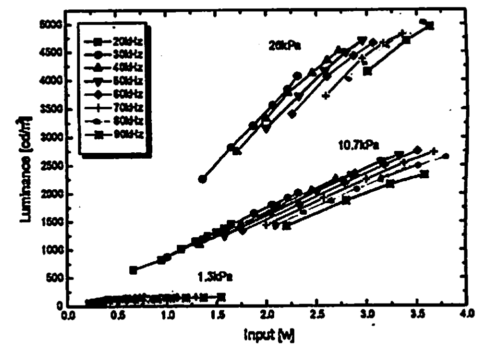
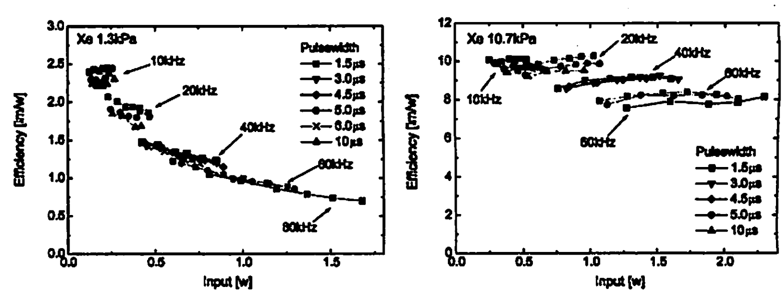


Fig. 30 The relations between the input power and the luminance of phosphor at pulse width of 1.5 μs.

Figs. 31 (a) and (b)[13] show the relations of the efficacy to input power at the xenon pressures of 1.3 kPa and 10.7 kPa respectively. As the frequency increases at a constant input power, the afterglow decreases and then efficacy decreases. At low xenon pressure, the radiation during the pulse on period is stronger than that of the afterglow. As the input power continues to increase at low xenon pressure, the intensity of radiation gradually saturates. Consequently the efficacy decreases. On the other hand, the radiation of afterglow is strong at high xenon pressures. As increasing input power, the afterglow becomes stronger. Hence the efficacy remains at a rather fixed value.



(a) 1.3 kPa (b) 10.7 kPa

Fig. 31 The relations of the efficacy to input power at the xenon pressure of 1.3 kPa and 10.7 kPa.

The electrostatic capacity C of the glass under a sheet of plate electrode is given by

$$C = \varepsilon \frac{S}{t}, \qquad (5)$$

where ε, S and t denote the permittivity, surface area of the plate electrode and thickness of the glass respectively.

Fig. 32[14] shows the relations between the illuminance and the input power of the Xe (13.3) lamp attached with two sheets of 2.5 mm × 40 mm aluminum plate as external electrodes when the lamp is operated at 40 kHz by pure and half-wave rectified sinusoidal voltages. The illuminance of the lamp of 0.2 mm glass thickness is more than two times higher than that of the lamp of 0.5 mm glass thickness.

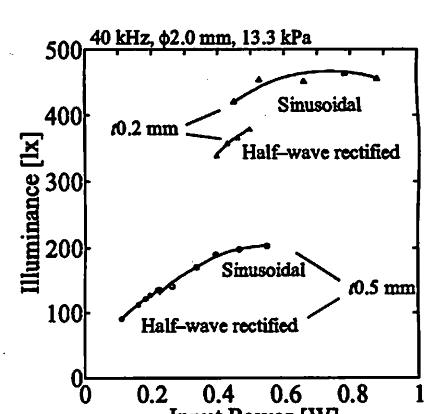
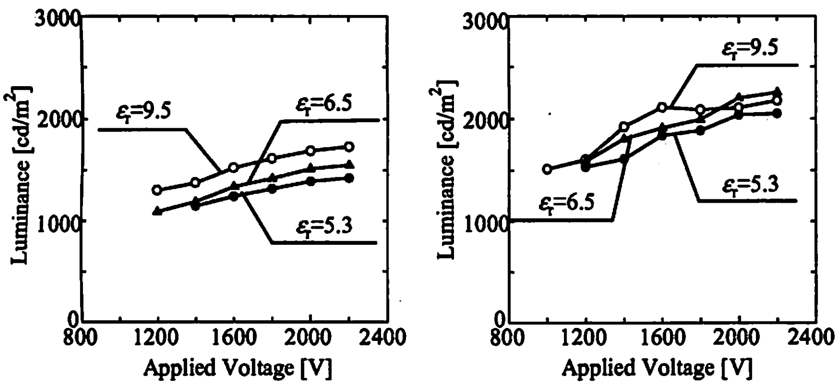


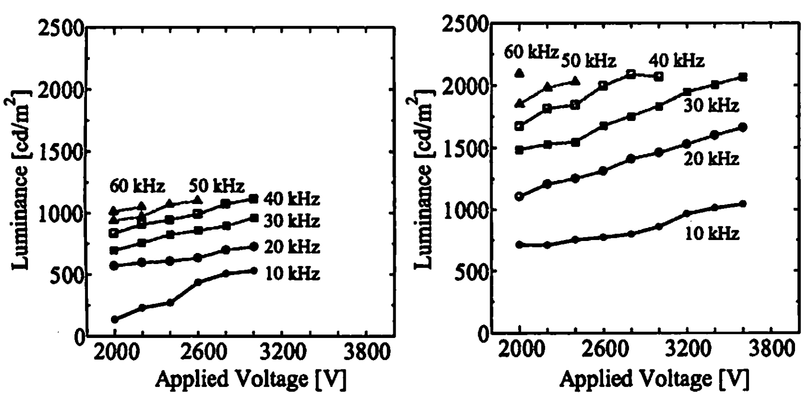
Fig. 32 The relations between the illuminance and the input power.

Fig. 33[15] gives the relations between the luminance of phosphor and the voltage for the Xe (13.3) lamp operated by the



(a) 30 kHz (b) 60 kHz

Fig. 33 The relations between the luminance of phosphor and the voltage for the Xe (13.3 kPa) lamp operated by the sinusoidal voltages at 30 kHz and 60 kHz.



(a) 5 mm × 80 mm (b) 10 mm × 80 mm

Fig. 34 The relations of the luminance of phosphor to the sinusoidal voltage for the Xe (13.3 kPa) lamp with electrodes of different sizes.

sinusoidal voltages at 30 kHz and 60 kHz. The relative permittivities of the tube glasses are 5.3, 6.5 and 9.5. High luminance is obtained with glass of high permittivity. However the luminance does not increase considerably with the increasing permittivity.

Fig. 34[15] indicates the relations of the luminance of phosphor to the sinusoidal voltage for the Xe (13.3) lamp III with electrodes of different sizes, 5 mm × 80 mm and 10 mm × 80 mm, at frequencies from 10 kHz to 60 kHz. Higher luminance is obtained by using electrode of lager surface area, but it does not increase in proportion to the surface area. The edge effect around the electrode circumference is likely to cause the reduction of luminance.

Fig. 35[16] shows the relations of the luminance of phosphor to the sinusoidal voltage for the Xe (46.6) lamp with the inner diameter of 2 mm, the glass thickness of 0.5 mm and the electrode surface area of 2.5 mm × 40 mm, at frequencies from 10 kHz to 60 kHz. The discharge during a half cycle takes place once at the low voltage and another at the high voltage as shown in Fig. 36[17]. The luminance increases sharply by applying a voltage between 2000 V and 2400 V at a frequency higher than 20 kHz. This is understood as follows. After the electric charge accumulated on the inner surface of the discharge tube is neutralized by the first discharge in the half cycle, if the potential difference across the tube due to the charge induced by the applied voltage exceeds over the starting voltage of discharge, a second discharge occurs. A luminance of 8100 cd/m^2 is obtained by the sinusoidal voltage of 2400 V at 60 kHz.

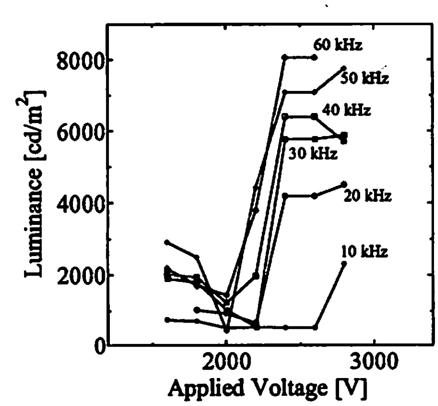
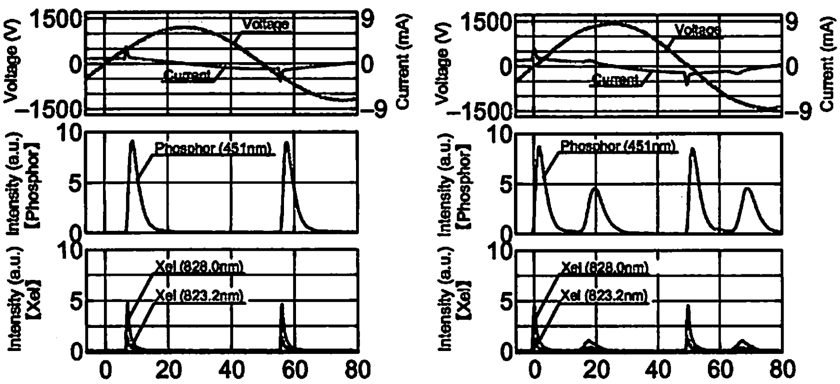


Fig. 35 The relations of the luminance of phosphor to the sinusoidal voltage for the Xe (46.6 kPa) lamp.

Fig. 37[18] shows the relations of the luminance of phosphor to the xenon pressure from 13.3 kPa to 53.3 kPa. The applied voltage is sinusoidal in shape. A higher luminance may be obtained at higher xenon pressures. Fig. 38[18] shows the waveforms of the



(a) 1.2 kV (b) 1.4 kV

Fig. 36 The voltage, the current and the phosphor radiation waveforms at the input voltage of 1.2 kV and 1.4 kV.

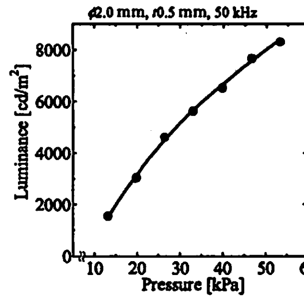
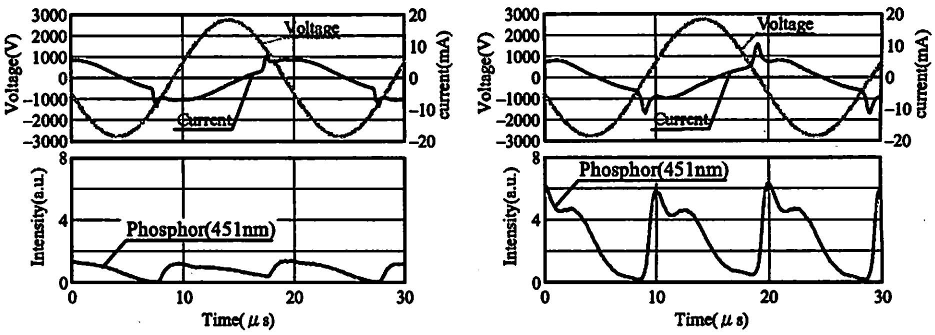
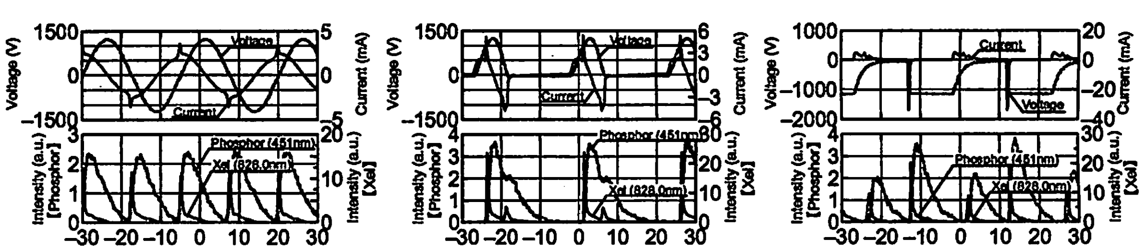


Fig. 37 The relations of the luminance of phosphor to the xenon pressure from 13.3 kPa to 53.3 kPa.



(a) 13.3 kPa (b) 53.2 kPa

Fig. 38 The waveforms of the voltage, the current and the radiation of phosphor for two xenon lamps filled 13.3 kPa and 53.3 kPa at sinusoidal voltage of 2800 V.



(a) sinusoidal (b) half-wave rectified sinusoidal (c) pulse

Fig. 39 The waveforms of the voltage, the current and the radiations of Xe I (8280) and phosphor.

voltage, the current and the radiation of phosphor for two lamps at 13.3 kPa and 53.3 kPa when operated by sinusoidal voltage of 2800 V. As the xenon pressure increases, the peak current, the peak radiation and the afterglow increase.

Fig. 39[19] shows the waveforms of the voltage, the current and the radiations of Xe I (8280) and phosphor. All applied voltages have the same peak value of 1200 V in the shapes of sinusoidal, half-wave rectified sinusoidal and pulse with duty ratio of 50%. Afterglow is not produced by the sinusoidal voltage because of the low voltage value. In the case of half-wave rectified sinusoidal, the discharge occurs twice during the rising and falling periods of the voltage, but the radiation at the second discharge is weak due to the small rate of voltage change. In the case of pulse, both the radiations in the voltage rising period and in the afterglow are strong due to rapid change of pulse voltage. Fig. 40[20] shows the relations between the input power and the efficacy of the Xe

(6.7) lamp, when the lamp is operated by sinusoidal, half-wave rectified sinusoidal and rectangular voltage with duty ratio of 50%. The highest efficacy is obtained by rectangular voltage while the lowest by sinusoidal voltage.

4 Conclusion

The positive column of a xenon discharge easily contracts to form a filament and transforms into a contracted state. In the contracted positive column, the infrared and visible radiations are intense but the ultraviolet radiation necessary for the excitation of phosphor is generally weak. So it was difficult to develop a new xenon discharge lamp with high luminance and high efficacy. However, the results obtained by the above experiments have illustrated the various characteristics of xenon discharge that are useful for realizing high luminance and high efficacy. It was found that the efficacy of xenon lamps can be improved by making use of the afterglow in pulsed discharge, multi-channel discharge and the high permittivity materials used in barrier discharge.

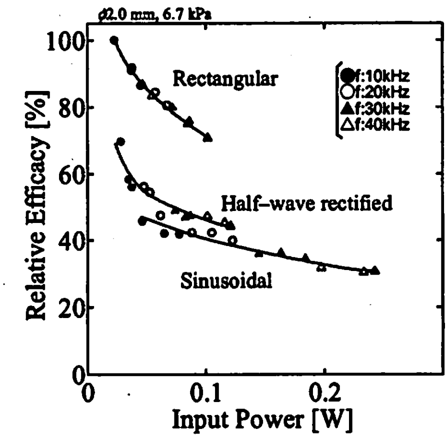


Fig. 40 The relations between the input power and the efficacy of the Xe (6.7 kPa) lamps operated by sinusoidal, half-wave rectified sinusoidal and rectangular voltage waveforms.

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