Paper

Emission Characteristics of Xenon and Xenon-Rare Gas Dielectric Barrier Discharge Fluorescent Lamps

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ABSTRACT

The profile of vacuum ultraviolet (VUV), visible and near IR emissions of xenon and xenon-rare gas pulsed discharge fluorescent lamps were observed as a fundamental research on developing a mercury-free fluorescent lamp. All lamps were operated by pulsed dielectric barrier discharge (DBD). As the pulse width decreases, higher intensity of VUV emissions is obtained, while luminance and efficacy also increase. As the pulse frequency increases, the intensity of VUV emissions increases, however the radiative output per one pulse period decreases and the efficacy decreases. The decay time of VUV emissions which are exciting a phosphor, can be controlled by introducing a rare-gas mixture into xenon.

KEYWORDS: Environment, Mercury-free, Fluorescent lamp, Pulsed discharge, VUV, IR

1. Introduction

Mercury is toxic so in many fields researchers have made efforts to eliminate its use, as for example in the field of dry batteries, where mercury was used as one of the indispensable materials, but now a mercury-free battery has been developed. On the other hand, in the field of lamps, it has been allowed to use mercury for fluorescent lamps because the amount of mercury introduced into one lamp is quite small and also there is no any other materials with which we can achieve the high efficacy found with mercury lamps. However, in the end of the 20th century the social demand had drastically changed and all products are requested to avoid using toxic materials. The field of lamps is not an exception any more. Therefore lamp manufacturers are now trying to develop new non-mercury light sources.

Xenon is suitable as a substitute for mercury because it is environmental-friendly and the emission characteristics are not influenced by ambient temperature. A lot of research on

low-pressure xenon discharges and its vacuum ultra-violet emissions (VUV, 147nm and 172nm) has been done¹⁾⁻⁵⁾, however, as long as we know, no high intensity low-pressure xenon discharge lamps has been developed for general lighting for example domestic lighting, office lighting and factory lighting. VUV emission characteristics at alternative square wave, i.e., bipolar operation, have been reported by many researchers and well known. However VUV characteristics under unipolar pulse operation is not well known yet. Therefore in order to identify the fundamental behaviour of VUV emission of xenon discharge, authors' group has been done researches on unipolar pulsed xenon discharge.

In this research we measured the VUV, phosphor emission and near-infrared emission characteristics of pulsed pure xenon dielectric barrier discharge (DBD) fluorescent lamps as a fundamental research for development of mercury-free discharge fluorescent lamps. In addition, the phosphor

Figure 1 The Schematic Illustration of the Lamp with MgF₂ Window Operated with External Electrodes

Figure 2 Electrical Circuit for Pulsed Operation

emission and strike voltage characteristics of xenon-rare gas mixture DBD fluorescent lamps were measured. These results are expected to be useful for understanding pulsed discharge phenomena and are helpful for modelling a pulsed discharge and its radiation for lamp development and design.

2. Experimental setup

The schematic of the lamp which is used for this research is shown in Figure 1. For pure xenon lamps, xenon is introduced with two different pressures of 1.3kPa and 10.7kPa. For xenon-rare gas mixture lamps, xenon and neon-argon mixture were introduced. The mixing ratio of neon to argon was fixed as 9:1 and the mixing ratios of xenon to rare gas mixture were 9:1, 8:2 and 7:3. The inner diameter of these lamps is 10mm. The lamps filled with pure xenon have a MgF₂ window for VUV measurements. Aluminium tapes are set on the external wall of each lamp as external electrodes and their width is 5mm. As shown in Figure 1 the lamps used for this research have inner electrodes as well as external electrodes. At higher gas pressure it is difficult to ignite discharge by only using external electrodes, therefore the inner electrodes are used to ignite the lamps. These inner electrodes are used only for ignition. They are operated by only external electrodes after the lamps are ignited. The half part in the axial direction of the inner wall of each lamp is coated with a blue phosphor (BAM). The reason why the BAM is used is that the response of BAM is fast and can follow pulsed discharge, and that BAM can be excited both 147nm and 172nm VUV radiation. The BAM has almost similar sensitivity at 147nm and 172nm. This also the reason why BAM is used and Green and Red phosphors are not used. The luminance of the phosphor-coated part was measured by a luminance meter (TOPCON BM-7). The luminous flux Φ of the lamps are calculated from the measured luminance assuming infinite cylindrical light sources and light emitting area has same length as external electrode following the equation,

$$\Phi = 2\pi^2 r l B \times (2\pi r l - S) / 2\pi r l$$

Here r is inner-diameter of the lamp, l is the length of an external electrode, B is the luminance and S is the area of external electrodes. In the calculation the surface area of the aluminium tapes on the lamp is treated as zero luminance area because the tapes prevent the visible light from phosphor coming out. Therefore "efficacy" in this paper means "estimated efficacy."

The pulsed circuit, used for the lamp operation is shown in Fig 2. The voltage pulse is generated by switching the MOS-FET connected to the capacitor C_1 which is charged by a DC power supply E . The pulse frequency and pulse width were controlled by a pulse signal to the gate of the FET from a digital pulse generator (Stanford Research DG-535). A negative pulse is applied to the lamp by this pulse circuit, and the maximum voltage of this system is 5.0kV. As shown in Fig. 1, a small capacitor C_2 (3.3nF) was placed between the anode and the earth in order to measure the input power to the lamp by measuring the accumulated charge to this capacitor⁶⁾. Hereafter in this paper "lamp input power" is simply called as just "input power." The input power is calculated by using V-Q Lissajous method. V-Q Lissajous figure is produced from lamp voltage and accumulated charge on the capacitor C_2 . The area of this Lissajous shows the input energy per one cycle. Therefore by multiplying this energy per one cycle and frequency of the pulse gives the lamp input power.

In the case of pure xenon lamps, the VUV emissions were introduced into the VUV monochromator through the MgF₂ window on each lamp, which was set in the vacuum chamber in which the pressure was less than 5.0×10^{-5} Pa. The IR emissions (828nm and 823nm) and phosphor emission were measured by a visible-near IR monochromator. The traces of current, voltage and emissions were observed and recorded by a digital oscilloscope.

By this configuration, the discharge in these lamps positive column are maintained as diffused positive column. Figure 3 shows photograph of a typical discharge. This photograph makes it clear that a strong emission near electrode which is sometimes observed is not observed in this research.

Figure 3 Photograph of Typical Discharge

3. Experimental Results

3.1 VUV and IR Emissions

A discharge driven by external electrodes is named as dielectric barrier discharge (DBD). When this type of discharge is driven by a pulsed voltage, generally traces of both emissions and current have two peaks per pulse. The first peak is observed during the discharge and just after the rise of the voltage, when the current flows in the forward direction of the applied voltage. As the current flows, electrical charges accumulate on the inner walls of the glass tube. Electrons accumulate on the inner wall of the anode side and ions accumulate on the inner wall of the cathode side. These accumulated charges form an inner electric field opposite to the external electric field applied by the pulsed circuit. As the inner electric field increases, the total electric field in the lamp decreases and when it becomes lower than the discharge voltage, the discharge stops. Then the voltage

pulse terminates and a reversed discharge starts by the accumulated electric charges on the inner walls. This second reversed discharge generates the second peak of current. The second peak of emission is not observed at all times but it depends on certain conditions such as frequency, pulse width etc.

3.2 VUV and IR Emissions

The VUV spectrum versus xenon pressure is shown in Figure 4. As shown in this figure, xenon resonance emission at 147 nm becomes weak and xenon excimer's emission at 172 nm becomes strong as the xenon pressure increases. Especially at over 10 kPa region 147 nm radiation becomes almost zero and 172 nm emission becomes strong and dominant.

The VUV spectra of pure xenon lamps, whose xenon pressures are 1.3kPa and 10.7kPa, operated by pulsed discharge are shown in Figures 5 and 6 respectively. The

Figure 4 Xenon VUV Spectra versus Xenon pressure

Figure 5 Traces of VUV and IR Emissions of Xenon (Pressure 1.3kPa, Frequency 20kHz, Pulse Width 1.5 μ s)

Figure 6 Traces of VUV and IR Emissions of Xenon (Pressure 10.7kPa, Frequency 20kHz, Pulse Width 1.5 μ s)

Figure 7 Traces of VUV and IR Emissions of Xenon (Pressure 10.7kPa, Frequency 20kHz, Pulse Width 10 μ s)

Figure 8 Traces of VUV and IR Emissions of Xenon (Pressure 10.7kPa, Frequency 50kHz, Pulse Width 1.5 μ s)

pulse frequency was 20kHz, the pulse width was 1.5 μ s and the voltage was 2.5kV. The traces of current, voltage and VUV (147nm and 172nm) and IR (823nm and 828nm)

emissions under the same condition are shown in the same Figs. The xenon excimer's emission at 172nm is not observed at the xenon pressure of 1.3kPa. The decay time constants of

the emission of 147nm are 6.1 μ s at 1.3kPa and 2.2 μ s at 10.7kPa. The decay time constant of 172nm excimer's emission at 10.7kPa is 3.1 μ s and this decay is slower than that of 147nm resonance atomic emission.

Figure 7 shows the traces of VUV and IR emissions at the pulse width of 10 μ s, the pulse frequency of 20kHz and the xenon pressure of 10.7kPa. In the case of 10 μ s pulse width, the second peaks of 147nm and 172nm emissions are observed as shown in Figure 7 though they are not observed in the case of 1.5 μ s pulse width as shown in Figures 5 and 6. At the operation with the 10 μ s pulse width, the maximum intensity of the first peaks of VUV emissions and the maximum intensity of IR emissions decrease comparing with the case of 1.5 μ s.

The traces of VUV and IR emissions at the pulse frequency of 50kHz, the pulse width of 1.5 μ s, and the xenon pressure of 10.7kPa are shown in Figure 8. In this case (50kHz), the IR emissions become weaker than the other cases shown in Figs. 5-7. This shows that the IR emission decreases as the pulse frequency increases.

3.3 Luminance and Efficacy

Figures 9 and 10 show the luminance and the efficacy versus the input power at the xenon pressures of 1.3kPa. In both Figure 9 and Figure 10, the frequency, applied voltage and pulse width were varied from 10kHz to 80kHz, from 2.5kV to 5.0kV and from 1.5 μ s to 10 μ s respectively.

Figures 9 and 10 show the luminance and the efficacy versus the input power at the xenon pressures of 1.3kPa. In both Figure 9 and Figure 10, the frequency, applied voltage and pulse width were varied from 10kHz to 80kHz, from 2.5kV to 5.0kV and from 1.5 μ s to 10 μ s respectively. At a constant input power, the luminance and the efficacy increase as the frequency decreases. These two figures show that as the pulse frequency increases, the input power increases. However, the increase of the luminance shows saturation and the efficacy decreases as the input power increases. At a constant input power and frequency, the luminance and the efficacy increase as the pulse width becomes shorter.

Figures 11 and 12 show the luminance and the efficacy versus the input power at the xenon pressures of 10.7kPa. In both Figure 11 and Figure 12, the frequency, the applied voltage and the pulse width were varied from 10kHz to 80kHz, from 2.5kV to 5.0kV and from 1.5 μ s to 10 μ s respectively. At a constant input power, the luminance and the efficacy increase as the frequency decreases or as the pulse width becomes shorter. This behaviour is also found in the case where the pressure of xenon is at 1.3kPa. On the contrary the efficacy is independent of input power. Higher luminance is obtained as the input power increases with constant frequency and pulse width. The luminance and the efficacy are improved compared to the values at 1.3kPa.

3.4 Xenon-Rare Gas Mixture Lamps

The breakdown voltage drops to 3.3kV (Xe:Ar-Ne $\approx$ 9:1) from 4.8kV (pure Xe) as shown in Figure 13. About 30% drop of the ignition voltage was achieved by adding only 10% of rare-gas mixture. Figure 14 shows the traces of phosphor emission at 451nm from xenon-rare gases mixture DBD lamps. The pressure ratio of xenon and rare gases were Xe : Rare Gases = 10:0, 9:1, 8:2 and 7:3. The total pressure was kept at 20kPa. The lamps were operated at a frequency of 20kHz with 1.5 μ s pulse width. This result shows that by adding an Ar-Ne mixture to pure xenon, the time constant of the decay of emission becomes large.

4. Discussion

4.1 Influence of Xe Pressure on the Emission Characteristics

In Figure 15, a simplified Grotrian energy level diagram of Xe atom and Xe dimer is shown. The xenon excimer, which radiates 172nm VUV emission, is mainly generated by the following process.

At 1.3kPa, the pressure is so low and this three-body collision process does not happen so frequently. This is the reason why 172nm VUV emission is not observed at 1.3kPa. The following process generates xenon resonance atoms ($1s_4$) that radiate the IR emission of 828nm.

The following process also generates xenon resonance atoms ($1s_4$) by quenching collisions between xenon atoms and xenon metastable atoms^{7,8}.

It seems that at low pressure the main process which generates xenon resonance atoms ($1s_4$) during the off period of voltage is the quenching process shown as (3) because Fig. 6 shows that though the 147nm resonance radiation lasts long after the discharge terminates, the IR radiation of 828nm finishes right after the cut off of the voltage pulse and the life time of the resonance atom ($1s_4$) is only 3.7ns long⁹. If process (2) was the main process then the 828nm radiation should appear during the off period of the voltage. As the xenon pressure increases, the three-body collision shown as (1) increases and becomes the main process comparing with the two-body quenching process shown as (3). As the xenon pressure increases the collision frequency increases and the metastable atoms are consumed rapidly and the decays of 147nm and 172nm VUV radiation become faster.

We measured the temporal behaviour of the number density of excited xenon atoms of $1s_4$ and $1s_5$ at the pressure of 1.3kPa, frequency of 20kHz and pulse width of 1.5 μ s by IR-Laser Absorption Spectroscopy¹⁰. This measurement shows that at 1.3kPa the metastable atoms which were generated

Figure 9 Luminance versus Input Power (Pressure 1.3kPa)

Figure 10 Efficacy versus Input Power (Pressure 1.3kPa)

Figure 11 Luminance versus Input Power (Pressure 10.7kPa)

Figure 12 Luminance versus Input Power (Pressure 10.7kPa)

Figure 13 Breakdown Voltage of Xenon-Rare Gas DBD Lamps

Figure 14 Traces of Phosphor Emission at 451nm of Pure Xenon and Xenon-Rare Gas DBD Lamps (Total Pressure 20kPa, Frequency 20kHz, Pulse Width 1.5μs)

during the discharge and just after it, are present for long and about 20% of the peak still exists at the time when the next discharge starts. The metastable number density at

peak is about $3 \times 10^{12} \text{ cm}^{-3}$. This is because for a pressure as low as 1.3kPa both processes (1) and (3) do not happen so much and the VUV emission decreases. Finally as shown in

Figs. 10 and 12, the efficacy becomes lower at 1.3kPa than at 10.7kPa

Generally it is said that as xenon pressure increases due to increase of three-body collision Xe^+ and 2Xe Xe_2^+ number density increases and by dissociative recombination number densities of $\text{Xe}(2p_6)$ and $\text{Xe}(2p_5)$ increase. However as shown in Figures. 5 and 6, as xenon pressure increases the intensity of the radiation at 823nm due to the transition from the $2p_6$ state to the $1s_5$ state does not change though the intensity of the 828nm radiation due to the transition from the $2p_5$ state to the $1s_4$ state. This means that in our lamps' something different processes happen and somehow $\text{Xe}(2p_6)$ is generated selectively. As a future work the authors must measure the densities of $\text{Xe}(2p_6)$ and $\text{Xe}(2p_5)$ to know what happens.

4.2 Influence of Pulse Frequency and Width on the Emission Characteristics

Figures 6 and 7 show that as the pulse width becomes shorter, the luminance increase because the first peak and the second peak of VUV emission superpose. A short pulse reduces the power consumption. This is the reason why the efficacy is improved with short pulse operation.

As the pulse frequency increases, the number of residual ions and electrons increases because of the length of non-discharge period. These increases in the number of residual ions and electrons reduce the electron temperature during a discharge. Then the excitations to higher levels decrease. This is quite understandable from the results shown in Figures 7 and 8 where the IR emissions become weak at high pulse frequency. On the other hand pulse width does not have strong influence as pulse frequency though as pulse width becomes shorter VUV emissions slightly increases. As shown in Figs. 7 and 8, VUV emission becomes weak as the pulse frequency increases. These results, i.e. the decrease in number of higher excited atoms and weaker emission of IR and VUV at higher frequency operation, lead us to the following conclusion that the excited atoms at resonance level ($1s_4$) are mainly generated by the transition from the upper level ($2p_5$), which is shown as the process (2). Also from these results it seems that dissociative recombination process due to increase of three-body collision Xe^+ and 2Xe generating Xe_2^+ is relatively not so significant than three-body collision $\text{Xe}(1s_5)$ and 2Xe or $\text{Xe}(1s_4)$ and 2Xe generating Xe_2^+ .

4.3 Effect of Rare-Gas Mixture on Xenon Discharge and Radiative Characteristics

The result of the decay of phosphor emission, i.e. the decay of VUV emission, could be explained by the energy pool effect by Ar metastables, i.e. by adding Ar to Xe, the input energy is transferred to Ar metastables because of Ar metastable's long lifetime and its difficulty in forming Ar excimer due to its lower pressure than Xe. After the discharge stops the pooled

Figure 15 Energy Levels of Xenon Atom and Dimer

energy by Ar metastables is transferred to xenon atoms, which then increases the population of xenon metastables. This can explain why the phosphor emission has a long decay constant with higher Ar pressure. This also means that the decay time of VUV radiation can be controlled by changing the partial pressure of the rare-gas mixture.

5. Conclusion

The emission characteristics of xenon dielectric barrier discharge fluorescent lamps were observed under pulsed operation. At the xenon pressure of 10.7kPa, the VUV radiation of xenon excimer at 172nm is observed and the luminance and efficacy of the lamps increase more than the case at 1.3kPa.

As the pulse frequency increases, the input power increases, however, the intensity of VUV emissions during one cycle decreases and the efficacy decreases. Finally these results show how to increase the luminance and efficacy, i.e., the short pulse gives both higher luminance and efficacy.

By introducing the Ar and Ne mixture gas to Xe at 10%, about 30% reduction of the breakdown voltage is achieved. It was also shown that the decay time of phosphor emission can be controlled by rare-gas addition.

The future work is to find optimum frequency at which xenon DBD fluorescent lamps achieve higher luminance and efficacy simultaneously.

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