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Yang-Kyu Lee [a] , Jong-Hyun Kang [a] , Sung-Taek Heo [a] , Seung-il Yoon [a] , Myung-Hoon Oh [a] & Dong-Gu Lee [a]

[a] Department of Information and Nano Materials Engineering, Kumoh National Institute of Technology, Gumi, Gyungbuk, Korea

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Properties of a Cross Type Xe Plasma Flat Fluorescent Lamp

Yang-Kyu Lee, Jong-Hyun Kang, Sung-Taek Heo, Seung-il Yoon, Myung-Hoon Oh, and Dong-Gu Lee
Department of Information and Nano Materials Engineering, Kumoh National Institute of Technology, Gumi, Gyungbuk, Korea

In this study, plasma flat fluorescent lamps (FFLs) having two different types of electrodes (line and cross types) for surface discharge were fabricated and characterized with variation of discharge shape, the distance between electrodes, and mixed gas (Xe-Ar-Ne-He) ratio. The firing voltage in both types of FFLs obeyed Paschen's law. From plasma discharge images, Xe plasma was not uniform compared to Ar, Ne, or He plasmas in a cross type FFL. The cross type FFL using pure Xe gas showed higher luminance due to its larger discharge area and lower luminous efficiency due to its higher current. However the use of 20%Xe-80%Ar gas mixture significantly improved the uniformity and stability of plasma in the cross type FFL, enhancing its luminance and efficiency.

Keywords: backlight unit (BLU); flat fluorescent lamp (FFL); screen printing; xenon plasma

INTRODUCTION

Among flat panel display devices, LCD has become the most popular display in market. However, since LCD is non-emissive type display, it always needs a backlight lamp on the backside of panel, which consumes a lot of power. Cold cathode fluorescent lamp (CCFL) has been conventionally used as a backlight [1]. Although CCFL

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Address correspondence to Prof. Dong Gu Lee Department of Information and Nano Materials Engineering Kumoh National Institute of Technology, Gyungbuk 730-701, Korea (ROK). E-mail: dglee@kumoh.ac.kr

is quite efficient in luminance, it contains small amount of mercury, which is very harmful to the human body and natural environment as well. Therefore, there have been some moves on restricting import of products containing hazardous materials such as Directives on the Restriction of certain Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE) in EU [2,3], Eventually it is essential to develop new eco-friendly backlight lamps. Xe plasma FFL is one of the eco-friendly lamps. However, the optimization of the Xe plasma FFL system has not been accomplished yet such as an efficient plasma lamp design, luminance, optimum gas mixture composition, luminous efficacy, etc. In this study, two types of Xe plasma FFLs having different electrode geometiy (cross and line types) were fabricated and characterized with variation of electrode gap distance, gas mixture, gas pressure, etc.

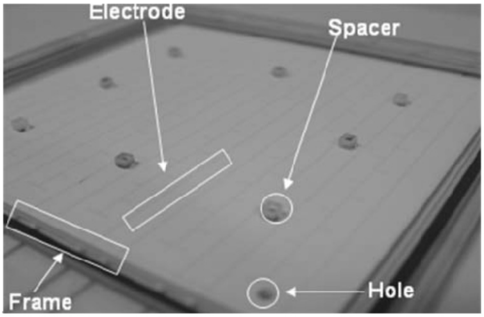
EXPERIMENTAL

Materials and Equipments for Fabrication

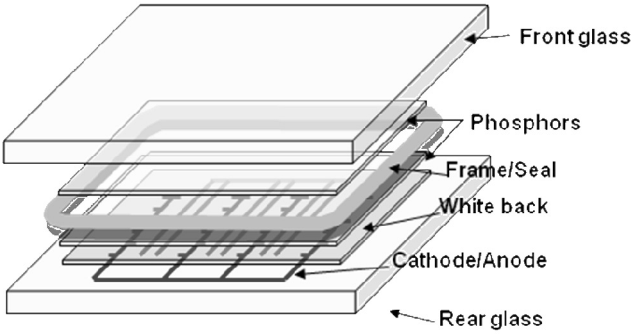
PD200 (Asahi Glass) was used as a panel glass because it does not deform even at firing temperature. Silver paste (Taiyo Ink) was used as an electrode material for good conductivity. To protect the electrode from ion bombardment during plasma discharge, the electrodes were covered with a dielectric material (lldong Chemical). White phosphor used in this study is composed of 33% red (Y_2O_3:Eu), 33% green ($LaPO_4$:Ce,Tb), and 34% blue ($BaMgAl_{10}O_{17}$:Eu) phosphors. Printing, sealing, and gas control of panels were used by screen printer (Bando Industrial), dispenser (Musashi Engineering), and sealing system (Avaco), respectively.

Fabrication of Panels

For assembling FFL panels, silver electrodes, a white back dielectric layer, and a phosphor layer were screen-printed on the rear glass and fired at 550, 450, and 570°C, respectively in sequence as shown in Figure 1. On the front glass, another phosphor layer was printed and fired. Both front and rear glasses were sealed together at 450°C under atmospheric pressure and then pumped down to a pressure of 10^{-3} torr at 150°C for 60 min to completely remove organic residues. He-Ne-Ar-Xe inert gas mixtures were introduced through a tube hole into the sealed panel after vacuuming 10^{-6} torr for efficient plasma



(a)



(b)

FIGURE 1 (a) Photo image and (b) schematic diagram of copianar type FFL.

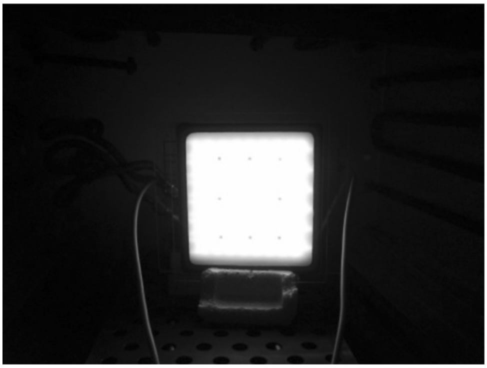


FIGURE 2 The emission picture of 7 inch FFL.

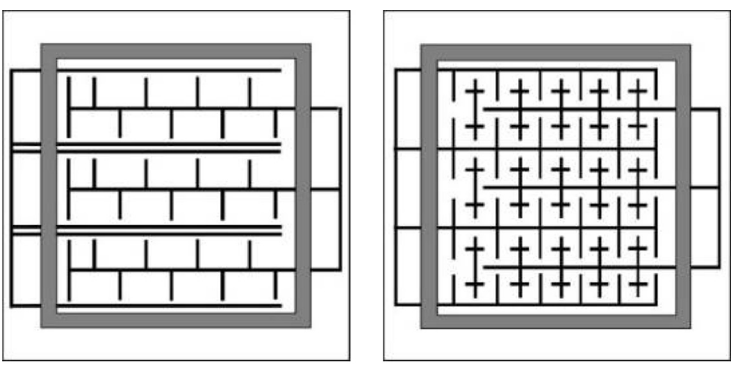
discharge. Figure 2 shows the emission image of an assembled 7 inch FFL panel.

MEASUREMENTS

The luminance characteristics of the two types of FFL were compared and characterized with variation of He-Ne-Ar-Xe gas composition, and pressure and FFL cell dimension using spectraradiometer (Minolta, Cs-1000A) and square pulse power supply (Ftlab, PDS-4000).

RESULTS AND DISCUSSION

Two types of FFLs were designed under basis of coplanar dielectric barrier discharge principle as shown in Figure 3. Line type FFL in Figure 3(a) is a simple and basic structure as a reference. Cross type FFL in Figure 3(b) is a modified structure of line type FFL to intentionally enlarge the plasma space in a cell, inducing larger vacuum ultraviolet and leading to higher luminance. The gap between cathode and anode was made to be the same distance in both types of FFLs. Figure 4 shows the emission images of FFL using only Xe gas. Abnormal glow discharge formed around the tips of electrode branches where electric field is large. The cross type FFL generated more glow discharge than the line type FFL owing to higher number of branches in a cell. Accordingly, the cross type FFL emits more



(a) (b)

FIGURE 3 FFL structure of (a) line type and (b) cross type.

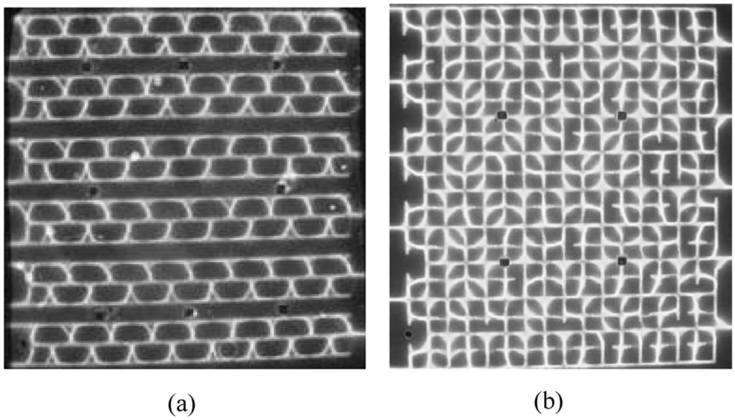


FIGURE 4 Xe emission image of (a) line type and (b) cross type FFL.

vacuum ultraviolet (VUV), which excites phosphors more, consequently inducing higher luminance as shown in Figure 5, Despite the higher luminance of cross type FFL, its luminous efficiency was lower than for line type FFL (Fig. 6). The efficiency (η) and the power

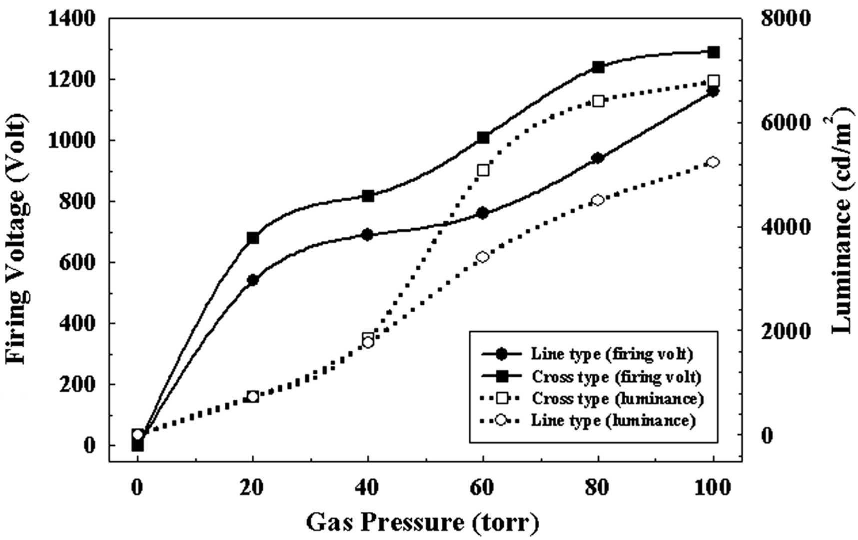


FIGURE 5 The luminance and firing voltage with gas pressure (sustain voltage: 1.4 kV, frequency: 25 kHz, duty: 25%, dielectric thickness: 150 μm, and distance of electrodes: 2.7 mm).

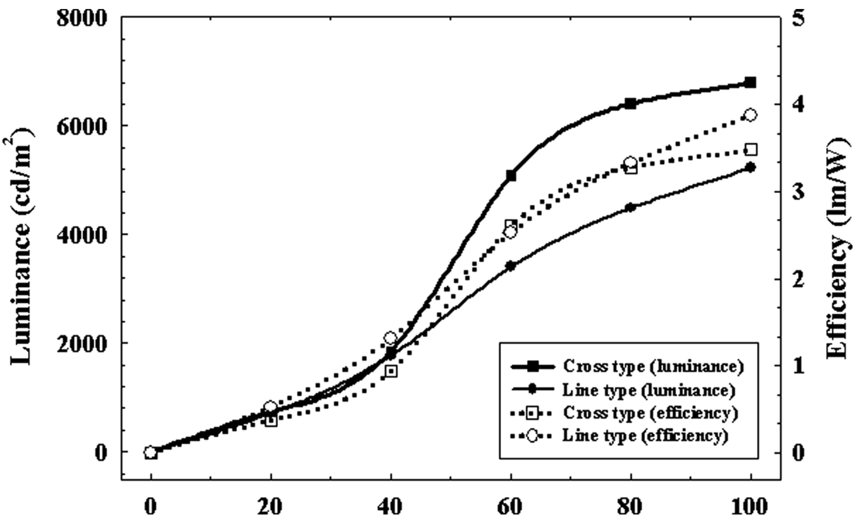


FIGURE 6 The efficiency and luminance with gas pressure of FFL (sustain voltage: 1.4 kV, frequency: 25 kHz, duty: 25%, dielectric thickness: 150 μm, and distance of electrodes: 2.7 mm).

consumption (P) could be obtained from the following equation;

$$\eta = \frac{\pi AL}{P}[\mathrm{lm/W}] \tag{1}$$

where π is constant, A is the area (=0.0158 m^2 for 7 inch panel), L is the luminance, and P is the power consumption. Power consumption was simply obtained from the product of a measured average current and an applied voltage of 1.4 kV at a frequency of 25 kHz and a duty of 25%, which is shown in Table 1. Actually electric current should be integrated from pulse wave of current

TABLE 1 Calculated Luminous Efficiency of two Types of FFLs (Sustain Voltage: 1.4 kV, Xenon Gas Pressure: 100 torr, Operating Frequency: 25 kHz, Duty: 25%, Dielectric Thickness: 150 μm, and Electrode Gap Distance: 2.7 mm)

	I (mA)	P (W)	L (cd/m^2)	η (lm/W)
Cross type	69.4	98	6795	3.477
Line type	48.4	68	5229	3.873

through real-time monitoring of oscilloscope. However, in this study, we could not measure accurate current due to our measurement limitation, which could cause the power consumption values to be different from real values. Larger number of branches of cross type FFL, which are advantageous to luminance, caused electric current on electrode (i.e., power consumption) to increase. Its luminance increment was a bit smaller than its power increment, leading to lower luminous efficiency. In addition, with increasing gas pressure in both types of FFLs, the firing voltage and luminance as well as luminous efficiency increased (Figs. 5 and 6). This result is related to Paschen's law [6], in which the firing voltage (V_f) is expressed as

$$V_f = \frac{Bpd}{\ln\left\{\frac{Apd}{\ln(1+\frac{1}{\gamma})}\right\}} \tag{2}$$

where A and B is constant, γ is Townsend secondary coefficient, p is gas pressure, and d is the distance between electrodes. Therefore, higher gas pressure in the lamp requires higher firing voltage

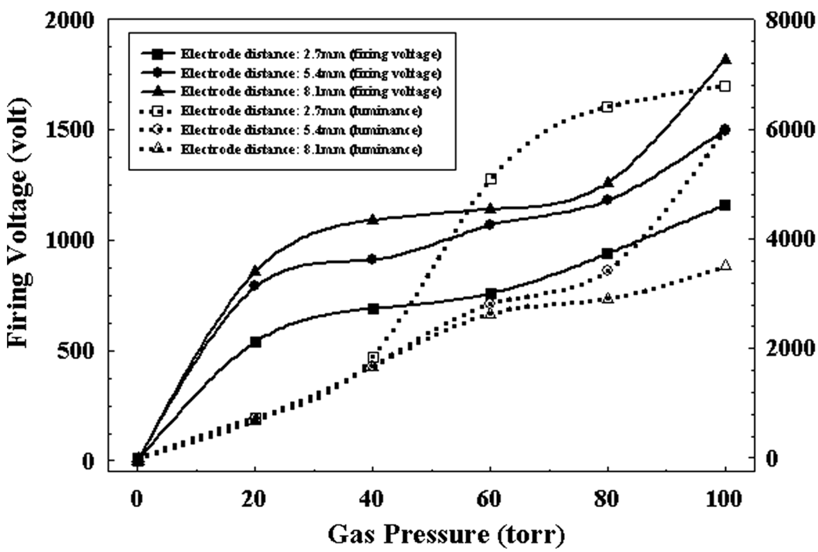


FIGURE 7 The luminance and firing voltage of cross-type electrode structure with gas pressure (sustain voltage: 1.4 kV, frequency: 25 kHz, duty: 25%, dielectric thickness: 150 μm).

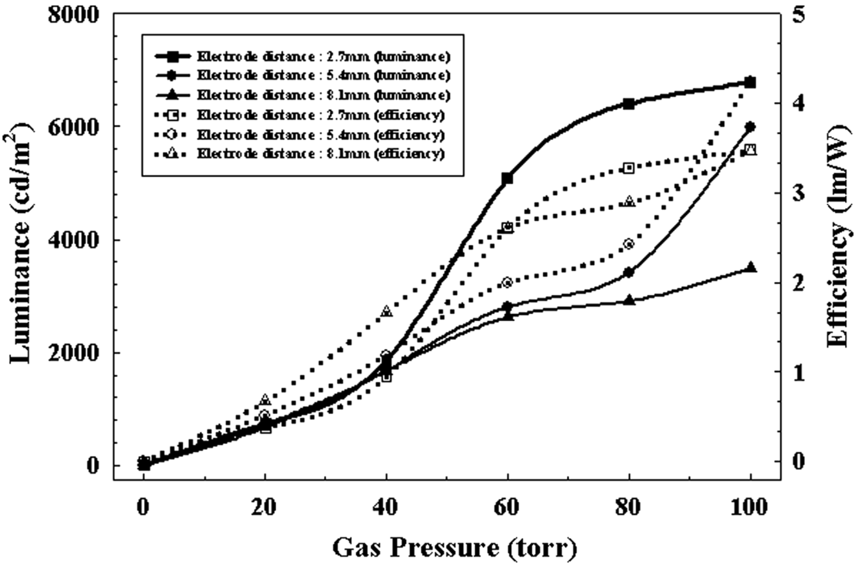


FIGURE 8 The efficiency and luminance of cross-type electrode structure with gas pressure (sustain voltage: 1.4 kV, frequency: 25 kHz, duty: 25%, dielectric thickness: 150 μm).

for glow discharge because electron energy become weaker from its frequent collisions with gas atoms.

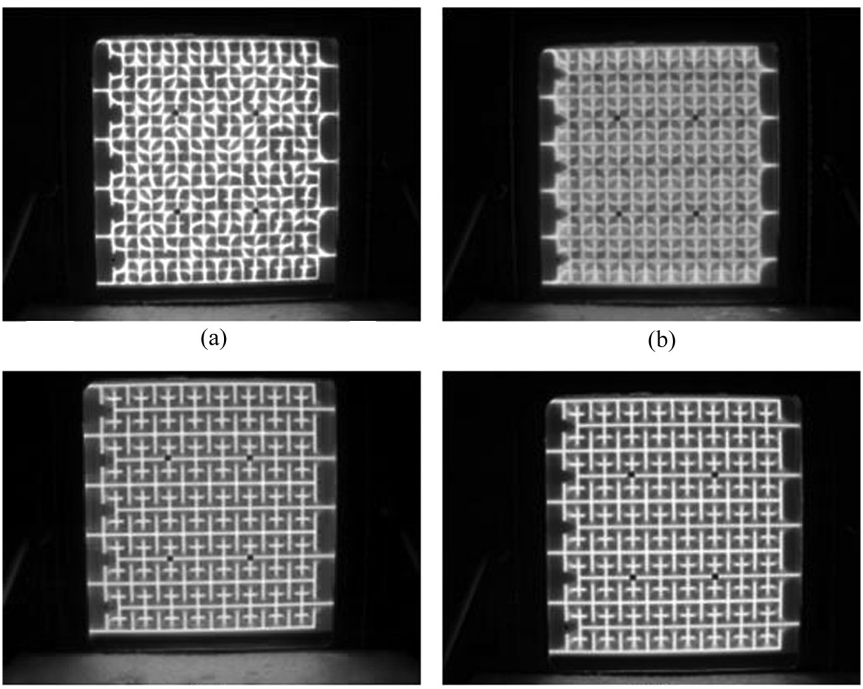
The cell dimensions of cross type FFLs (the distance of electrodes = 2.7, 5.4, and 8.1 mm) were varied for luminance characteristics as shown in Figures 7 and 8. In case of cross type FFL, as the gap distance of electrodes (cell dimension) is larger, its firing voltage increased (Fig. 7) as expected from Paschen's law. Smaller cell dimension of FFL means larger number of discharge cell per area as well as larger electrode area, which gave higher power consumption and luminance. However, its luminous efficiency decreased for smaller cell dimension due to higher increase rate in power consumption compared

TABLE 2 Lonization Energy and Atomic Weight for the Noble Gases

Gas	He	Ne	Ar	Xe
Lonization energy (eV)	24.5	21.5	15.7	12.1
Atomic weight	4.0	20.1	39.9	131.2

to luminance. From the trade-off of luminance and power consumption, the efficiency of cross type FFL was the best for the electrode distance of 5.4 mm in this study.

When plasma was generated by electrons excited from an applied voltage, its property is affected by gas species having inherent electron energy. Generally, inherent electron energy is proportional to ionization energy, which is inversely proportional to ionization cross-section [3–5]. The ionization and electron energy of xenon is the smallest among theses noble gases and the ionization cross-section is the largest (Table 2). That means that Xe plasma is confined to smaller area than other He, Ne, or Ar plasmas due to more electron collisions at short distance. Figure 9 shows the glow discharge of noble gases. Xe gas panel showed more concentrated plasma around the electrodes with irregular distribution (Fig. 9(a)). However, Ar gas panel formed more uniform plasma around electrodes with regular pattern due to



(a) (b) (c) (d)

FIGURE 9 Plasma images of (a) Xe, (b) Ar, (c) He, and (d) Ne gases using cross type electrode.

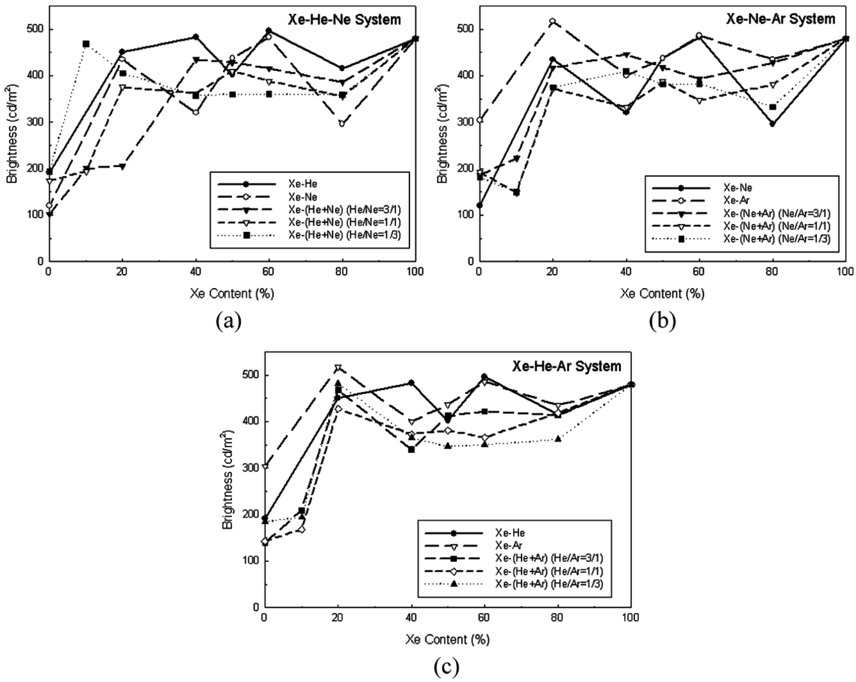


FIGURE 10 Luminance of FFLs using (a) Xe-Ne-Ar, (b) Xe-He-Ne, and (c) Xe-He-Ar gas system.

its smaller ionization cross-section than Xe (Fig. 9(b)). On the other hand, He and Ne plasmas were evenly distributed to whole area of panels without much concentration of plasma around electrodes (Figs. 9(c) and (d)).

On the basis of this basic knowledge about noble gas plasmas, luminance was measured according to ternary gas mixture ratio (Xe-He-Ne, Xe-Ne-Ar, and Xe-He-Ar) as shown in Figure 10. In all ternary gas systems, gas mixtures having less than 20% of Xe showed significantly low luminance. Over 20% of Xe in ternary gas system, its luminance appeared to be almost close to pure Xe luminance although there are some fluctuations in luminance with Xe content. Among ternary gas systems, Xe-He-Ar system gave the least fluctuation in luminance with Xe content (Fig. 10(c)). In binary gas systems, the decreasing order of luminance was Xe-Ar, Xe-He, and Xe-Ne. In our study, 20%Xe-80%Ar gas system showed the highest luminance. Ar and Xe gases played a role in more stable plasma and better luminance, respectively. It is also clearly seen from the

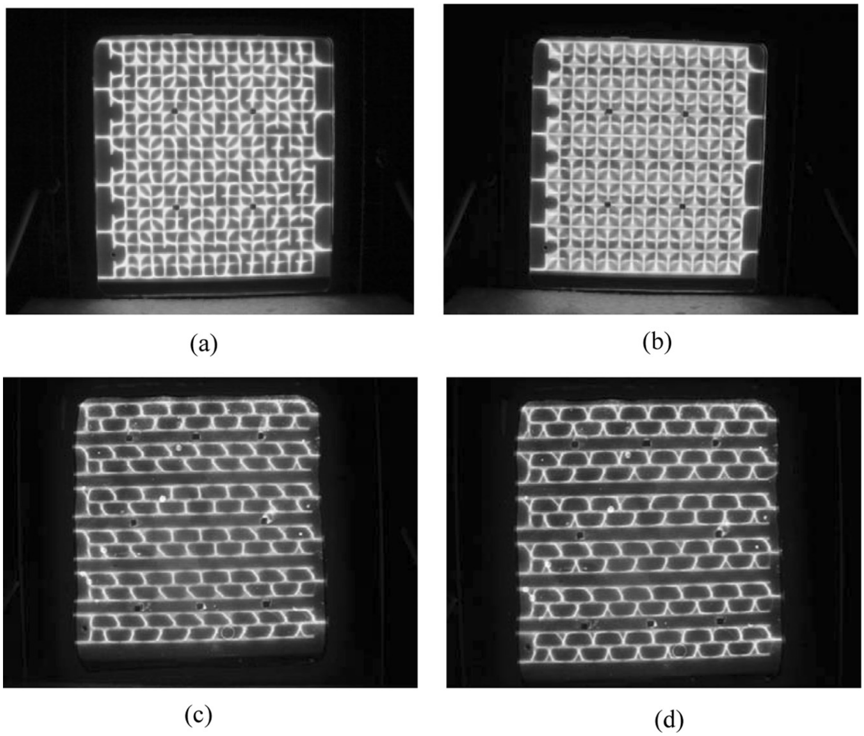


FIGURE 11 Emission pictures of cross/line type FFL using (a) (c) pure Xe and (b) (d) 20%Xe-80%Ar.

comparison images of pure Xe plasma (Fig. 11(a)) and Ar-Xe plasma (Fig. 11(b)) in cross type FFL. By mixing Ar with Xe gases, the plasma distribution was significantly improved in cross type FFL, enhancing luminance. However, in case of line type FFL (Figs. 11(c) and (b)), the plasma distribution was not much changed because of unchangeable plasma discharge structure. Owing to the significant increment in luminance in cross type FFL using 80%Ar-20%Xe gas mixture, the luminous efficiency was greater than line type FFL at around 100 torr (Fig. 12).

CONCLUSION

Two types of FFLs (line and cross types) were fabricated and compared. The firing voltage obeyed Paschen's law in both types of FFLs. From plasma discharge images, Xe plasma was not uniform compared to

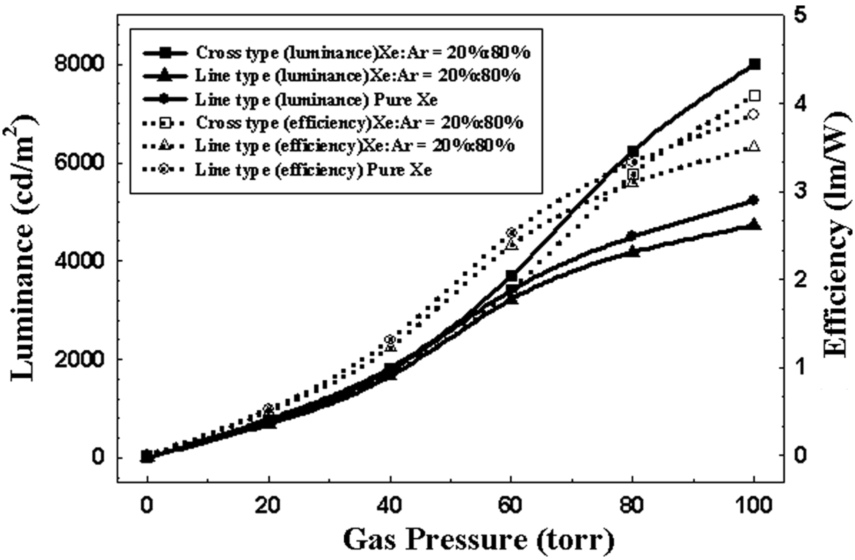


FIGURE 12 Comparison of efficiency and luminance in cross and line type FFLs using pure Xe and Xe-Ar gases (sustain voltage: 1.4 kV, frequency: 25 kHz, duty: 25%, dielectric thickness: 150 μm).

Ar, Ne, or He plasma in cross type FFL. In comparison of line and cross type FFL using pure Xe gas, the luminance and luminous efficiency was higher and lower in cross type FFL due to larger discharge area and higher current, respectively. However the use of 20%Xe-80%Ar gas mixture significantly improved the uniformity and stability of plasma in cross type FFL, enhancing its luminance and efficiency.

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