New Color-Enhancing Discharge Mode Using Self-Erasing Discharge in AC Plasma Display Panel

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***Abstract*—A new color-enhancing discharge mode using a self-erasing discharge is proposed based on an analysis of the Ne emission mechanism in a Ne–Xe gas mixture. The effects of the new color-enhancing discharge mode produced by a ramped-square sustain waveform on improving the color reproducibility are examined in an alternate current plasma display panel (ac-PDP) filled with a Ne–Xe gas mixture. When the ramped-square sustain pulses are applied at 150 kHz, the color purities of the blue and green visible emissions are both improved, thereby expanding the color gamut area by about 5.4% without reducing the luminance.**

***Index Terms*—Color gamut, improvements of color reproducibility in ac plasma display panel (PDP), Ne emission characteristics, new color-enhancing discharge mode, ramped-square sustain pulse, self-erasing discharge.**

I. Introduction

THE COLOR IMAGES on a plasma display panel (PDP) are displayed based on a combination of the colors red, green, and blue, which are emitted from the stimulation of red, green, and blue phosphor layers excited using vacuum ultraviolet (VUV) during a Ne–Xe plasma discharge. A neon (Ne) emission, which is an orange light with a wavelength of 585 nm, is also produced during a Ne–Xe plasma discharge [1]. This Ne emission is considered as the main culprit in deteriorating the color purity of the PDP device, because the Ne emission decreases the purity of the blue and green colors. Thus, the area of the color gamut in a PDP is smaller than that in National Television Systems Committee (NTSC) due to the Ne emission, meaning that the color reproducibility of a PDP is also lower than that of NTSC. Accordingly, the Ne emission needs to be reduced in order to improve the color purity in a PDP. In addition to the development of new red, green, and blue phosphor materials with high-color purities, various methods have also been suggested for minimizing the intensive Ne emission based on the use of optical filters [2]–[4] or optimizing the gas chemistry [5]. When the visible transmittance of an optical filter is tuned low near the Ne-emission region, this can improve the color purity. However, since this also decreases the transmittance in all other regions, except for the Ne-emission region, the total luminance is reduced. In a conventional Ne–Xe plasma discharge, an orange light of 585 nm is only emitted under high-electric field intensity conditions because the energy state of Ne^{**} is relatively high [6]. Therefore, as the plasma discharge intensity decreases or increases, the corresponding Ne emission intensity also weakens or strengthens accordingly. This implies that a decrease in the luminance due to a reduction in the Ne emission is, thus, unavoidable in a conventional plasma discharge from PDP cells. Consequently, weakening the Ne-emission intensity without reducing the luminance in the visible light emitted from PDP cells would appear to be very difficult. The development of a new color enhancing discharge mode driven by a sustain pulse is, therefore, required to improve the color purity of a PDP, a concept that so far has been neglected. Accordingly, the current paper presents a self-erasing discharge as new discharge mode that can produce VUV efficiently even in a low-electric field. The self-erasing discharge is produced by a ramped-square sustain pulse, which was previously reported on by the current authors in relation to improving the luminance and luminous efficiency [7], [8]. Whereas the previous work focused on improving the luminance and luminous efficiency, the significance of improving the color purity using a self-erasing discharge was neglected. In the case of a self-erasing discharge, the luminous intensity does not exhibit the same tendency as the discharge intensity because a visible light can be induced twice per sustain pulse due to the self-erasing discharge.

The remainder of the paper analyzes the Ne and Xe reaction mechanism in a Ne–Xe gas mixture to identify an appropriate method for minimizing the orange light while simultaneously enhancing the VUV generation. Then, a new color-enhancing discharge mode using a self-erasing discharge is proposed based on the analysis of the Ne emission mechanism in a Ne–Xe gas mixture. Finally, the effects of the new color-enhancing discharge mode produced by a ramped-square sustain waveform on improving the color purity are examined in an ac-PDP filled with an Ne–Xe gas mixture.

II. Experiment

Fig. 1 shows the optical measurement system used to investigate the optical characteristics of the red, green, and blue lights emitted from a 4-in test panel. The luminance, spectrum of the visible range, and color chromaticity were measured using a PR-704 spectrometer. The 4-in test panel was composed of 30×60 red, green, and blue cells (cell pitch: 1.08 mm) and filled with a Ne–Xe (4%) gas mixture with a pressure of 400 torr. The red, green, and blue phosphors utilized in the current study were (Y, Gd) BO_3: Eu, $(Zn, Mn)_2$ SiO_4, and (Ba, Eu) $MgAl_{10}O_{17}$, respectively. To measure the visible and Ne emission spectra from the 4-in test panel, 10×10 pixels were used,

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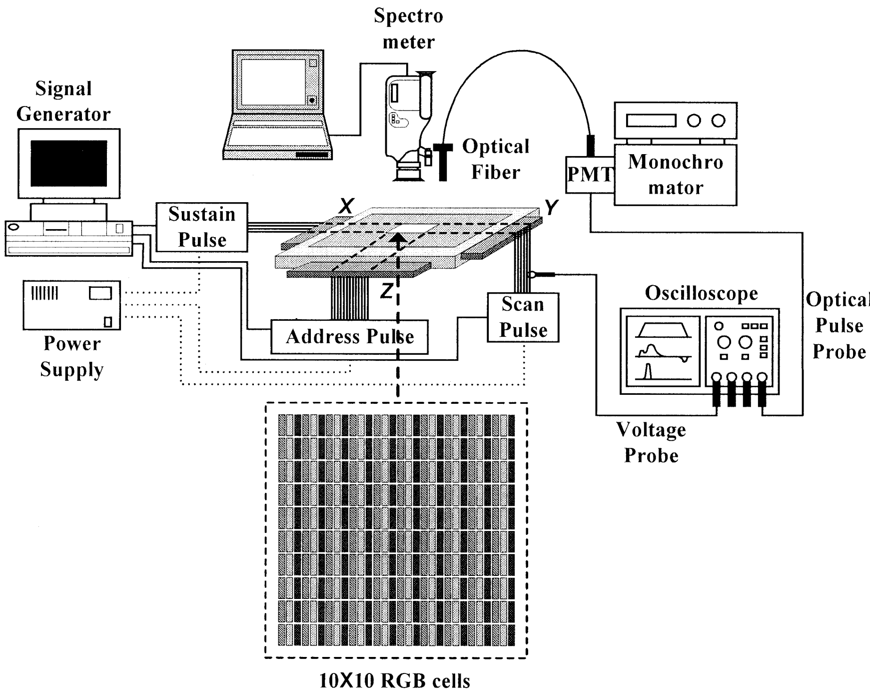


Fig. 1. Optical measurement system for measuring optical characteristics of red, green, and blue lights emitted from a 4-in test panel.

so that 100 red, green, and blue cells were utilized, respectively, as shown in Fig. 1. Sustain, scan, and address pulses were applied to the three electrodes, X, Y, and Z of the 10×10 pixels in the 4-in test panel from a signal generator, as shown in Fig. 1. The timing diagrams of the voltage pulse waveforms applied to the three electrodes, X, Y, and Z are shown in Fig. 2(a) and (b). To investigate the effects of the self-erasing discharge on the Ne emission characteristics, two different types of sustain voltages, *i.e.*, a square sustain voltage and ramped-square sustain voltage were applied to the sustain electrodes during a sustain-period. The driving frequency was varied from 50 to 150 kHz. In the ramped-square sustain pulse, the increasing voltage slope was varied from 13.3 V/μs to 30.0 V/μs.

III. Self-Erasing Discharge due to Ramped-Square Sustain Pulse

Figs. 3(a) and (b) show the voltage and infrared (IR: 823 nm) waveforms measured from the 4-in test panel in the case of an (a) conventional square sustain waveform and (b) ramped-square sustain waveform, respectively. The sustain voltage in Fig. 3(a) was 190 V, whereas the amplitudes in Fig. 3(b) at the rising and falling edges were 190 and 230 V (constant slope: 13.3 V/μs), respectively. The other driving conditions in Figs. 3(a) and (b) were a frequency of 100 kHz and duty ratio of 30% (pulse width: 3 μs). The wall charges were accumulated below two sustain electrodes via an address period. Thereafter, the electric field generated between the two sustain electrodes by the applied voltage plus the wall voltage produced the main discharge. The corresponding infrared (IR), i.e., the first IR peaks in Figs. 3(a) and (b), were emitted simultaneously. In the case of the conventional square sustain pulse, an IR of 823 nm was only emitted once per sustain voltage pulse and its duration was about 0.64 μs, indicating that the IR intensity decreased rapidly. In this case, the energetic space charges and metastable

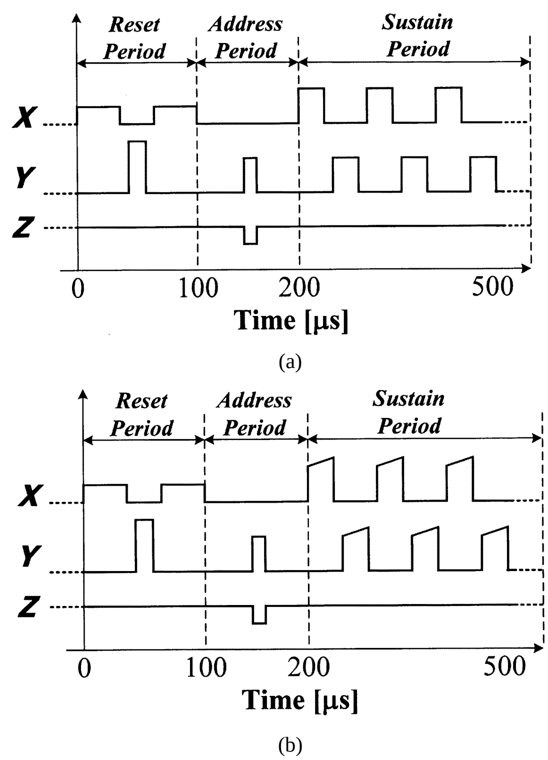
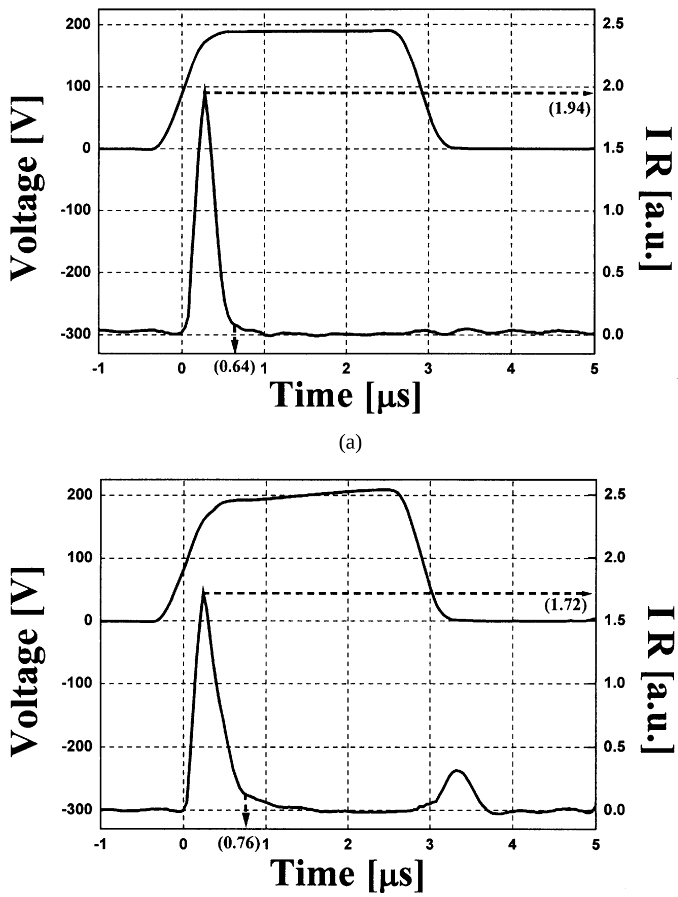


Fig. 2. Timing diagrams of voltage waveforms applied to three electrodes, X, Y, and Z. (a) Conventional square sustain waveform. (b) Ramped-square sustain waveform.

atoms remained still within the cells after the extinction of the main discharge. However, in the case of the ramped-square sustain pulse, the constantly increasing voltage slope prevented any rapid reduction of the electric field caused by an accumulation of wall charges. Therefore, since the ramped-square sustain pulse prevented an immediate extinction of the plasma discharge, this induced a longer sustaining discharge to emit an IR



(a)

(b)

Fig. 3. Sustain voltage and IR waveforms. (a) Conventional square sustain waveform. (b) Ramped-square sustain waveform.

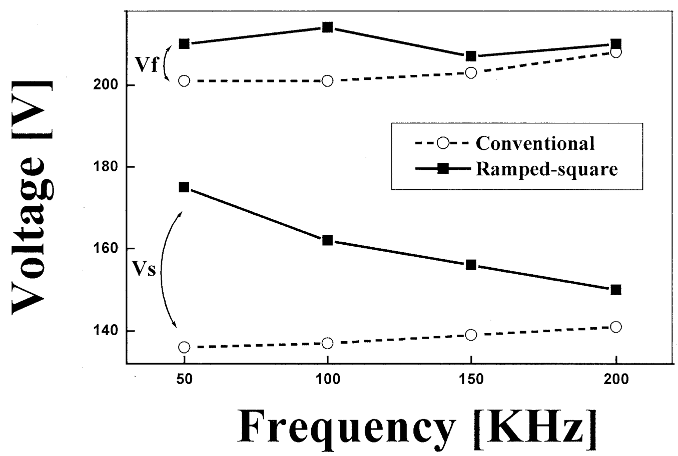


Fig. 4. Static voltage margins between ramped-square sustain pulse and conventional square sustain pulse relative to driving frequency.

of 823 nm for a longer time, which was verified by the experimental result of the IR emission emitted for 0.76 μs per ramped-square sustain pulse during the main discharge. However, this increasing voltage does not induce the longer emission of the Ne because the magnitude of the increasing voltage is small and the main discharge is also produced under the relatively weak electric field condition due to the previous self-erasing discharge. In addition, the wall charges accumulated due to the constantly increasing voltage slope produced an additional discharge, called a self-erasing discharge, as shown by the small second IR peak at the falling edge of the ramped-square sustain pulse in Fig. 3(b).

Due to the self-erasing discharge, the main discharge intensity in the ramped-square sustain pulse became slightly weaker, compared with that in the conventional square sustain pulse. The IR peak intensity of the square sustain pulse in Fig. 3(a) was 1.94, whereas the IR peak intensity of the ramped-square sustain pulse in Fig. 3(b) was 1.72. The intensity of the self-erasing discharge was very weak compared with that of the main discharge because the plasma was only produced by the wall charges. Thus, a self-erasing discharge was produced under very weak electric field conditions. Since the self-erasing discharge did not require any additional power consumption, the luminous efficiency was also improved. Therefore, even though the main discharge in the ramped-square sustain waveform decreased slightly, the longer sustaining main discharge and additional self-erasing discharge were able to improve the luminance and luminous efficiency. When compared with the conventional square waveform in Fig. 3(a), the ramped-square waveform in Fig. 3(b) achieved a 36.6% higher luminance and 48.7% higher luminous efficiency in the 4-in test panel at 100 kHz. However, at 150 kHz, the luminance and luminous efficiency were improved by about 30% and 16%, respectively. The detailed mechanism between the main discharge and the self-erasing discharge caused by the ramped-square sustain waveform has been previously reported [7], [8].

The sustain voltage pulse applicable to the current PDP driving circuit requires a static voltage margin greater than at least 50 V between the firing and sustaining voltages. In the ramped-square sustain pulse with a constantly increasing voltage slope, the voltage margin was also checked for application to the current PDP driving circuit. The static voltage margin for the ramped-square sustain pulse relative to the conventional square sustain pulse was measured with a variation in the driving frequency, as shown in Fig. 4. In the conventional square sustain pulse, the static voltage margin remained almost constant (64 V $\sim$ 67 V) irrespective of any increase in the driving frequency. On the contrary, in the ramped-square sustain pulse, with a voltage difference of 40 V between the rising and falling edges, the static voltage margin increased from 35 V at 50 kHz to 60 V at 200 kHz, indicating that a static voltage margin at a frequency higher than 100 kHz was sufficient. The detailed static and dynamic voltage margin characteristics for the ramped-square sustain pulse with various increasing voltage slopes will be reported elsewhere. The variations in the static voltage margins relative to the driving frequency are shown in Table I.

IV. Neon Emission Mechanism in PDP Cells Filled With Neon-Xenon Gas Mixture

The Ne emission and VUV radiation characteristics in a Ne–Xe gas mixture are governed by various reactions, such as excitation, spontaneous emission, and recombination [6]. A reaction diagram for the generation of orange light (585 nm) and VUV (147 or 173 nm) in PDP cells filled with a Ne–Xe

TABLE I
STATIC VOLTAGE MARGINS FOR RAMPED-SQUARE SUSTAIN PULSE RELATIVE TO CONVENTIONAL SQUARE SUSTAIN PULSE WITH DRIVING FREQUENCY

Frequency [KHz]		50	100	150	200
Margin	Conventional	65	64	64	67
[V]	Ramped-Square	35	52	51	60

gas mixture is shown in Fig. 5. The detailed reactions related to the Ne emission and the VUV generation in Fig. 5 can be expressed by the following equations [6], [9], [10]:

$$\mathrm{Ne}^{**}(18.7\ \mathrm{eV}) \rightarrow \mathrm{Ne}^{*}(16.7\ \mathrm{eV}) + h\nu\ (585\ \mathrm{nm}) \quad (1)$$

$$\mathrm{Xe}^{**}(10.3\ \mathrm{eV}) \rightarrow \mathrm{Xe}^{*}(8.44\ \mathrm{eV}) + h\nu\ (828\ \mathrm{nm}) \quad (2)$$

$$\mathrm{Xe}^{*}(8.44\ \mathrm{eV}) \rightarrow \mathrm{Xe} + h\nu\ (147\ \mathrm{nm}) \quad (3)$$

$$\mathrm{Xe}^{**}(10.3\ \mathrm{eV}) \rightarrow \mathrm{Xe}^{*}(8.32\ \mathrm{eV}) + h\nu\ (823\ \mathrm{nm}) \quad (4)$$

$$\mathrm{Xe}^{*}(8.32\ \mathrm{eV}) + 2\mathrm{Xe} \rightarrow \mathrm{Xe}_2^{*}(7.18\ \mathrm{eV}) + \mathrm{Xe} \quad (5)$$

$$\mathrm{Xe}_2^{*}(7.18\ \mathrm{eV}) \rightarrow 2\mathrm{Xe} + h\nu\ (173\ \mathrm{nm}). \quad (6)$$

As shown in (1), an orange light of 585 nm can only be emitted under high electric field intensity conditions, because the emission of 585 nm occurs from the transition of the highly excited states of Ne^{**} with a relatively high energy level (18.7 eV) into the excited states of Ne^{*}. In other words, to produce Ne^{**} from a Ne atom, high energy corresponding to 18.7 eV must be supplied to the PDP cells from the external sustain voltage, as shown in the reaction diagram in Fig. 5. On the other hand, a VUV of 147 or 173 nm is produced efficiently even at a low electric field intensity, because the energy states of the excited Xe and excited Xe dimer are low, as shown in (3) and (6). Moreover, the energy states of the highly excited Xe (10.3 eV) which can produce the excited Xe are relatively low, as shown in (2) and (4). The reactions about the Xe and Ne gas mixture indicate that the discharge can be produced under a weak electric field condition for the independent control between the VUV and Ne emissions. In general, the plasma in PDP cells is produced at a high electric field intensity because the real electric field is generated by the sustain voltage plus the wall voltage. Accordingly, if the gas chemistry remains constant, it is difficult to control the VUV and Ne emissions independently in the case of conventional square sustain pulses.

In this experiment, it was observed that the electric field intensity for the self-erasing discharge was relatively weak because the self-erasing discharge was only produced by the wall charges. Therefore, under the self-erasing discharge conditions, only VUV was produced without intensifying the Ne emission intensity. Accordingly, the current study used this self-erasing discharge as a new color enhancing discharge mode for improving the color purity.

V. RESULTS AND DISCUSSION

A. Visible and Neon Emission Relative to Driving Frequency in Conventional Square Sustain Waveform

The color reproducibility characteristics of PDPs are known to be poor due to the production of undesirable emissions from the phosphor layers and Ne gas, particularly orange light from the Ne discharge [2], [3]. Therefore, the reproduction of a good color image on a PDP requires the independent control of the visible emission intensity from stimulating the red, green, and blue phosphor layers and the orange light intensity from the Ne discharge in the Ne–Xe mixture gas. This means that the visible emission intensity should be strengthened without increasing the Ne emission intensity. The realization of this control strongly depends on whether or not the Xe and Ne reactions in the Ne–Xe gas mixture can be controlled separately. In this sense, the variations in the red, green, and blue visible and Ne emission intensities were investigated relative to the driving frequency of a conventional square sustain pulse. The spectrum of visible light emitted through the green and blue phosphor layers from the 4-in ac-PDP cells is shown in Fig. 6. When the frequency changed from 50 to 100 kHz, the peak intensity of 525 nm in the green emission spectrum increased by about 31%, while the peak of 585 nm in the undesirable Ne emission increased by about 30%, as shown in Fig. 6(a). Similarly, when the frequency changed from 50 to 150 kHz, the peak intensity of the green light increased by about 78%, while the peak intensity of the undesirable Ne emission increased by about 64%. As for the green emission spectrum, it is difficult to measure the changes in the only Ne emission relative to the driving frequency because the Ne and green emission spectra partially overlap. However, it is easy to observe the changes in the Ne emission relative to the driving frequency in the blue cells because the Ne and blue emission spectra are completely separated. In Fig. 6(b), when the frequency changed from 50 to 100 kHz, the peak intensity of 450 nm in the blue emission spectrum increased by about 53.7%, while the peak intensity of 585 nm in the undesirable Ne emission increased by about 42%. Similarly, when the frequency changed from 50 to 150 kHz, the peak intensity of the blue light increased by about 92%, while the peak intensity of the undesirable Ne emission increased by about 61.4%,

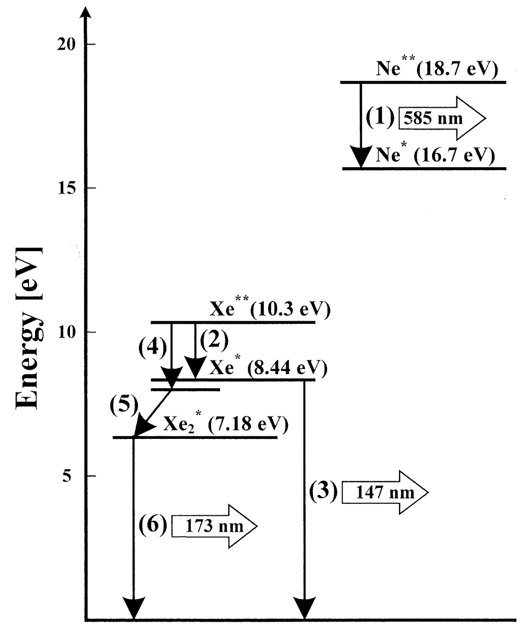
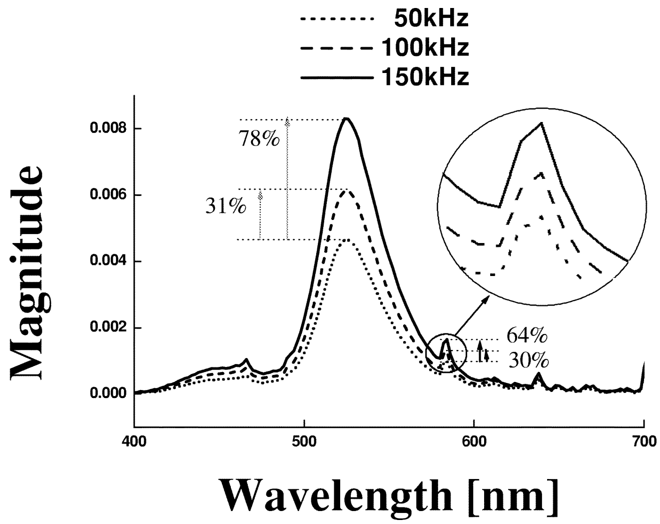
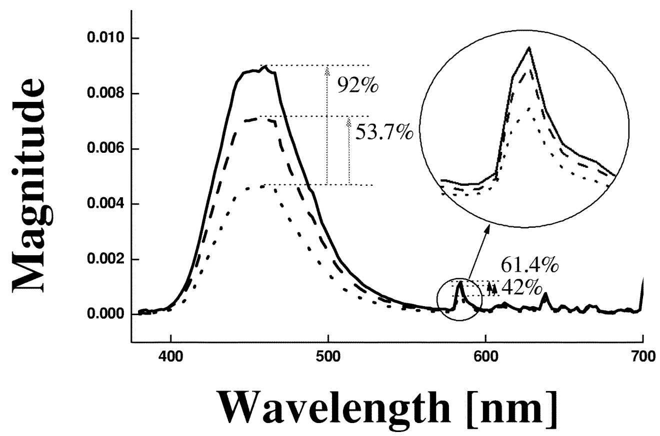


Fig. 5. Reaction diagram for orange light of 585 nm and VUV of 147 and 173 nm in Ne–Xe gas mixture.

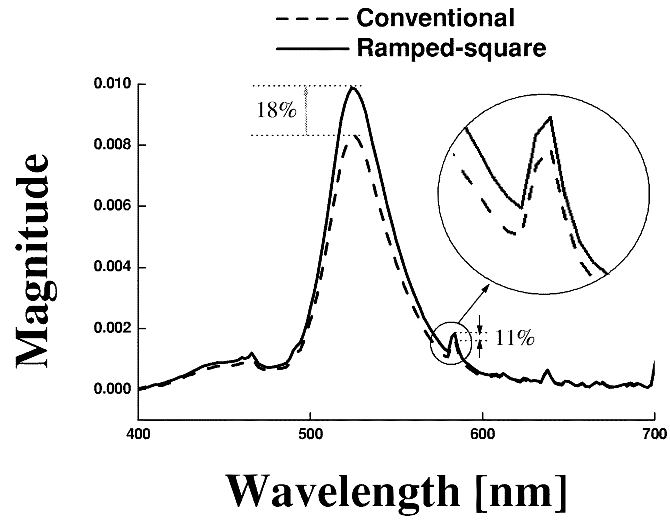


(a)

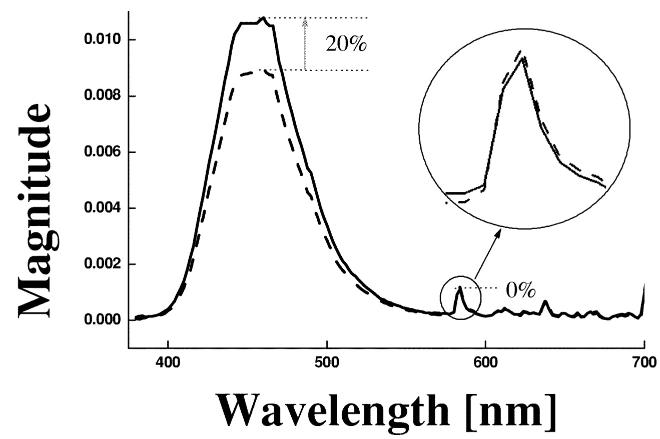


(b)

Fig. 6. Visible emission intensity from (a) green and (b) blue cells relative to driving frequency in conventional sustain square waveforms.



(a)



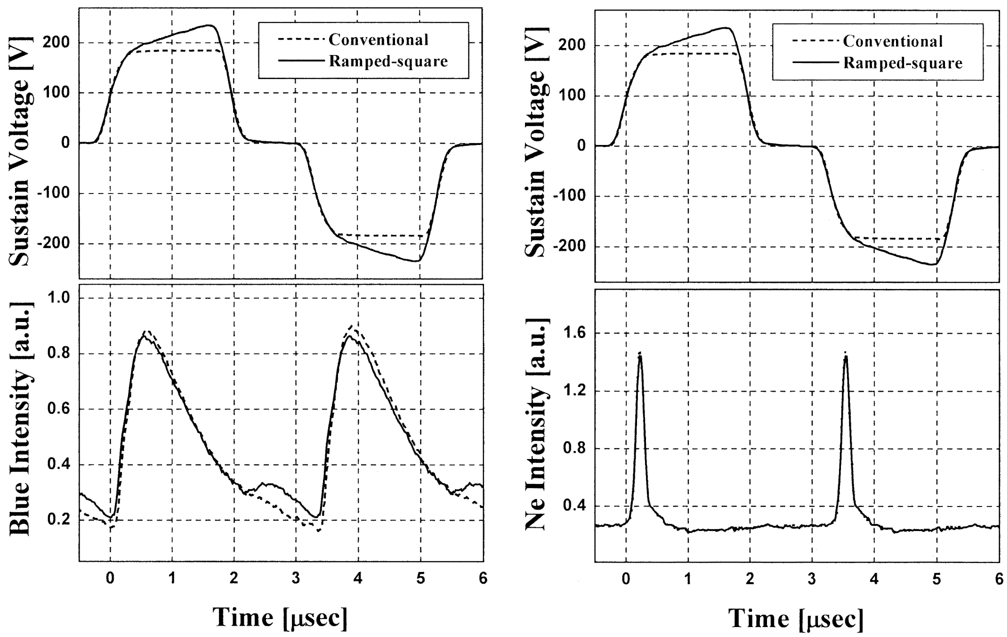
(b)

Fig. 7. Visible emission intensity from (a) green and (b) blue cells in ramped-square sustain waveform relative to conventional square sustain pulse at 150 kHz.

as shown in Fig. 6(b). This result shows that the color reproducibility of a PDP can be slightly improved when the driving frequency was increased. The increase in the driving frequency implies the increase in the survival possibility of many priming particles until the initiation stage of the following sustain discharge. Accordingly, the discharge efficiency can be improved by increasing the driving frequency because the priming particles can contribute to lowering the electron temperature of the plasma [11], [12]. The presence of priming particles can produce an efficient discharge even under a weak electric field condition, implying that the weak electric field can promote the production of VUV from Xe^* and Xe_2^* instead of the generation of orange light from Ne^{**} because the energy state of Ne^{**} is relatively high. However, the result of Fig. 6 shows that the Ne emission intensity increases in proportion to the increase in the green and blue emission intensities with a driving frequency, indicating that the fast driving condition does not induce a significant difference of the intensities between the visible and Ne emissions. This result is mainly due to the saturation characteristics of the red, green, and blue phosphors which convert the VUV from Xe^* and Xe_2^* into a visible light. The red, green, and blue phosphors show a very longer life time than that of the Ne^{**} [13], [14]. In particular, the red and green phosphors have a longer life time than that of the blue phosphor. With an increase in the driving frequency, the blue emission shows a linear increase, whereas the green emission shows the saturated emission characteristics. Accordingly, the increase in the green and blue emission intensities is not directly proportional to the efficient production VUV from Xe^* and Xe_2^* under fast driving conditions.

B. Comparison of Visible and Neon Emission Between Conventional Square and Ramped-Square Sustain Waveform

Figs. 7(a) and (b) illustrate the spectrum of visible emission emitted through the green and blue cells of the 4-in test panel in the case of applying the conventional square and ramped-square sustain pulses, respectively. The driving conditions were a frequency of 150 kHz and a duty ratio of 30% (pulsewidth: 2 μs). With the ramped-square sustain pulse, the amplitudes of the sustain voltage at the rising and falling edge were 180 and 240 V (constant slope: 30 V/μs), respectively. As shown in Fig. 7(a), with the ramped-square sustain pulse, the peak intensity of the green emission increased by about 18%, whereas the Ne emission peak intensity of 585 nm near the undesirable emission region increased by about 11%. This increase in the Ne peak inten-



(a) (b)

Fig. 8. Time behavior of blue peak emission intensity of (a) 450 nm and Ne emission intensity of (b) 585 nm measured based on 10 × 10 pixels when applying conventional square and ramped-square sustain pulses.

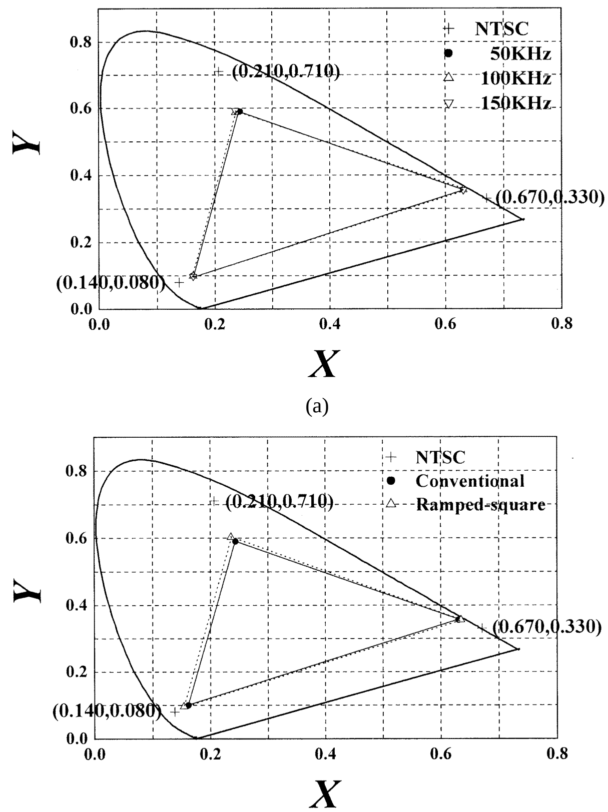
sity was presumably due to the additional green emission caused by the self-erasing discharge. Currently, it is not clear whether or not the increase in the 585 nm in the visible spectrum from the green cells was only due to a variation in the Ne emission intensity.

In contrast, when ramped-square sustain pulses were applied to the blue cells, the peak intensity of the blue emission increased by about 20%, whereas the Ne-emission peak intensity of 585 nm remained unchanged or slightly decreased. Unlike the green cells, since the visible spectrum emitted from the stimulation of the blue phosphor layer was completely separated from the orange light of 585 nm produced in the blue cells, this clearly indicated the variation in the Ne emission characteristics due to the self-erasing discharge. As a result, the ramped-square sustain pulse was found to produce a self-erasing discharge that induced an additional stimulation from the red, green, and blue phosphor layers, thereby resulting in an increased visible emission intensity from the phosphor layers in the PDP cells. However, almost no orange light of 585 nm was emitted from the excited neon atoms during the self-erasing discharge which was only induced under the weak electric field. Accordingly, the self-erasing discharge provides a new color-enhancing discharge mode, whereby the color purity can be enhanced based on separate control of the Xe and Ne reactions in the Ne–Xe gas mixture. To check the discrepancy of emission characteristics between the visible emission from the stimulated phosphor layers and the Ne emission from the Ne discharge, the time behavior of the blue peak emission intensity of 450 nm and Ne emission intensity of 585 nm was observed for the red, green, and blue cells when the conventional square and ramped-square sustain pulses were applied, respectively, as shown in Fig. 8(a) and (b). The driving conditions of Fig. 8 were identical to those in Fig. 7. The blue emission was produced once per square sustain pulse, yet twice per ramped-square sustain pulse. The blue light intensity of 450 nm emitted during the main discharge by the square sustain pulse was slightly higher than that by the ramped-square sustain pulse. However, as for the ramped-square sustain pulse, an additional blue emission was obtained by the self-erasing discharge, as shown in Fig. 8(a). As a result, the total blue emission intensity was somewhat higher by applying the ramped-square sustain pulse than by applying the conventional square sustain pulse, as shown in Fig. 7(b). As shown in Fig. 8(b), the Ne emission was produced once per sustain pulse for both the conventional square and the ramped-square sustain pulses, confirming that no Ne emission was generated during the self-erasing discharge. Furthermore, the Ne emission intensity produced by the ramped-square sustain pulse in the main discharge was almost the same as that produced by the conventional square sustain pulse.

C. Change in Color Gamut Area due to Self-Erasing Discharge

The area of the color gamut basically determines the range of color reproducibility of an ac-PDP. In the case of employing the conventional square and new ramped-square sustain waveforms, the changes in the color gamut area in the CIE Chromaticity Diagram (1931) measured from the 4-in test panel are displayed in Fig. 9(a) and (b), respectively. The data in Fig. 9(a) show that the color gamut area changed relative to the driving frequency with the conventional square sustain pulses. The color gamut was changed slightly when the driving frequency was increased from 50 to 150 kHz and expanded by approximately 2%. It would appear that the priming particles under the fast driving frequency condition contributes to this small increase in the color gamut area.

When the ramped-square sustain pulses were applied at 150 kHz, the color purities of the blue and green visible emissions both improved, particularly the blue emission, as shown in Fig. 9(b). When compared with the conventional square



(b)

Fig. 9. Changes in color gamut area in CIE Chromaticity Diagram (1931) (a) in case of conventional sustain pulse relative to driving frequency and (b) ramped-square sustain pulse at 150 kHz compared with conventional square sustain pulse at 50 kHz .

sustain pulse at 50 kHz, the color gamut area was expanded by about 5.4% in the case of the ramped-square sustain pulse. Therefore, this result demonstrates that the color purity of the PDP can be improved without reducing the luminance based on the new color enhancing discharge mode using a self-erasing discharge.

VI. Conclusion

The color reproducibility in an ac-PDP was improved based on a new color enhancing discharge mode using a self-erasing discharge. The Ne and Xe reaction mechanism in the Ne–Xe gas mixture was analyzed so as to identify a new color enhancing discharge mode that could minimize the orange light, while simultaneously enhancing the VUV generation. When the ramped-square sustain pulses were applied at 150 kHz, the color purities of the blue and green visible emissions were both improved, particularly the blue emission, thereby expanding the color gamut area by about 5.4%.

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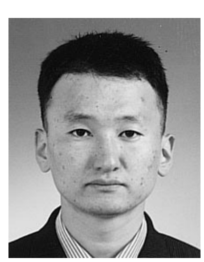

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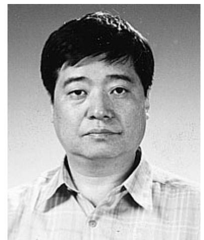

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