A New AC Plasma Display Panel With Auxiliary Electrode for High Luminous Efficacy

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***Abstract*—A new ac plasma display panel (PDP) for high luminous efficacy is proposed, and its characteristics are investigated. The new ac PDP has a coplanar gap of 200 μm and an auxiliary electrode located between the scan and common electrodes. The periodic pulses are applied to the auxiliary electrode during the sustain period, which plays the roles of enhancing the infrared emission and reducing the discharge current. The sustain voltage decreases with the increase of the auxiliary pulse voltage until 80 V. When the voltage of the pulse applied to the auxiliary electrode is 50 V, the luminous efficacy reaches its peak value and is approximately 8.7 lm/W obtained from the measurement of Ne + 20% Xe gas-mixture discharges in the green cells. The luminous efficacy of the new proposed test ac PDP with Ne + 13% Xe and Ne + 20% Xe gas mixtures is improved by 190% and 320%, respectively, compared to that of the conventional ac PDP with a Ne + 13% Xe gas mixture.**

***Index Terms*—Auxiliary electrode, high efficacy, long coplanar gap, plasma display panel (PDP).**

I. INTRODUCTION

AC plasma display panels (PDPs) with trielectrodes are widely used for commercial displays and digital television screen. The ac PDP with trielectrodes was introduced by Dr. Shinoda in the early 1980s [1]. The ac PDP with trielectrodes has been adopted by almost all of PDP module makers and has become a standard structure of the commercial products. The ac PDP with trielectrodes has many strong points such as simple structure, relatively low driving voltage, and a long lifetime. However, some drawbacks have appeared as the commercial products have spread and started to compete with other large-area flat panels. In particular, the power consumption of the ac PDP with trielectrodes is relatively higher compared to that of thin-film transistor liquid-crystal display at full white level [2]. In an ac PDP, the electrical power is consumed at the panel, circuit, and so on. The power efficiency of the PDP is very low, and its power consumption is directly related to the luminous efficacy of the PDP. We have to improve the luminous efficacy of the plasma display to reduce the power consumption. Currently, the luminous efficacy of the ac PDP with trielectrodes is relatively low, and those of the luminous efficacy of the commercial ac PDP product are about 1.5–2 lm/W. The reason why ac PDP has a low luminous efficacy is due to the high ion heating rate of microplasma in a display pixel. Actually, vacuum ultraviolet (VUV) photons emitted from the excited xenon particles are needed to stimulate the photoluminescence phosphor. However, 24% of the dissipated energy in microplasma is used for exciting xenon, and only 14% of that is used for generating VUV photons when a Ne + 5% Xe gas mixture is employed for the ac PDP with trielectrodes [3]. The fluorescent lamp, whose principle is basically same as PDP, shows a luminous efficacy higher than 80 lm/W. The fluorescent lamp has a very long electrode gap (several centimeters) between the cathode and anode so that it can produce a low electric field and enhance the electron excitation rate. Therefore, the positive column discharges due to a very long electrode gap produce numerous ultraviolet (UV) photons with wavelengths of 254 nm emitted from mercury. Furthermore, the energy conversion efficiency of the lamp is greater than that of PDPs because of the small Stokes shift from photons with wavelength of 254 nm to visible light photons. These two factors of long electrode gap and small Stokes shift are the main reasons for the high luminous efficacy of the fluorescent lamp. The ac PDP with trielectrodes has a coplanar gap of 60–100 μm and usually uses a neon and xenon gas mixture with a xenon concentration of 4%–6%. Generally, in an ac PDP, 147 and 173 nm UV photons emitted from xenon monomer and dimmer, respectively, are utilized to stimulate a photoluminescent phosphor. Therefore, the Stokes shift from VUV photons to visible photons in an ac PDP is larger than that of a fluorescent lamp. These types of short gap and large Stokes shift are the main reasons behind the lower luminous efficacy compared to the fluorescent lamp. During the past ten years, many approaches have been tried to improve luminous efficacy [4]–[8]. There were some trials to employ the small Stokes shift of excimer gases [9] and an N_2 gas mixture [10]. However, in the case of a small-Stokes-shift gas mixture, it is not easy to find out the proper photoluminescent phosphor for the excimer and N_2 gas mixture. One of the promising approaches is to increase the electron excitation rate. There are several kinds of method to increase the electron excitation rate. One of them is to increase the discharge electrode gap as in the case of the fluorescent lamp. However, in an ac PDP, the discharge electrode gap cannot be increased too large because the pixel

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size is limited by resolution. Furthermore, there was a study in which the UV intensity emitted from the positive column discharge was decreased with an increase in gas pressure [11]. Currently, the gas pressure of an ac PDP is about 400–500 torr, at which the UV intensity of the positive column discharge is supposed to be lower than that of the negative glow [11]. In a given pixel pitch, the discharge space is vertically restricted by barrier ribs. The height of the barrier rib is also an important factor to make an efficient discharge when the discharge gap is increased. In a previous work, the coplanar gap was optimized from the point of view of luminous efficacy [12]. When the coplanar gap was 200 μm, the maximum efficacy was observed in the ac PDP with trielectrodes. The luminous efficacy of the coplanar-gap discharge was increased as the coplanar gap was increased in the range of 80–200 μm. In the case of a coplanar gap of 300 and 500 μm, the luminous efficacy was lower than that of 200 μm because of the narrowness of the coplanar-gap discharge. There is another approach to improve efficacy, which is to utilize a perturbation pulse [13]. When the pulse was applied to the auxiliary electrode that was adjacent with the main display pixel, the microplasma was perturbed, and its luminous efficacy was improved. The pulses applied to the auxiliary electrode directly influenced the charged particles during glow or afterglow and indirectly changed the distribution of the excited and metastable particles [14]. As the effect of the perturbed pulse was proved in a dc PDP, it is expected that it can be adopted to an ac PDP as well. In this paper, we propose a new ac PDP with auxiliary electrode and long coplanar gap to realize the high luminous efficacy. The features of the new ac PDP are the long coplanar gap of 200 μm and the auxiliary electrode between the scan and common electrodes. Of course, the coplanar gap of 200 μm can be changeable in accordance with the gas-mixing ratio and the height of the barrier rib. The auxiliary electrode is used for perturbing the afterglow during the sustain period. We investigated the new ac PDP with four electrodes from the viewpoint of luminous efficacy.

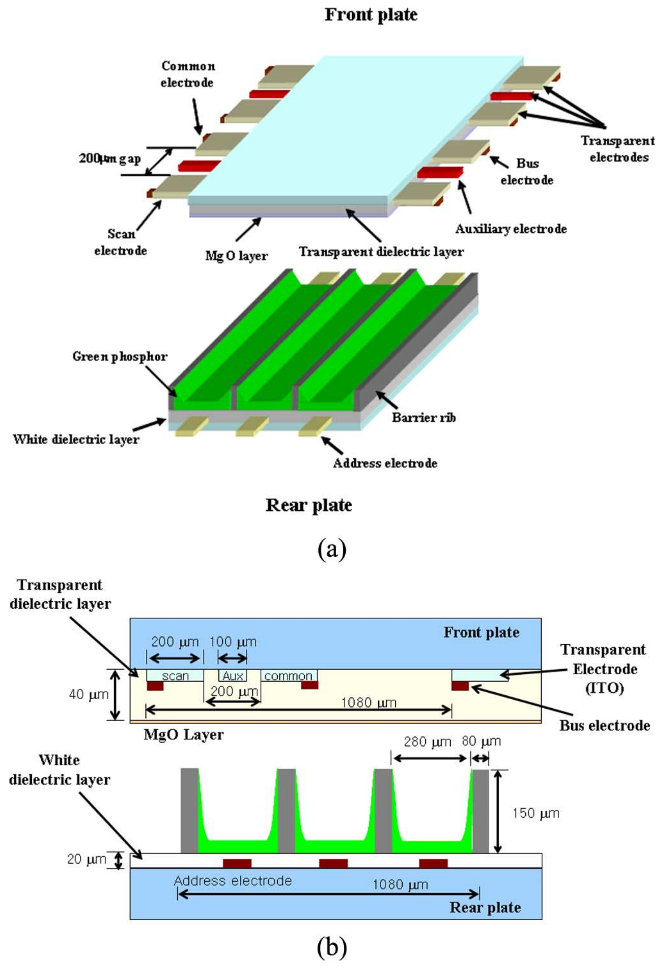


Fig. 1. (a) Schematic drawing of the proposed new ac PDP with four electrodes. (b) Cross-sectional view of the proposed test PDP and its dimension.

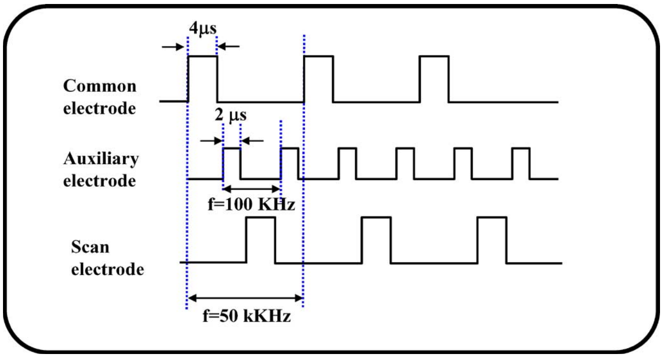


Fig. 2. Pulse waveforms applied to scan, common, and auxiliary electrodes in the front plate.

II. TEST PANEL PREPARATION AND EXPERIMENTAL SETUP

The schematic drawing of the proposed new ac PDP with four electrodes is shown in Fig. 1. There are two kinds of differences between the proposed and the conventional panels: One is the coplanar-gap distance, and the other is the auxiliary electrode located between the scan and common electrodes. Usually, the coplanar gap of the conventional ac PDP with three electrodes is in the range of 60–100 μm. In this paper, the coplanar gap is fixed at 200 μm. As mentioned before, the coplanar gap was optimized in a previous work [12]. We fabricated a 3-in test ac PDP, as described in Fig. 1. In the front plate, the width of the scan electrode is 200 μm, whereas the width of auxiliary electrode is 100 μm. The thicknesses of the transparent dielectric and MgO film are 40 μm and 500 nm, respectively. In the rear plate, the width of the address electrode is 100 μm. The thickness of the white dielectric layer is 20 μm. The height and width of the barrier rib are 150 and 80 μm, respectively. The shape of barrier rib is a stripe type. The green phosphor was coated on the barrier rib by the screen printing method. A Ne + Xe gas mixture is filled up to 450 torr. Ne + 13% Xe and Ne + 20% Xe gas mixtures are employed, respectively. Fig. 1(b) shows the cross-sectional view of the proposed test panel and its dimension.

Fig. 2 shows the pulse waveforms applied to each electrode in the front plate. The sustain pulses are applied to the common and scan electrodes during the sustain period. In this paper, the width of the sustain pulse is 4 μs, and its frequency is 50 kHz. The pulse applied to the auxiliary electrode has a width of 2 μs and a frequency of 100 kHz. The timing of the pulse applied to

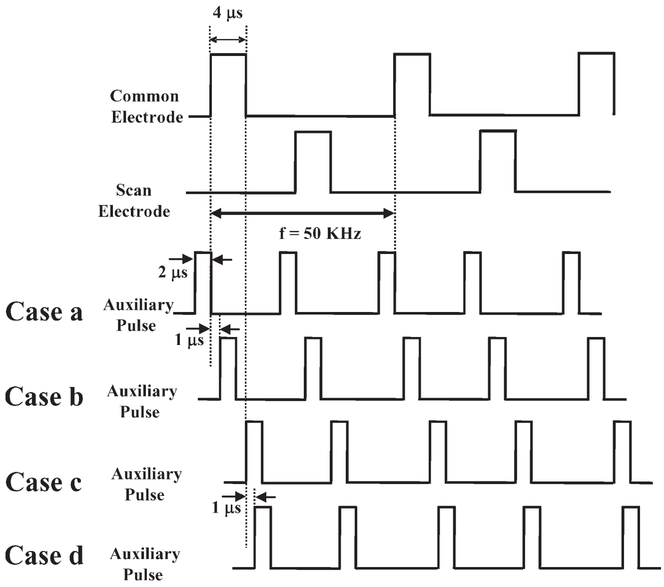


Fig. 3. Timing of the pulse applied to the auxiliary electrode.

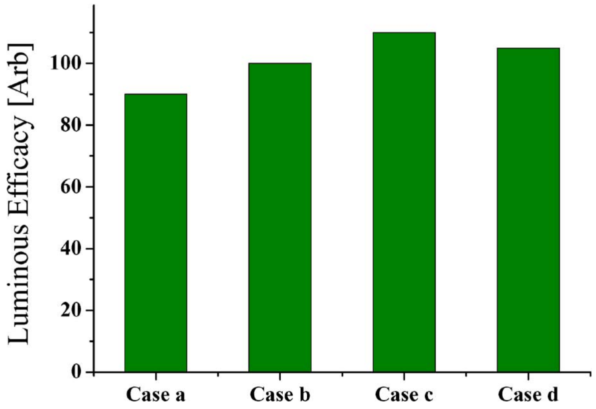


Fig. 4. Relative luminous efficacy in accordance with cases (a), (b), (c), and (d) of Fig. 3.

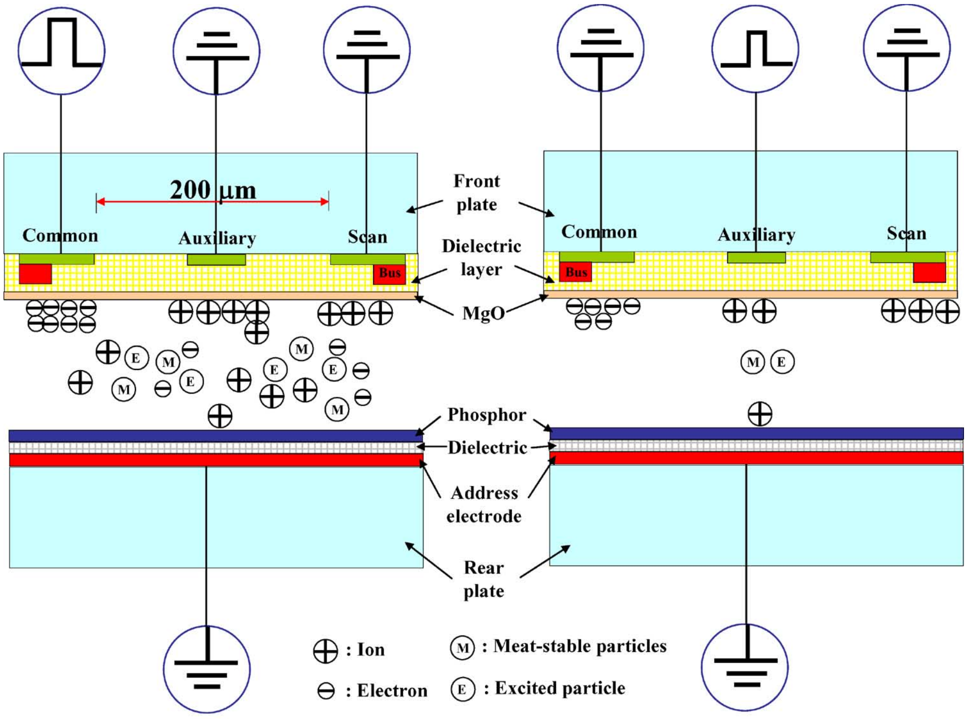
the auxiliary electrode is one of the important factors to achieve the improved luminous efficacy.

Fig. 3 shows the timing of the pulse applied to the auxiliary electrode. In case (a) of Fig. 3, the auxiliary pulse is applied before the sustain pulse. The ending point of the auxiliary electrode is equal to the starting point of the sustain pulse. In case (b) of Fig. 3, the time interval between the sustain pulse and auxiliary pulse is 1 μs. The sustain pulse is applied to the scan or common electrode, and then, after 1 μs, the pulse is applied to the auxiliary electrode. In case (c) of Fig. 3, the auxiliary pulse is applied right after the sustain pulse ending. The ending point of sustain pulse is timely identical to the starting point of the auxiliary pulse. In case (d) of Fig. 3, the auxiliary pulse is applied at 1 μs after the end of the sustain pulse.

Fig. 4 shows the relative luminous efficacy in accordance with each case shown in Fig. 3. We used a Ne + 13% Xe gas mixture in the proposed ac PDP. Case (c) has the maximum luminous efficacy. The luminous efficacy of case (d) is the second highest value among the four cases. Actually, in the previous work, the wall charge accumulation and space decay time was about 4 μs [15]. When the auxiliary pulse is applied after the 4-μs duration of the sustain pulse, the effect of the auxiliary pulse on afterglow is maximized from a viewpoint of luminous efficacy. The mechanism of these phenomena is thought to be related to the time scales of the wall charge accumulation and the space charge decay. When the pulse is applied to the auxiliary electrode at earlier than 4 μs, the wall charge is not sufficiently accumulated on the auxiliary electrode. When the pulse is applied to the auxiliary electrode at later than 4 μs, the more space charges are decayed. However, the more detail mechanism needs further study. In this paper, we use case (d) for investigating the effect of auxiliary pulse on the luminous efficacy in the proposed new ac test PDP.

III. CHARACTERISTICS OF THE INFRARED (IR) EMISSION AND DISCHARGE CURRENT

The proposed cell structure is featured by a coplanar gap of 200 μm and the auxiliary electrode. Fig. 5 shows the schematic drawing of the operation of the proposed cell during the sustain period. The main role of the auxiliary electrode is supposed to improve the luminous efficacy during the sustain period. In general, the sustain discharges are repeated by periodical pulses that, in turn, create glow and afterglow. In this paper, the glow is defined as the discharge-on period when the sustain pulse is applied to the common or scan electrode. Usually, the pulse discharge in an ac PDP elapses less than 1 μs. Therefore, the glow is ended within 1 μs, and IR emission can be observed within 1 μs after the discharge starts. The afterglow is defined as the discharge-off period. During glow discharges, the space charges and the excited particles, including meat-stable species, are generated and decay, and some of the space charges are turned into wall charges on the dielectric layer. During afterglow, a few of the space charges and some of the metastable particles including the excited species remain alive. In the proposed cell structure, the periodical pulses are applied to the auxiliary electrode after applying the sustain pulse. The existence of the auxiliary electrode and the applying pulse influence the distribution of the charged particles and the excited particles during both glow and afterglow. For example, the case of applying a positive pulse to the common electrode will be explained. If there is no auxiliary electrode, the positive wall charges are only accumulated on the scan electrode. However, when there is an auxiliary electrode between the common and scan electrodes, positive wall charges are accumulated on both the auxiliary and scan electrodes during glow. During afterglow, the pulse applied to the auxiliary electrode erases some of the wall charges accumulated on the auxiliary electrode, and the polarity of wall charges on the auxiliary electrode is the same with those on the scan electrode in low voltage of the pulse applied to the auxiliary electrode. Consequently, the next periodic discharge occurs between the common and scan electrodes because the high-enough voltage of the positive pulse is applied to the scan electrode. At that time, the discharge between the auxiliary electrode and common electrode does not occur because the electric field is not strong enough. However, the discharge can spread from the scan to the auxiliary electrode during glow. In a case of high-enough voltage of the auxiliary pulse, the discharge can occur between the common and auxiliary electrodes during afterglow. Then, the polarity of



(a) (b)

Fig. 5. Schematic drawing of the operation of the proposed cell structure (a) during glow and (b) during afterglow.

the wall charges on the auxiliary electrode can be inverted and becomes the same with that on the common electrode. Consequently, the next periodic discharge can occur between the scan and auxiliary electrodes.

Fig. 6 shows the characteristics of IR emission in accordance with the conditions of an auxiliary electrode when a Ne + 4% Xe gas mixture is used as the discharge gas for the proposed structure. Compared to the IR emission from a coplanar gap of 200 μm without an auxiliary electrode, the cell with a pulse of 50 V applied to the auxiliary electrode has stronger IR emission. However, the intensity of the IR emission decreases as the voltage of the pulse applied to the auxiliary electrode rises over 80 V. The role of the auxiliary electrode is to make a strong IR emission during glow. In particular, the cathode region, including the scan electrode, has stronger IR emission compared to the case of nonauxiliary electrode in a coplanar gap of 200 μm. Furthermore, we can see another strong IR emission around the auxiliary electrode. Usually, compared to the short-gap discharge, the long-coplanar-gap discharges have a higher excitation rate because of the relatively low electric field. In addition, the auxiliary electrode enhances the excitation rate of the microplasma generated in the coplanar gap of 200 μm.

Fig. 7 shows the IR emission during afterglow when the auxiliary electrode is grounded and a 50-V pulse is applied to the auxiliary electrode, respectively. In the case of the grounded auxiliary electrode, there is no IR emission during afterglow. However, a slight IR emission near the common and auxiliary electrodes is observed when a 50-V pulse is applied to the auxiliary electrode during afterglow. This kind of small IR emission does not contribute to the creation of discharge current flow. The applied pulse to the auxiliary electrode can indirectly cause the excited particles to be activated during afterglow, consequently influencing the next step periodic discharge. This result can be explained by the previous result that the perturbation pulse during afterglow can influence indirectly the distribution of the excited and the metastable particles [14]. Therefore, we can say that another role of the auxiliary electrode is to create prime particles during afterglow.

Fig. 8 shows the discharge current in the display cells with and without an auxiliary electrode. Fig. 8 takes into account all types of discharge current flowing into the common, scan, auxiliary, and address electrodes. In the low voltage range of the auxiliary pulse, the discharge current flowing into the auxiliary electrode is negligible. In the high voltage range such as 100 and 130 V, the magnitude of the discharge current flowing into the auxiliary electrode is less than 1% of the magnitude of the discharge current flowing into the sustain electrode. The discharge current in Fig. 8 is measured at the mid value of the voltage of the sustain pulse. As shown in Fig. 8, the discharge current can be reduced as the pulses are applied to the auxiliary electrode. The existence of the auxiliary electrode between the scan and common electrodes plays a role in the reduction of the discharge current flowing into display cells. As mentioned earlier, the pulse applied to the auxiliary electrode erases some of the wall charges during the afterglow, and then the next periodic discharge current can be decreased due to the reduced wall charges. However, when the voltage of the pulse applied to the auxiliary electrode rises over 100 V, the discharge current starts to increase rather than decrease. It is thought that the discharges between auxiliary and sustain electrodes occur in the case of an applying pulse with more than 100 V to the auxiliary electrode. During the sustain period, the main discharge occurs between the scan and common electrodes in the low voltage range of the auxiliary pulse. When the voltage of the pulse

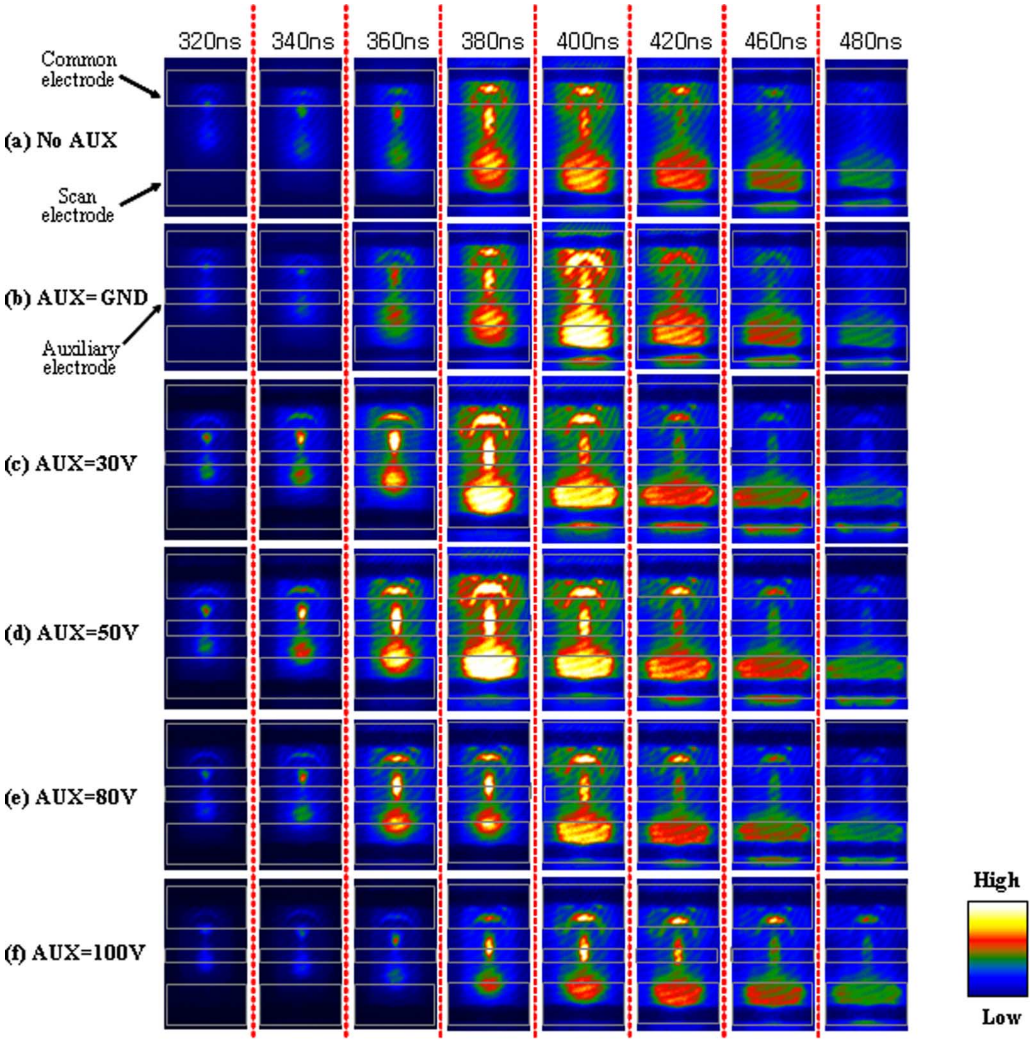


Fig. 6. Characteristics of IR emission in accordance with the conditions of the auxiliary electrode. (a) Nonauxiliary electrode. (b) Grounded auxiliary. (c) Voltage of the pulse applied to the auxiliary is 30 V. (d) Voltage of the pulse applied to the auxiliary is 50 V. (e) Voltage of pulse applied to the auxiliary is 80 V. (f) Voltage of pulse applied to the auxiliary is 100 V.

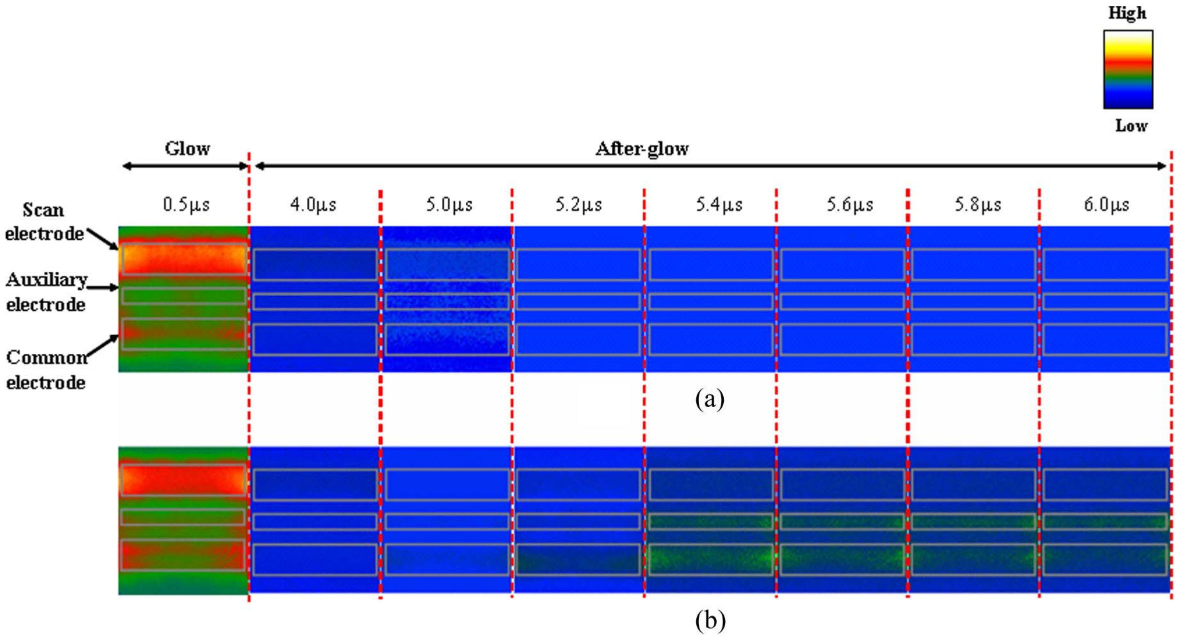


Fig. 7. IR emission during afterglow when (a) the auxiliary electrode is grounded and (b) a 50-V pulse is applied to the auxiliary electrode.

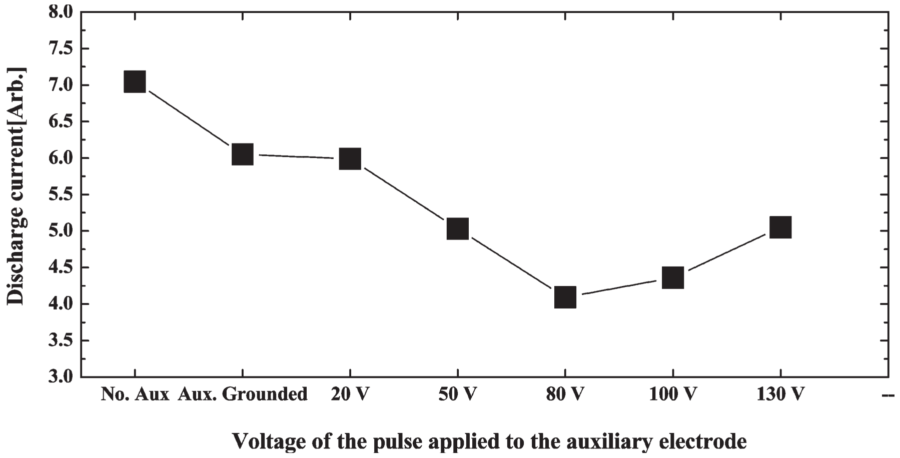


Fig. 8. Discharge current in display cells in accordance with the conditions of the auxiliary electrode.

applied to the auxiliary electrode is high enough, the auxiliary electrode is concerned with the main discharges. We can see that another important role of the auxiliary electrode is reducing the current flowing into the display cells.

The roles of the auxiliary electrode can be summarized as follows: 1) enhancing IR emission during glow; 2) making a small excitation rather than ionization during afterglow; and 3) reducing discharge current. Therefore, the pulses applied to the auxiliary electrode located between the scan and common electrodes increase the excitation rate of microplasma generated in the display cells of the ac PDP with a coplanar gap of 200 μm. The proposed structure in this paper is named as the "Fourth Electrode for enhancing the Excitation rate of the microdischarges in a Long coplanar gap (FEEL)" PDP.

IV. CHARACTERISTICS OF LUMINOUS EFFICACY

The proposed new ac PDP called FEEL PDP is supposed to have a higher sustain voltage compared to the conventional ac PDP because the FEEL PDP has a longer sustain gap. The sustain voltage without auxiliary electrode is almost the same with the case of floated auxiliary electrode in Fig. 9. We investigate the effect of the auxiliary electrode on the sustain voltage. Fig. 9 shows the maximum and minimum sustain voltages in accordance with the conditions of the auxiliary electrode. As expected, the sustain voltage is higher because of the longer sustain gap and the high xenon content gas mixture such as Ne + 13% Xe and Ne + 20% Xe. The maximum and minimum sustain voltages of the main display discharge are changed when the pulses are applied to the auxiliary electrode. Both the maximum and minimum sustain voltages are decreased as the auxiliary pulse voltage increases until 80 V. Thereafter, the sustain voltage increases. The sustain voltage margin decreases as the voltage of the pulse applied to the auxiliary electrode increases. The reason behind why the voltage margin is decreased by increasing the auxiliary pulse voltage is that the applying auxiliary pulse erases some of wall charges accumulated on the auxiliary electrode.

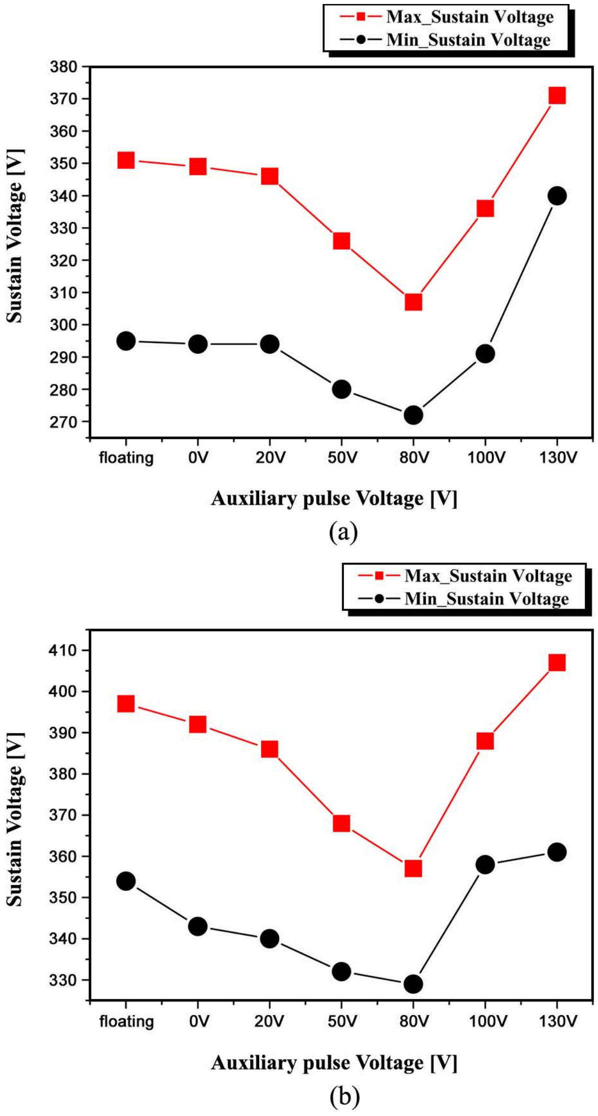


Fig. 9. Maximum and minimum sustain voltages in accordance with the conditions of the auxiliary electrode. (a) Net + 4%Xe. (b) Net + 20%Xe.

Fig. 10 shows the luminous efficacy of the test FEEL PDP with Ne + 13% Xe as a function of the sustain voltage in accordance with the conditions of the auxiliary electrode. The black squares in Fig. 10 are the reference values obtained from Ne + 13% Xe gas-mixture discharges in the conventional structure. The reference luminous efficacy is in the range

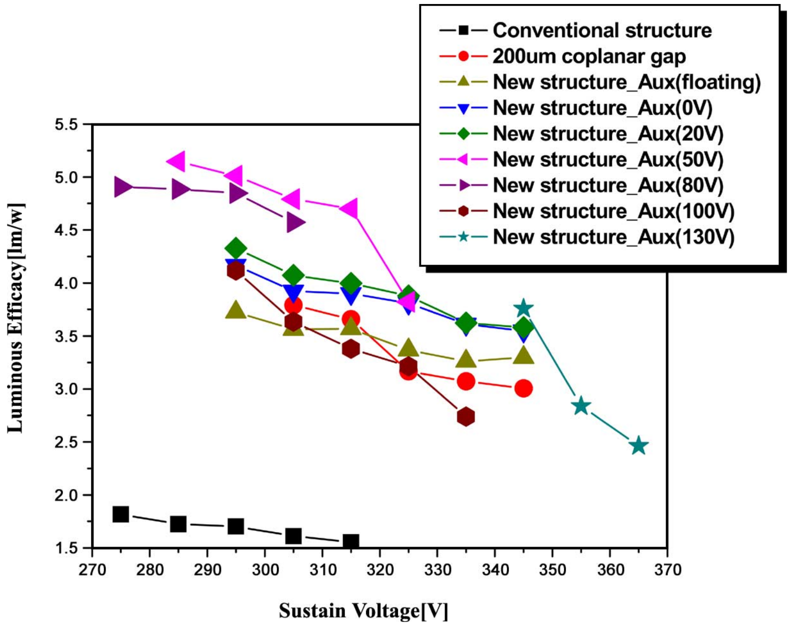


Fig. 10. Luminous efficacy of the test FEEL PDP with Ne + 13% Xe as a function of the sustain voltage in accordance with the conditions of the auxiliary electrode.

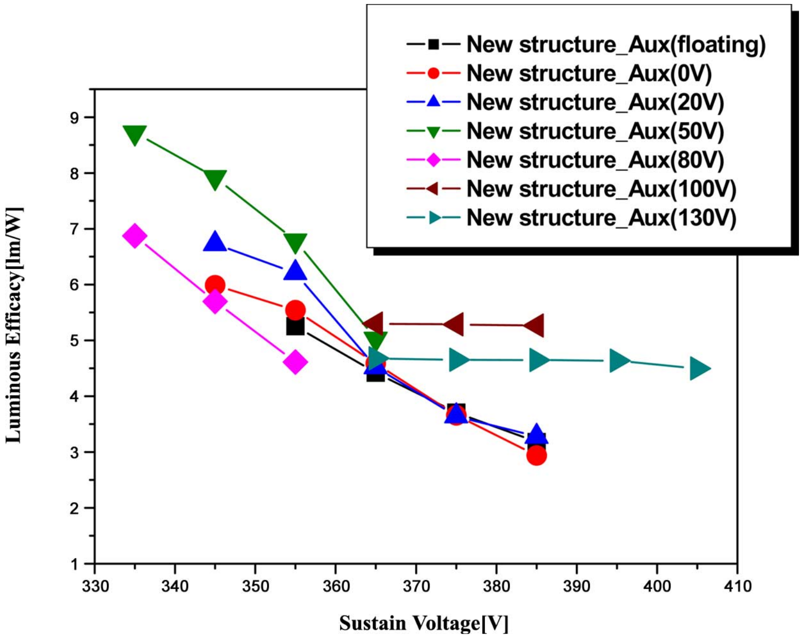


Fig. 11. Luminous efficacy of the test FEEL PDP with Ne + 20% Xe as a function of the sustain voltage in accordance with the conditions of the auxiliary electrode.

between 1.55 and 1.81 lm/W. In a coplanar gap of 200 μm, the luminous efficacy is increased due to the effect of the long sustain gap. In addition, the auxiliary electrode enhances the luminous efficacy by applying pulses to the auxiliary electrode during the afterglow. In the case of Ne + 13% Xe gas-mixture discharges, the luminous efficacy is increased until the voltage of the pulse applied to the auxiliary electrode is 50 V. When the auxiliary pulse voltage is over 100 V, the luminous efficacy starts to decrease. The applications of the auxiliary pulse during the afterglow enhance the excitation rate of the microplasma and improve the luminous efficacy. However, when the voltage of the pulse applied to the auxiliary electrode is over 100 V, there should be unnecessary discharges between auxiliary and sustain voltage during afterglow, which change the distribution of the wall charge and increase the sustain voltage as shown in Fig. 9. There should be a transition region between 50 and 100 V of the auxiliary pulse, which requires further study. The maximum luminous efficacy is about 5.15 lm/W measured from the green cells when the auxiliary pulse voltage is 50 V.

Fig. 11 shows the luminous efficacy of the test FEEL PDP with a Ne + 20% Xe mixture as a function of the sustain voltage in accordance with the conditions of the auxiliary electrode.

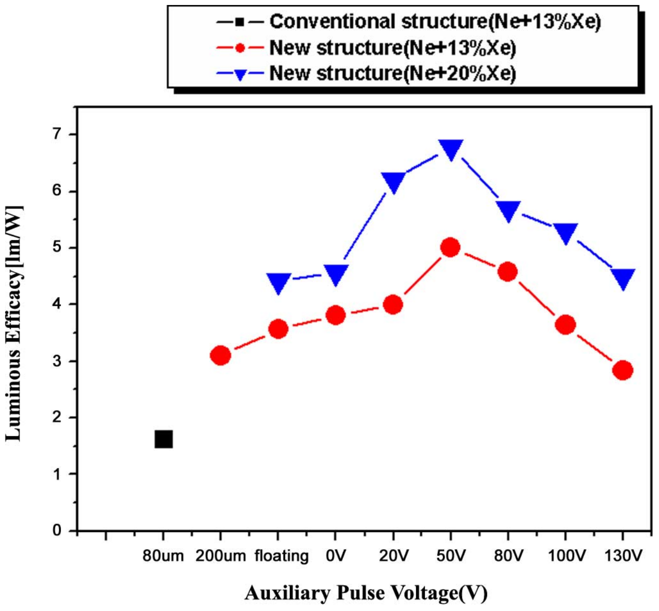


Fig. 12. Comparison of luminous efficacy between the reference cells and the test FEEL PDP cells with Ne + 13% Xe and Ne + 20% Xe gas mixtures in accordance with the coplanar gap and the voltage of the pulse applied to the auxiliary electrode.

The behavior of the luminous efficacy of the Ne + 20% Xe gas mixture in the test FEEL PDP is almost the same as that of Ne + 13% Xe. The luminous efficacy reaches its maximum value when the voltage of the pulse applied to the auxiliary electrode is 50 V. The maximum efficacy is about 8.7 lm/W. All kinds of discharge current are taken into account for estimation of luminous efficacy. Compared to the case of the floated and the grounded auxiliary electrodes, the sustain voltage of the case of applying a pulse with 20–80 V shifts to the left-hand side in Fig. 11. As with the sustain voltage in Section III, the behavior of the case of auxiliary pulse voltages of 100 and 130 V are different from those of 20, 50, and 80 V.

Fig. 12 shows comparison of luminous efficacy between the reference cells and the test FEEL PDP cells with the Ne + 13% Xe and Ne + 20% Xe gas mixtures in accordance with the coplanar gap and the voltage of the pulse applied to the auxiliary electrode. The reference luminous efficacy is about 1.6 lm/W, which was obtained from the green cells, with a coplanar gap of 80 μm and Ne + 13% Xe. The luminous efficacy of a coplanar gap of 200 μm without an auxiliary electrode is about 3.1 lm/W. Both cases of the Ne + 13% Xe and Ne + 20% Xe gas mixtures have the improved luminous efficacy by using the pulse applied to the auxiliary electrode. The values of the luminous efficacy shown in Fig. 12 are obtained at the medium point of the sustain voltage. The luminous efficacy of the Ne + 13% Xe and Ne + 20% Xe gas mixtures is improved by 190% and 320%, respectively, compared to the reference cells. The maximum efficacy point in Fig. 12 corresponds to the maximum IR emission, as shown in Fig. 6.

V. CONCLUSION

A new ac PDP featured by a coplanar gap of 200 μm and an auxiliary electrode is proposed in this paper. We would like to name it FEEL ac PDP. The roles of the pulse applied to the auxiliary electrode are creating more IR emission during the sustain period and reducing the discharge current flowing into the display pixel. Consequently, an auxiliary pulse with a certain range of voltage enhances the excitation rate of the microdischarges generated in the coplanar gap of 200 μm. The test ac PDPs with a coplanar gap of 200 μm and an auxiliary electrode are fabricated and tested with a filled high xenon gas mixture such as Ne + 13% Xe and Ne + 20% Xe. The IR emission from the discharges in a coplanar gap of 200 μm has its maximum intensity when the voltage of the pulse applied to the auxiliary electrode is 50 V. It is also found that a weak IR emission is observed during the afterglow when the auxiliary pulse is applied after the sustain pulse. The sustain margin decreases with the increase of the auxiliary pulse voltage. Both maximum and minimum voltages decrease until the auxiliary pulse voltage becomes 80 V. The luminous efficacy of the new ac PDP is also improved by applying pulse to the auxiliary electrode. The luminous efficacy of the test FEEL ac PDP has its maximum value when the voltage of the pulse applied to the auxiliary electrode is 50 V, which corresponds to the results of IR emission. We can say that the luminous efficacy of the new proposed ac PDP with Ne + 13% Xe and Ne + 20% Xe is improved by 190% and 320%, respectively, compared to that of the conventional type ac PDP with a Ne + 13% Xe gas mixture.

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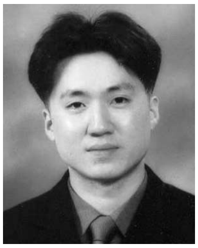

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