Improvement of luminous efficiency using high helium content in full-HD plasma-display panels

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Abstract — The influence of the Xe (15%) and He (70%) fractions on the discharge and driving characteristics was compared in 50-in. full-HD plasma-display panels. The same improvement in the luminous efficacy was obtained when increasing either the Xe or He fraction. However, the discharge current with a high He fraction was smaller than that with a high Xe fraction. While the breakdown voltage was hardly influenced by an increase in the He fraction, it was significantly changed when increasing the Xe fraction. The formative and statistical time lags were only slightly changed with a high He fraction, yet significantly increased with a high Xe fraction. In addition, the relatively low luminance and driving-margin characteristics with a high He fraction were compensated for by controlling the capacitance of the upper dielectric layer.

Keywords — Luminous efficacy, high helium, driving margin, full-HD PDP, address discharge delay.

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1 Introduction

In plasma-display panels using a gas discharge, the composition of the noble gases filled in the PDP cell is very important to determine the performance of a PDP. With a low Xe fraction in the PDP gas composition, the binary gas with Ne–Xe was used because the address discharge delay was not serious. However, when using a high Xe fraction in the binary composition with Ne–Xe so as to achieve a high luminous efficiency, the address discharge delay increases remarkably, thereby causing a serious driving problem under the ADS (address-display-separated) driving scheme of the ACPDPs, especially full-high-definition (full-HD) grade PDPs. The ternary gas composition with He–Ne–Xe, in which a helium gas replaces some part of the neon gas as a buffer gas, is thought to be favorable for overcoming the address discharge aggravation when using a high Xe fraction. In particular, because current flat-panel-display devices require a high resolution, improving the luminous efficiency of an ACPDP with very small cells, such as full-HD grade, has become a critical factor.1–4 Moreover, increasing the number of discharge cells increases the address period and can reduce the number of the subfields, thereby degrading the image quality. Consequently, for the full-HD grade with a fine cell structure, it is very important to increase the luminous efficiency without aggravating the address capability. In this sense, the influences of the ternary gas composition with He–Ne–Xe on the both discharge and driving characteristics need to be investigated in an ACPDP with a high resolution.

Accordingly, this paper compared the effects of the He or Xe portion of the ternary gas composition with He–Ne–Xe on both the discharge and driving features such as the luminance, power consumption excluding the reactive power, luminous efficacy, and address discharge delay, for 50-in. full-HD test panels. For various ternary gas compositions with He–Ne–Xe, the breakdown-voltage and wall-voltage variations were examined by using the $V_t$ closed-curve analysis5–9 and, the address discharge delays were compared by using the Lane plot. Furthermore, the capacitance of the upper dielectric layer was slightly increased by adjusting its thickness and epsilon in order to improve the luminance and driving margin of the 50-in. test panel with a high He fraction.

2 Experimental setup

Figures 1(a) and 1(b) show the cell structure and driving waveforms, respectively, of the 50-in. full-HD ACPDP used in this work. The detailed specifications of the 50-in. full-HD ACPDP are listed in Table 1. To compare the high He-based discharge with the high Xe-based discharge, three gas conditions were examined, where case 1 was Xe (11%) – He (50%) – Ne, case 2 was Xe (11%) – He (70%) – Ne, and case 3 was Xe (15%) – He (50%) – Ne. Case 1 was the reference gas composition. In case 2, only the He fraction was increased from 50 to 70% without changing the Xe fraction in case 1. Meanwhile, in case 3, only the Xe fraction was increased from 11 to 15% without changing the He fraction in case 1. For the high-He-gas condition, the thickness and epsilon (dielectric constant) of the upper dielectric layer were slightly modified to improve the luminance and driving margin. The discharge cell structure and dimensions of the 50-in. full-HD test panel were the same as those of a commercial plasma-TV. The gas pressure of the test panel was 420 Torr, and barrier rib height and sustain gap were 120 and 70 μm, respectively. The MgO layers of all the test
panels used in this experiment were deposited by the ion-plating method. The used doping materials were Ca, Al, and Si, and the oxygen flow rate during the deposition process was 500 sccm. These conditions were exactly the same for all the test panels. Conventional ADS (address-display-separated) driving waveforms comprising the reset, address, and sustain periods were employed, as shown in Fig. 1(b). The main reset with a high ramp pulse ($V_{set}$) was only applied to the first subfield, while the selective reset was applied to the other subfields. During the 1-TV field, the nine subfields were used and the total number of the applied sustain pulses was fixed at 400. The sustain frequency was 250 kHz. The used 50-in. test panels included the driving boards such as the common (X)-, scan (Y)-, address (A) boards, SMPS (switch mode power supply), and logic board. Each board was the same as that of a commercial PDP product. The luminance and power consumption were measured using a color analyzer (CA-100 Plus) and power meter (WT210), respectively, when displaying the white test image with a display load (i.e., displayed area) of 30%. The spatial luminance uniformity of the 50-in. test panels was within about 5% for all the test panels employed in this experiment. The $V_t$ closed curves 5–9 were measured to analyze the breakdown voltage and wall voltage using an IR detector (Photosensor Amplifier, c6386).

### 3 Results and discussion

#### 3.1 Comparison of luminous characteristics with high Xe (15%) or high He (70%) fraction

Figures 2(a) and 2(b) show the changes in the luminance and net power consumption and corresponding luminous efficacies relative to the sustain voltage ($V_s$), ranging from

<table>
<thead>
<tr>
<th>Front Panel</th>
<th>Rear Panel</th>
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<tr>
<td>ITO width</td>
<td>200 μm</td>
</tr>
<tr>
<td>Bus width</td>
<td>80 μm</td>
</tr>
<tr>
<td>Sustain gap</td>
<td>70 μm</td>
</tr>
<tr>
<td>Resolution</td>
<td>1920 × 1080</td>
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<tr>
<td>Cell pitch</td>
<td>192 μm x 576 μm</td>
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<tr>
<td>Pressure</td>
<td>420 Torr</td>
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<tr>
<td>Gas composition</td>
<td>Xe11%-He50%-Ne (Case 1)</td>
</tr>
<tr>
<td></td>
<td>Xe11%-He70%-Ne (Case 2)</td>
</tr>
<tr>
<td></td>
<td>Xe15%-He50%-Ne (Case 3)</td>
</tr>
<tr>
<td>Upper dielectric layer (under case 2)</td>
<td>D = 32 μm - ε = 12 (Case 2A)</td>
</tr>
<tr>
<td></td>
<td>D = 32 μm - ε = 13 (Case 2B)</td>
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<tr>
<td></td>
<td>D = 30 μm - ε = 13 (Case 2C)</td>
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</table>

FIGURE 2 — (a) Changes in luminance and net power consumption and (b) corresponding luminous efficacy of 50-in. test panel relative to sustain voltage for three different gas conditions: Xe (11%) – He (50%) – Ne (case 1), Xe (11%) – He (70%) – Ne (case 2), and Xe (15%) – He (50%) – Ne (case 3).
190 to 220 V for cases 1, 2, and 3, respectively. In Fig. 2(a), the net power consumption $P_{\text{net}}$ was defined as $P_{\text{net}} = P_{\text{on}} - P_{\text{off}}$, where $P_{\text{on}}$ was the power measured from 50-in. test panel when displaying the white test image with a display load of 30% and $P_{\text{off}}$ was the power measured when displaying the entire black image. Both the $P_{\text{on}}$ and $P_{\text{off}}$ were measured when the same number of sustain pulses, which was fixed at 400, was applied. Thus, in $P_{\text{net}}$, the reactive power including the displacement current was excluded completely; namely, $P_{\text{net}}$ is the real power including only the sustain and address discharge currents. Accordingly, the variations of the $P_{\text{net}}$ were determined mainly by the sustain discharge current since the power consumption by the address discharge current was very small in comparison with that by the sustain discharge current.

The luminous efficacy was defined as follows.

\[
\text{Luminous efficacy (lm/W)} = \pi \times \frac{\text{luminance (cd/m}^2\text{)} \times \text{displayed area (m}^2\text{)}}{P_{\text{net}} (W)}. \tag{1}
\]

When comparing cases 2 and 3 with case 1 under the same sustain voltage, case 3 (i.e., a high Xe fraction: [Xe (15%) – He (50%) – Ne] showed the highest luminance, whereas case 2 (i.e., a high He fraction: [Xe (11%) – He (70%) – Ne] showed the lowest net power consumption. In the case of a high He fraction (case 2), the reduction of $P_{\text{net}}$, which completely excluded the reactive power consumption by displacement current, represented a decrease in the sustain discharge current, which also implied a reduction in the amount of electron–ion pairs generated during the sustain discharge. When the He partial pressure among the three gases was increased, the amount of electron–ion pairs generated by the same sustain voltage was decreased because helium has the highest ionization energy among the three noble gases (He: 24.58 eV, Ne: 21.56 eV, and Xe: 12.13 eV). With a high He fraction, the small atomic radius of helium induced an increase in the mean free-path of the charged particles (ions and electrons), allowing them to gain more energy under the constant electric-field intensity. The production of electrons with a higher energy level may then have enhanced the probability of Xe excitation, even though fewer ion-electron pairs were produced. Therefore, as shown by case 2 in Fig. 2, despite a low net power consumption due to a small discharge current, the luminance was only slightly lower or almost the same when compared to case 1. For a high Xe fraction (case 3), more Xe ions were generated easily due to the relatively small ionization energy of Xe atoms, thereby resulting in a strong cathode sheath field between two sustain electrodes. The cathode sheath with a strong electric field induced higher electron heating \cite{10} resulting in a higher electron heating efficiency. Consequently, the higher luminance was obtained due to the higher electron heating efficiency, even though the net power consumption were almost the same, as shown in case 3 of Fig. 2.

In Fig. 2(b), the luminous efficacies for cases 2 and 3 were shown to be much higher than that for case 1. With a high He fraction, the improvement in the luminous efficacy was mainly due to the low net power consumption, whereas with a high Xe fraction, the luminous-efficacy improvement was mainly due to the high luminance. The improved luminous efficacies were almost the same for cases 2 and 3, meaning that from the viewpoint of the luminous efficacy, increasing the Xe content by 4% had the same effect as increasing the He content by 20%. Also, for cases 2 and 3, the maximal luminous-efficacy improvement obtained was about 15% at a sustain voltage of 205 V, as shown in Fig. 2(b).

### 3.2 Comparison of driving characteristics with high Xe (15%) or high He (70%) fraction

Despite the same improved luminous efficacy for cases 2 and 3, the driving characteristics, such as the firing condition, margin, and address discharge delay, were checked for differences.

Figure 3 shows the first quadrant of the $V_t$ closed curve on the cell voltage plane measured from the test panels with the three different gas compositions. The $V_t$ closed curve displayed on the cell voltage plane means the threshold breakdown voltage among the three electrodes determined by the intrinsic panel characteristics such as the gas composition, cell configuration, MgO material, etc. In Fig. 3, the horizontal axis, $V_{\text{CXY}}$ and the vertical axis, $V_{\text{CAY}}$ are the cell voltages between the X–Y electrodes and between the A–Y electrodes, respectively. Side I of the $V_t$ closed curve in Fig. 3 represents the threshold breakdown voltage between the X–Y electrodes in terms of the cell voltage, whereas side II of the $V_t$ closed curve in Fig. 3 represents the threshold breakdown voltage between the A–Y electrodes in terms of cell voltage.\cite{3,6} The breakdown voltages between the X–Y electrodes and between the A–Y electrodes were almost the same for cases 1 and 2, yet increased by about 10 V for case 3. When comparing the three cases,
the results in Fig. 3 indicate that increasing the He partial pressure did not affect the breakdown voltage, whereas increasing the Xe partial pressure caused a higher breakdown voltage. As such, it is possible that the higher He fraction may have facilitated a secondary electron emission (SEM) from the MgO layer due to the low ionization energy of helium, whereas the high Xe fraction may have aggravated the SEM characteristics due to the low ionization energy of xenon. In addition, when the He atoms replaced the Ne atoms, the penning effects, i.e., penning ionizations, were not deteriorated since the excitation energy of He atoms was higher than that of Ne atoms.

Figure 4 shows the shift of the Vt closed curves on the applied-voltage plane induced by the X and Y sustain discharge. The threshold breakdown voltage in the applied-voltage plane as a variation of the wall voltage can be obtained from the relation \( V_{ct} = V_{at} + V_w \), where \( V_{ct} \) is the breakdown voltage in the cell voltage plane, \( V_{at} \) is the threshold breakdown voltage in the applied voltage plane, and \( V_w \) is the wall voltage. If \( V_w = 0 \), then \( V_{at} \) is equal to \( V_{ct} \), meaning that the \( V_t \) closed curves measured from the PDP cell without wall charges (i.e., the reference \( V_t \) closed curves in Fig. 4), indicates the breakdown voltages under a zero wall-voltage condition, which is exactly the same as those in Fig. 3. Since \( V_{ct} \) is fixed, \( V_{at} \) changes, depending on the variation in \( V_w \), implying that the \( V_t \) closed curve, a set of \( V_t \) closed curves, can be shifted to the direction opposite to the polarity of the accumulating wall charges (wall voltage vector) in the cell on the applied-voltage plane. Because the shifts of the \( V_t \) closed curve in Fig. 4 are caused by variations in the wall voltage \( V_w \) among the three electrodes in the PDP cells, this means that the wall voltage can be obtained from the shift of the \( V_t \) closed curves. Plus, since the firing of the sustain discharge is determined by the sum of the wall voltage and the applied sustain voltage, the wall voltage level plays an important role in reducing the applied sustain voltage. As shown in Figs. 4(a) and 4(b), with a high He fraction (case 2), the wall voltage was 136 V for the X–Y electrodes, which was smaller than that (144 V) in case 1. However, with a high Xe fraction (case 3), the wall voltage was 167 V for the X–Y electrodes, which was larger than that in case 1, as shown in Fig. 4(c). The small discharge current for case 2 in Fig. 2(a) resulted in a small wall voltage for case 2 in Fig. 4(b).

Figures 5(a) and 5(b) show the minimum sustain voltage \( V_s \) and minimum address voltage \( V_a \) when the voltage levels of the negative falling ramp pulse \( V_{nf} \) were varied from 140 to 190 V. In Figs. 5(a) and 5(b), to maintain a constant voltage difference between the X–Y electrodes at 280 V, the common bias \( V_{com} \) applied to the X electrode was changed from 140 to 90 V according to the variations in the negative falling ramp pulses. The voltage difference between the negative falling ramp voltage and the negative scan voltage \( \Delta V = |V_{nf}| - |V_{scl}| \) was fixed at 15 V. The \( V_{nf} \) applied during a reset period and \( V_{scl} \) applied during an address period were found to have a great influence on the driving margin, as the wall voltage, \( V_w \) produced by the reset and address discharges depends on the voltage levels of \( V_{nf} \) and \( V_{scl} \), respectively. When \( V_{nf} \) was varied, the minimum \( V_s \) was measured under a constant \( V_a \) (55 V), while the minimum \( V_a \) was measured under a constant \( V_s \) (210 V). As shown in Fig. 5(a), the minimum sustain voltages in cases 1 and 2 remained almost unchanged, irrespective of a variation in \( V_{nf} \) or \( V_{scl} \). Yet the minimum sustain voltage in case 3 was reduced considerably with a variation in \( V_{nf} \) or \( V_{scl} \). With a high He fraction, a variation in \( V_{nf} \) or \( V_{scl} \) did not affect the minimum sustain voltage, whereas with a high Xe fraction, a variation in \( V_{nf} \) or \( V_{scl} \) affected the minimum sustain voltage by about 10 V. This phenomenon was mainly due to the difference in the breakdown voltage and wall-charge accumulation on each electrode between the high Xe and high He fractions. As for the minimum address voltage,
all cases showed the same tendency, i.e., the minimum \( V_a \) was decreased and saturated with a variation of \( |V_{nf}| \) from 140 to 190 V, as shown in Fig. 5(b). When \( |V_{nf}| \) was varied from 140 to 190 V, the potential difference between the A–Y electrodes was increased, resulting in an address discharge under a higher-address-voltage condition. Meanwhile, in Fig. 5(b), case 3 with a high Xe fraction showed the highest minimum address voltage, as fewer wall charges necessary for the address discharge were accumulated during a reset period due to the high breakdown voltage with the high Xe fraction. Conversely, case 2 with a high He fraction showed a higher minimum address voltage than case 1, as the amount of wall charges accumulated on the scan electrode was relatively small due to the small address discharge current under the high-He-partial-pressure condition, as explained in Fig. 4.

For the three different gas conditions, the changes in the address discharge delays were measured using the driving waveforms in Fig. 1(b), where \( V_a, V_s, V_{nf}, V_{sc}, V_{com}, \) and \( V_{set} \) were 55, 210, –180, –195, 100, and 360 V, respectively. In particular, the image pattern used was a single dot pattern, and the address pulse was only applied to the first sub-field with the main reset.

Figure 6 shows a Laue plot of the address discharge delays measured for the green cells in the 50-in. test panels with the three different gas conditions (cases 1, 2, and 3) based on address discharge delay data accumulated from up to 500 discharges. As shown by the Laue plot in Fig. 6, the characteristics of the address discharge delay in cases 1 and 2 were almost the same, whereas in case 3, the address discharge delay was increased. The Laue plot in Fig. 6 can be described by the following equation:

\[
\text{Probability of non-discharge } (P) = \exp\left[-\left(t - T_f\right)/T_s\right] \quad (t \geq T_f)
\]

\[
= 1 \quad (0 \leq t \leq T_f),
\]

where \( T_f \) is the formative delay time, \( T_s \) is the statistical delay time, and \( T_D (= T_f + T_s) \) is the total delay time. In Eq. (2), \( P = 1 \) means that no address discharge was completely produced, whereas \( P = 0 \) means that every address discharge was produced. The detailed values of \( T_f, T_s, \) and \( T_D \) were obtained using Eq. (2) and the measured Laue plot in Fig. 6, as shown in Fig. 7. In Fig. 7, \( T_f \) and \( T_s \) were almost the same for cases 1 and 2, meaning that even when the He partial pressure was increased from 50 to 70% with a constant Xe fraction of 11%, \( T_f \) and \( T_s \) did not vary. Since the breakdown voltage remained almost constant for the high He fraction, the wall charges accumulating on each electrode after the reset discharge continued to be almost constant. With a high He fraction, the SEM capability for the MgO layer was also almost the same. Thus, increasing the He fraction from 50 to 70% did not influence the address discharge delay characteristics. However, with a high Xe fraction (case 3), \( T_f \) and \( T_s \) were both increased by about 100 and 120 nsec, respectively, meaning that increasing the Xe fraction (about 4% in this case) delayed the address discharge. For a high Xe fraction, this increase in the address discharge delay \( (T_f \text{ and } T_s) \) was due to the poor SEM capability for the MgO layer and the small wall charges accumulated on each electrode after the reset discharge, which were mainly due to the higher breakdown voltage.
3.3 Improvement in luminance and driving margin based on proper control of upper dielectric layer with high He (70\%) fraction

As shown in Sections 3.1 and 3.2, the reference gas composition with low He (50\%) and Xe (11\%) fractions showed relatively low luminous efficacy, whereas the high Xe (15\%) gas compositions showed the long address discharge delays. On the other hand, the high He (70\%) gas composition showed an improved luminous efficacy and good address discharge delay characteristics, yet poor luminance and driving-margin characteristics.

Thus, the side effects when adopting a high He (70\%) fraction were mainly due to the small amount of wall charge accumulated after the discharge. However, since this can be solved by properly adjusting the capacitance of the front dielectric layer, which strongly depends on its thickness and dielectric constant, this also implies that the amount of wall charge accumulated between the X–Y electrodes can be enhanced by adjusting the thickness and dielectric constant of the dielectric layer on the front glass. The capacitance is obtained from the following equation:

\[
\text{Capacitance} = \varepsilon \times \frac{A}{D},
\]

where \(\varepsilon\) is the dielectric constant of the upper dielectric layer, \(A\) is the electrode area, and \(D\) is the distance from the surface of the dielectric layer to the surface of the X (or Y) electrode. As a variation in the thickness of the upper dielectric layer means a change in the distance \(D\) in Eq. (3), the capacitance of the front glass is increased if \(\varepsilon\) is increased, while \(D\) is simultaneously decreased.

Figures 8(a) and 8(b) show the changes in the luminance and net power consumption for a 50-in. test panel with Xe (11\%) – He (70\%) – Ne gas composition (case 2) relative to sustain voltage when using three different dielectric thicknesses and dielectric constants for the upper dielectric layer: thickness = 32 \(\mu\)m and \(\varepsilon = 12\) (case 2A), thickness = 32 \(\mu\)m and \(\varepsilon = 13\) (case 2B), and thickness = 30 \(\mu\)m and \(\varepsilon = 13\) (case 2C). When increasing the capacitance of the upper dielectric layer by adjusting its thickness and dielectric constant, the luminance was increased considerably, as shown in Fig. 8(a). The large increase in the luminance and net power consumption with a slight change in the capacitance of the upper dielectric layer can be explained below. First, more wall charges were accumulated on each electrode after a strong discharge due to the higher capacitance of the upper dielectric layer. Accordingly, under the identical sustain voltage condition, the luminance and net power could be increased thanks to the increased wall voltage. Second, when the sustain voltage was applied to the sustain electrode, higher voltage was applied to the discharge space since the voltage applied to the upper dielectric layer was decreased according to the increase in the capacitance of the upper dielectric layer. In this case, thanks to the increase in the effective gap voltage applied to the discharge space, the more-intensive electric field was applied to the discharge space. Thus, stronger discharge could be generated thanks to increased wall charge and higher gap voltage, thus resulting in higher luminance and an increase.
in the discharge current, as shown in Figs. 8(a) and 8(b). The luminance for case 2C in Fig. 8 was higher than that for case 3 (i.e., high Xe (15%) fraction) in Fig. 2(a). Therefore, the slight increase in the capacitance in the upper dielectric layer by adjusting its thickness and dielectric constant could improve the luminance without aggravating the luminous efficacy.

Figures 9(a) and 9(b) show the changes in the minimum sustain voltages and minimum address voltages when applying the driving waveforms in Fig. 1(b) with various negative fall ramp pulses (V_{nf}) to a 50-in. test panel with Xe (11%) – He (70%) – Ne gas composition (case 2) when using three different dielectric thicknesses and dielectric constants for upper dielectric layer: thickness = 32 μm and ε = 12 (case 2A), thickness = 32 μm and ε = 13 (case 2B), and thickness = 30 μm and ε = 13 (case 2C).

The variations in the address discharge delay times with respect to the thickness and dielectric constant of the upper dielectric layer are presented in Fig. 10. Despite the slight change in the capacitance of the upper dielectric layer, the formative and statistical delay times remained almost constant, as shown in Fig. 10. Consequently, by properly adjusting the capacitance of the upper dielectric layer in the 50-in. test panel with a high He (70%) fraction, the luminance and driving margin were improved without increasing the address discharge delay. The characteristics resulting from the high He (70%) fraction (case 2C) are compared with those from the high Xe (15%) fraction (case 3) in Table 2.

**Table 2** — Luminous and driving characteristics for case 3 (high Xe: 15%) and case 2C (high He: 70%).

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<tr>
<td>Case 3: High Xe (15%)</td>
<td>155 at V_s = 200 V</td>
<td>75.2 at V_s = 200 V</td>
<td>&gt;920 nsec</td>
<td>&gt;195 V</td>
<td>&gt;43 V</td>
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<tr>
<td>Case 2C: High He (70%)</td>
<td>175 at V_s = 200 V</td>
<td>80 at V_s = 200 V</td>
<td>&gt;670 nsec</td>
<td>&gt;188 V</td>
<td>&gt;40 V</td>
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</table>

**Conclusion**

To improve the luminous efficacy without increasing the address discharge delay, a higher He (70%) gas content was proposed as a promising gas composition for a full-HD ACPDP. The corresponding discharge characteristics, including the luminance, power consumption, breakdown voltage, driving margin, and address discharge delay were all investigated carefully. As a result, an improved luminous efficacy...
in a 50-in. full-HD ACPDP was obtained without increasing the address discharge delay with a high He (70%) fraction. Nonetheless, the high He (70%) gas composition showed a relatively low luminance and driving margin when compared with other gas compositions, such as Xe (11%) – He (50%) – Ne or Xe (15%) – He (50%) – Ne. Yet, this was easily compensated for by controlling the capacitance of the upper dielectric layer.

Acknowledgment

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References