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High-resolution Plasma Display Panel (PDP)

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We have developed two types of high-resolution plasma display panels (PDPs): a 25-inch SXGA (1280 × 1024) panel for engineering workstations (EWSs) and personal computers (PCs), and a 42-inch 1024 × 1024 panel for HDTV. First, this paper investigates the discharge characteristics of small PDP cells. Then, this paper describes some of the features of the new panels, for example, the improved characteristics of their cells and their unique Alternate Lighting of Surfaces (ALIS) discharge method, which improves both the resolution and the brightness of the panels.

1. Introduction

Plasma display panels (PDPs) can be made in large sizes and are expected to be the best candidates for wall-mount displays that are too big to be made using CRTs (i.e., 40-inch and larger). PDPs have so far been used mainly for TVs with the relatively small number of pixels used in the VGA format (640 × 480 pixels). This is because the discharge control of small pixels has been difficult. However, broadcasting of high-definition TV (HDTV) will start when digital TV broadcasting begins, and resolutions exceeding one million pixels will be required even for standard TV units. Also, the monitors for personal computers (PCs) and workstations (WSs) are being equipped with bigger and higher resolution screens and the demand for 20-inch and larger high-resolution CRT monitors is increasing. Because of their space-saving advantage over CRTs and other considerations, the arrival of a large flat-panel display is eagerly awaited in the 60-million-unit market for large monitors.

To meet these demands for a high-resolution display, we decided to develop a high-resolution PDP with surface discharge type cells. We also developed a new panel fabrication process and studied panel characteristics (e.g., driving voltage margin, luminance, and luminance efficiency) and high-speed driving methods. In the Japan Electronics Show held in 1997, we exhibited a prototype 25-inch-diagonal SXGA color PDP. Also, we developed a new high-resolution display panel for TVs using the Alternate Lighting of Surfaces (ALIS) driving method, which is completely different from conventional ones. As a result of our efforts, we succeeded in commercializing a practical PDP that has enough luminance, luminance efficiency, and resolution for TVs.

This paper mainly describes the discharge cell size, discharge characteristics, and driving method of the 25-inch SXGA PDP and 42-inch ALIS HDTV panel we have released on the market.

2. High-resolution PDP for workstations

The major reason for the high demand for flat panel displays for PCs and WSs is that they need a smaller installation space than CRT monitors. An ordinary 17-inch CRT monitor is at least 40 cm deep and occupies more than half of the depth of a standard office desk. This large depth of CRT monitors makes the distance between the operator and the screen (hereinafter called the "operation distance") as short as 40 to 50 cm. At this distance, the proper size of a screen should be 14 to 17 inches in consideration of the angle of the movement of the operator's eyes. What then would be the optimal screen size of a thin, flat panel display when it is installed on an office desk? If a flat panel display is installed at the back of the desk so that the amount of free desk space is maximized, the operation distance will be 70 to 80 cm. Then, to obtain the same optimal angle of eye movement, the diagonal screen size of the flat panel display should be 21 to 25 inches. Regarding the resolution, we decided to design a high-resolution PDP with at least 1280 × 1024 pixels (SXGA) so the operator can read 10.5-point characters easily and use the PDP for computer-aided design (CAD).

Compared to conventional large PDPs for TVs, the high-resolution PDP we developed is smaller and has a higher resolution (at least twice as many scan lines as a conventional large PDP). To attain this, we developed the following three technologies.

1) Panel fabrication processes

Processing technologies for fabricating fine-pitched narrow barrier ribs of the required height and for forming phosphor layers uniformly between the barrier ribs for sufficient discharge space.

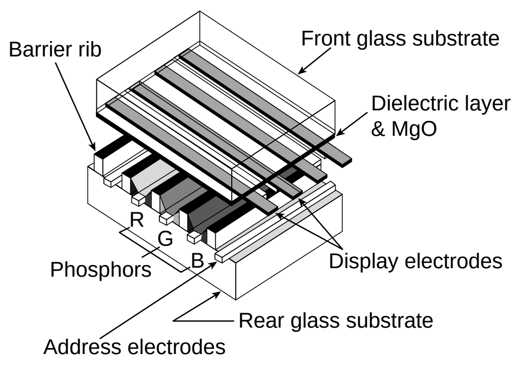


Figure 1
Structure of experimental panel.

2) Panel characteristics

A cell structure technology for a practical driving voltage margin, luminance, and luminance efficiency.

3) High-speed driving method

A drive technology for addressing a large number of scan lines (twice as many as on a VGA panel) without using the expensive dual scan drive method.

2.1 Basic study of high-resolution PDP

2.1.1 Panel structure and fabrication process

For our high-resolution PDP, we avoided using a complex panel structure and basically adopted a three-electrode surface discharge type structure which had already been used for large PDPs and has a low manufacturing cost. **Figure 1** shows the cell structure of our prototype high-resolution PDP.

In this paper, a unit discharge area corresponding to a color is called a "discharge cell," a unit area consisting of the three primary colors is called a "pixel," and the cell pitch in the horizontal (line) direction is called the "rib pitch."

The key fabrication technologies for the high-resolution PDP enable the fabrication of fine-pitched barrier ribs (having a pitch nearly half that of conventional PDPs) and the formation of uniform phosphor layers between the barrier ribs.[1] We improved the conventional sand blasting method and developed a new technology for fabricating ribs that are 30 µm wide and 100 µm high and have a rib pitch of 110 µm. We also developed a new technology for forming highly accurate phosphor layers using a photosensitive phosphor paste. These technologies enabled us to make an experimental panel to test pixels of an arbitrary size at pixel pitches of 0.33 mm or more. **Figure 2** shows SEM images of the barrier ribs we fabricated for the 42-inch PDP and the ones we fabricated for the high-resolution PDP. The barrier ribs have almost the same heights, but the pitch of the barrier ribs for the high-resolution

PDP is about one-third of the pitch of the barrier ribs for the 42-inch TVs.

2.1.2 Physical limitations of discharge cell size

It has been reported that the minimum discharge cell size required to provide a sufficiently high luminance and a high luminance efficiency is around 30 mm, which corresponds to the diameter of a common fluorescent tube. If the discharge space is less than 30 mm, the discharge voltage will increase and the luminance efficiency will decrease. With a surface-discharge type cell structure having straight ribs, there is less discharge space that can be effectively used. This is because not only is the rib pitch one-third of the pixel pitch in the row direction but also the rib pitch is affected by the rib width, the thickness of the phosphor on the side walls, and the thickness of the ion sheath formed around each rib.

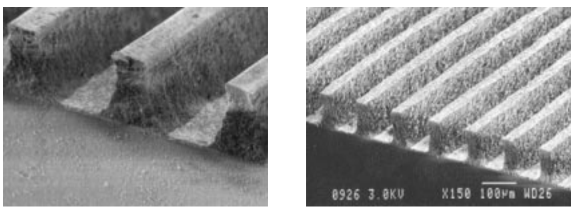
We could easily see that the discharge characteristics of the high-resolution PDP would largely depend on the cell size in the line direction. The ion sheath is a dark space that forms between a conductor or insulator and a plasma. The inside of the ion sheath is not electrically neutral. The ion sheath isolates the discharge space from the influence of the barrier ribs, but also reduces the discharge space. The thickness of the ion sheath is determined by the electron density and electron temperature in the discharge space, and these values vary over time and position within each discharge cell. In general, an ion sheath of around 30 μm thick is formed on the inner wall of each discharge cell of the PDP.

Based on the assumption that the narrowest barrier rib that can be fabricated is 20 μm, the cell pitch must be at least 80 μm when an ion sheath of 30 μm thick is formed on both sides of each barrier rib. In consideration of the thickness of the phosphor formed on the side walls of each rib and the practical maximum limit of the discharge voltage, the practical limits of cell pitch and pixel pitch should be around 100 μm and 300 μm, respectively.

2.1.3 Discharge cell size and discharge voltage

As described above, we had to consider the thickness of the ion sheath when deciding the pixel pitch for the high-resolution PDP. We therefore investigated the relation between the rib pitch and discharge characteristics.

We made a 12-inch-diagonal test panel with rib pitches from 0.11 to 0.56 mm (pixel pitch: 0.33 to 1.68 mm) and measured the static discharge-voltage characteristics of a small area (about 20 mm × 30 mm). **Figure 3** shows the changes in discharge voltages when only the rib pitch was changed while the dimensions of the front plate (including the discharge gap, display electrode



(× 150) (× 150)

(a) 42-inch panel

Height : 150 μm
Width : 80 μm
Pitch : 360 μm

(b) High-resolution panel

Height : 100 μm
Width : 45 μm
Pitch : 130 μm

Figure 2
Comparison of rib shapes.

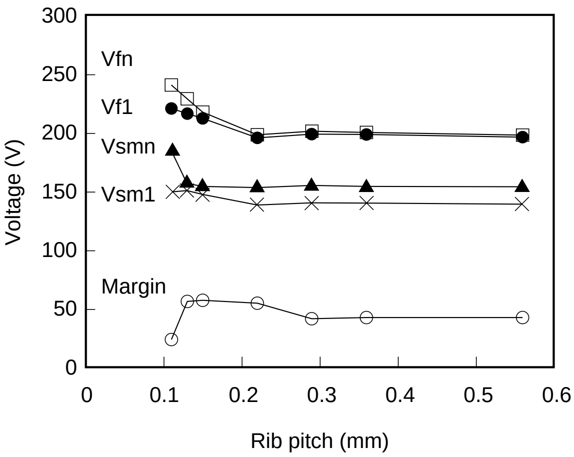


Figure 3
Voltage vs. rib pitch.

width, dielectric film thickness, rib width, and rib height) were kept the same. When the rib pitch was 0.22 mm or more, each voltage was almost constant throughout the range of rib pitches. The firing voltages (Vfl and Vfn) rose gradually as the rib pitch was reduced below 0.22 mm. At rib pitches below 0.13 mm, the sustain voltage (Vsmn) started rising suddenly and the driving voltage margin decreased. These changes in voltages were due to the influence of the discharge space size, which is determined by the rib pitch and ion sheath thickness and almost agreed with the ion sheath thickness mentioned above.

Figure 4 shows the voltage characteristics measured when the dimensions of the front plate (including the display electrode width) were enlarged and reduced with reference to the dimensions of a conventional 42-inch display panel (with a pixel pitch of 1.08 mm) while the dielectric film thickness, rib width, and rib height were kept the same. When the pixel pitch was varied between 1.68 mm and 0.66 mm, there was an almost linearly proportional change in both the firing and sustain voltages. We therefore concluded that the rib pitch did not influence the voltage characteristics in this cell size range and, therefore, that the voltage characteristics followed the analogy of the display electrode size. When the pixel pitch was reduced to less than 0.66 mm, the firing and sustain voltages started rising again. The rate at which the firing voltage (Vf1) rose was less than the rate for the sustain voltage (Vsmn), and the driving voltage margin was narrow. These results showed that the driving voltage margin was as high as about 50 V, even with the smallest pixel pitch (0.33 mm) and that we could make a high-resolution PDP equivalent to a CRT or LCD.

2.1.4 Discharge cell size and luminance efficiency

As described above, we found that we could attain the electrical characteristics required for a high-resolution PDP with a pixel pitch of 0.33 mm. However, we still did not know whether we could attain the display characteristics required for a high-resolution PDP.

Figure 5 shows the luminance and discharge current density measured when the test panel was driven with a constant sustain voltage. The values for the luminance and discharge current density at each pixel pitch are values normalized for a 42-inch panel. The discharge current density (I_D) is the discharge current flowing through a unit area, which is defined by the following formula:

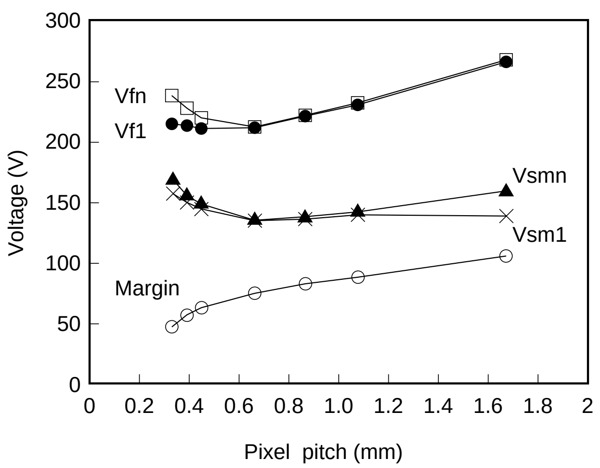


Figure 4
Voltage vs. pixel pitch.

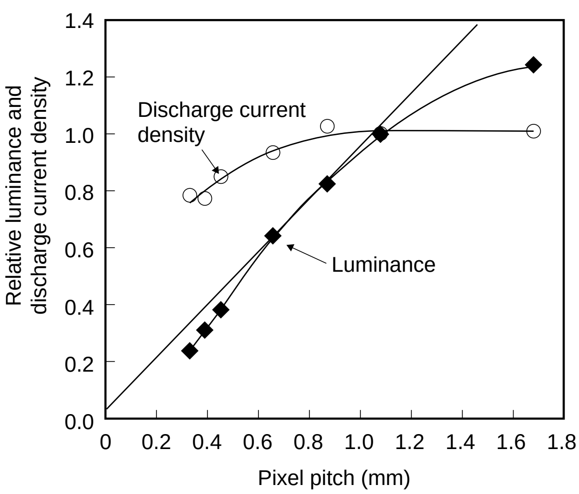


Figure 5
Luminance and discharge current density vs. pixel pitch.

$$I_D = \frac{I_{ON} - I_{OFF}}{S} \quad (A/m^2) - (1),$$

where I_{ON} is the sustain current that flows when the cell light is on, I_{OFF} is the sustain current that flows when the cell is off, and S is the lighting area (area of a cell × number of cells).

Where the pixel pitch was 1.0 mm or less, the luminance changed almost in proportion to the pixel pitch, but saturation of luminance occurred where the pixel pitch was over 1.0 mm. This indicated that the luminance we can obtain for a high-resolution PDP with a pixel pitch of 0.33 mm would be about 25 percent of the luminance of a 42-inch PDP with a pixel pitch of 1.08 mm.

On the other hand, decreasing the pixel pitch also decreased the discharge current density, although the rate of decrease was less than that of the luminance. The discharge current density decreased to about 80 percent when the pixel pitch was 0.33 mm.

Based on the above results, we assumed that the PDP was a perfect diffused light source and calculated the luminance efficiency by using formula (2). **Figure 6** shows the results of the calculation. The value of luminance efficiency η is shown after normalization for the 42-inch size.

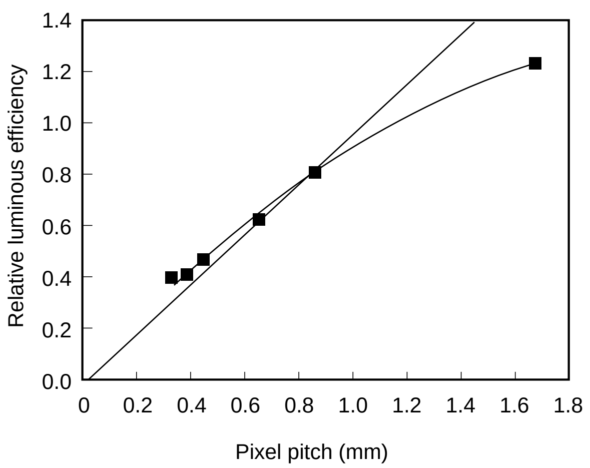


Figure 6
Luminous efficiency vs. pixel pitch.

$$\eta = \frac{\pi \times L \times S}{(I_{ON} - I_{OFF}) \times V_S} = \frac{\pi \times L}{I_D \times V_S} \quad (1/W) - (2),$$

where L is the luminance (cd/m^2) and V_S is the sustain voltage (V).

As shown in Figure 6, the luminance efficiency increased almost in proportion to the pixel pitch over the range from 0.6 to 1.0 mm. This was because the discharge current density was consistent over this range of pixel pitch and the luminance was proportional to the pixel pitch. For pixel pitches over 1 mm, the luminance efficiency stopped increasing in proportion to the pixel pitch because of the saturation of luminance described above. In the area where the cell size was 0.6 mm or less, the decrease in luminance efficiency was less than the decrease in luminance. This was caused by the decrease in the discharge current density itself, as shown in Figure 5. These results showed that the luminance efficiency we can obtain for a high-resolution PDP with a pixel pitch of 0.33 mm would be about 40 percent of the luminance efficiency of a 42-inch PDP with a pixel pitch of 1.08 mm.

From the above results, we concluded that the discharge current density decreased only to a certain extent, even when the pixel pitch decreased, and that the luminance decreased in proportion to the pixel pitch and the luminance efficiency decreased. In other words, there was an increase in the amount of energy lost during the conversion of discharge current to visible light. This loss could be caused by the charge diffusion to the side walls of the barrier ribs or by a decrease in the extraction efficiency of visible light. We suspected that the increase in loss was due to a reduced extraction efficiency and made further investigations for ways to increase the luminance and luminance efficiency.

2.2 Improvements in the characteristics of fine-pitched cells

2.2.1 Improvements in luminance and luminance efficiency

Based on the above basic study of high-resolution design, we decided on a cell pitch and pixel pitch of 0.13 mm and 0.39 mm, respectively, after considering the fabrication process and the margins of characteristics. Accordingly, we decided to develop a 25-inch-diagonal, high-resolution PDP with 1280 × 1024 pixels (SXGA). We made test panels with this pixel pitch, collected basic characteristics data, and searched for ways to improve their characteristics.

A popular method of improving luminance is to increase the reflection rate by mixing a white filler into the insulating films deposited onto the rear panel and into the rib material. We therefore made one type of test panels with black ribs (conventional type) and another type with white ribs using a white filler.[2] We then used these test panels to investigate luminance improvement rates. The result of this investigation showed that the luminance improvement rates with pixel pitches of 0.39 mm, 0.66 mm, and 1.08 mm were 1.9, 1.36, and 1.25, respectively. On the panel with the white ribs, the luminance improvement rate increased as the cells became smaller. With a pixel pitch of 0.39 mm, the luminance of the white rib panel was about 1.9 times higher than that of the black rib panel. When the white rib panel was driven at an average sustain frequency of 25 kHz, the luminance was 222 cd/m² and the luminance efficiency was 0.7 lm/W.

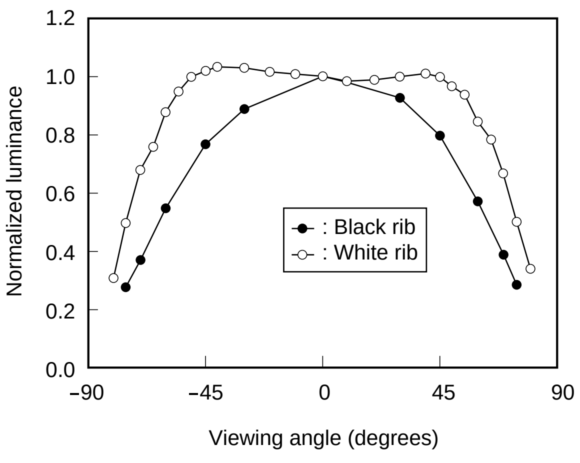


Figure 7
Luminance vs. viewing angle.

On a high-resolution PDP, the ratio of the rib surface area to the surface area of a discharge cell would be larger than in a conventional PDP. We could therefore infer that the luminance would be greatly affected by the phosphor layer thickness on the side walls of ribs and by the reflection rate of ribs. This investigation made it clear that the cause of the increase in loss on the high-resolution test panel (as described in Subsection 2.1.4) was a decrease in the extraction efficiency of visible light.

2.2.2 Improvements in viewing angle

In our high-resolution design, the viewing angle would be too narrow because the aspect ratio of rib pitch to rib height would be high. In the case of the black rib structure type panel described in Subsection 2.2.1, the viewing angle (defined as the angle over which the luminance is within 50% of the luminance when the unit is viewed from the front) narrowed to around 130 degrees when the rib pitch was 0.13 mm. A narrow viewing angle not only lowers the luminance of pixels viewed at a certain horizontal angle but also causes a problem of chroma change by which display colors are tinged with red because the luminance ratio of Ne orange light emission increases. **Figure 7** shows the measured luminance over different viewing angles for the two types of structures. Compared with the standard black rib structure, the white rib structure had a much larger viewing angle of at least 160 degrees, which was equivalent to that of a 42-inch panel. **Figure 8** shows the chroma change in relation to the viewing angle. In the figure, the amount of chroma change is represented by the vertical distance from the color coordinate of white in the xy chromaticity diagram. As shown in the figure, the white rib structure causes only a small chroma change in relation to the viewing angle.

2.3 High-speed driving method

To obtain 256 gray scales on a high-resolution

SXGA panel, the addressing cycle time must be less than 1.5 μs per line (**Table 1**). This addressing speed is twice as fast as the speed required for a VGA type panel. Such a high addressing speed requires an address frequency exceeding 700 kHz, and the higher the addressing frequency, the larger the power consumption and the higher the cost of the address drivers.

In the conventional driving method, addressing discharge occurs and a sufficient wall charge is formed on a selected cell (selected to discharge at the sustaining period according to display data) in the addressing discharge. In the wall charge forming addressing method, no matter how fast the addressing discharge occurs, the address pulse cannot be narrow because it needs time to form the wall charge on the selected cell after the addressing discharge. One way to reduce the pulse width is to raise the addressing voltage, but this might cause a problem of high power consumption.

When designing a new driving method for our high-resolution panel, we set the following three objectives:

1) High addressing speed (1.0 μs per line)
2) Low address voltage
3) Wide operating voltage margin

To achieve these objectives, we changed the addressing method from forming a wall charge to erasing a wall charge.

Figure 9 shows the driving waveform of the new driving sequence using the erasing wall charge addressing method.[3] The new driving sequence consists of three steps: writing and wall charge formation, addressing, and sustaining. We developed and used the Address Display Period Separated Subfield (ADS) method for this purpose.

Figure 10 shows a wall charge model of the new driving sequence.

First, a wall charge is formed on every cell. In the addressing period, only unselected cells are

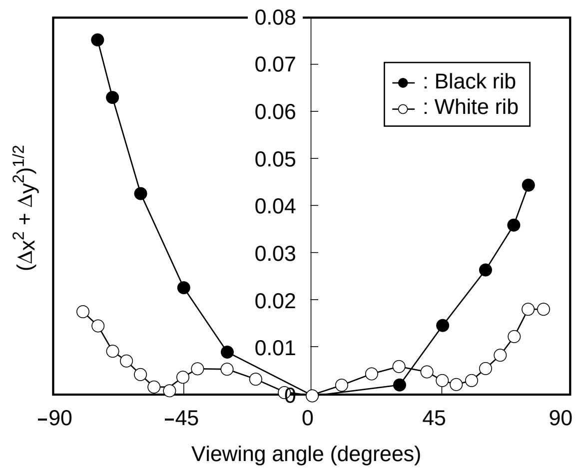


Figure 8
Color shift vs. viewing angle.

Table 1
Addressing times for high-resolution color PDPs.

Panel type	Pixels	Sustain cycle/frequency	Address time
VGA	640 × 480	5 μs/27 kHz	3.6 μs
SXGA	1280 × 1024	5 μs/27 kHz	1.5 μs
UXGA	1600 × 1200	5 μs/27 kHz	1.0 μs

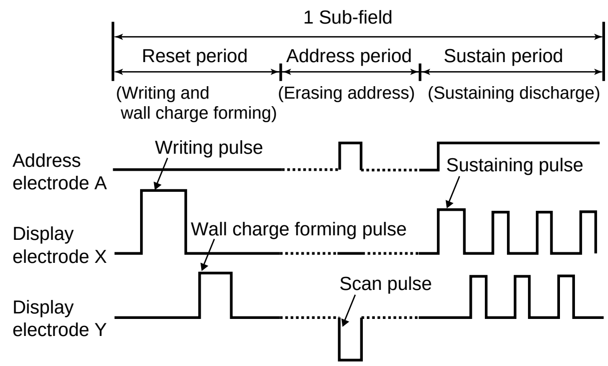


Figure 9
Waveform of new driving method.

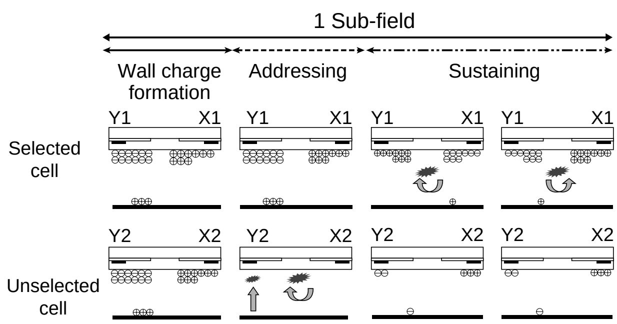


Figure 10
Wall charge model of the new driving method.

addressed and the wall charges formed on the sustain electrodes are erased. On each cell that has not been addressed, the wall charge remains and can be discharged in the sustaining period. An erase addressing discharge can rise quickly because of the priming effect on the wall charge. Also, because a wall charge does not need to be formed after erase addressing discharge, the scan pulse width can be narrow.

As shown in **Figure 11**, with a scan pulse of 1.5 μs, which is the pulse width required for an SXGA type panel, the operating voltage margin is wide enough (nearly 40 V). As another advantage, this new driving method enables us to reduce the scan pulse voltage by 100 V or more from that of the conventional driving method.

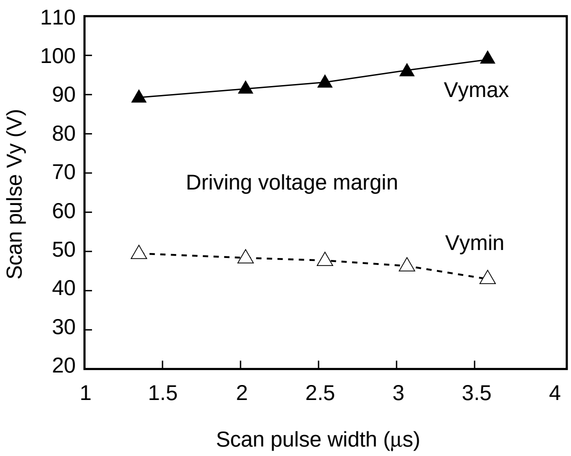


Figure 11
Scan voltage vs. pulse width.

Figure 12
25-inch SXGA PDP Monitor.

2.4 Product overview

Figure 12 shows a photograph of the 25-inch, SXGA high-resolution color PDP we developed on the basis of the research reported here. **Table 2** lists its main specifications. This PDP is suitable for use with a personal computer or workstation. It can display a large quantity of data at high resolution and will expand the application of color PDPs.

3. High-resolution PDP for High-definition Television (HDTV)

3.1 Required characteristics of PDP for HDTV

Because a PDP for HDTV displays mainly full-color dynamic images, it must have certain characteristics that are not required in a PDP for workstations. Especially, a high peak luminance and smooth representation of gray scale are important requirements.

The input signal specifications are limited to some extent by the broadcasting and recording specifications. The progressive system (720P) using 720 scan lines and the interlaced system (1080I) using 1080 scan lines will become standard format. With the 1080I system, the signals on odd-numbered and even-numbered lines are displayed alternately every 1/60 of a second. The image pickup for HDTV should conform to the 1080I system. To reproduce interlaced signals accurately, the display system should also conform

Table 2
Specifications of 25-inch SXGA monitor.

Display pixels	1280 × 1024
Pixel pitch (mm)	0.39 (0.13 × 3) × 0.39
Effective display size (mm)	499 × 399
Number of colors	260 000 (64 gradations of RGB)
Luminance (cd/m^2)	150 (white peak)
Contrast ratio (in dark room)	80 :1
Weight (kg)	10
Power consumption (W)	200 (typ.)
Viewing angle	Greater than 160°

to the interlaced display. Conventional matrix-type display equipment, e.g., PDPs and LCDs, could not conform to the interlaced system and had to convert interlaced image signals to progressive image signals before they could be displayed. The missing pixel data had to be obtained through interpolation at conversion, which resulted in lower quality images. Now, we have developed a new PDP system that can fully handle interlaced signals.

3.2 New discharge method

In a surface-discharge plasma display, the display discharge is generated by applying a voltage between two parallel sustain electrodes. **Figure 13** compares the display discharges of the conventional method and the ALIS method.[4] In the conventional method, each display line consists of a pair of sustain electrodes and the spaces between display lines are not used for the discharge because a sufficient distance is needed to prevent interference between vertically adjacent cells. In the ALIS method, on the other hand, the sustain electrodes are arranged at identical intervals and the spaces between them are used as display lines. Therefore, the resolution can be doubled compared with a conventional display having the same number of electrodes. Discharge can be controlled steadily by alternately generating a discharge for the odd and even display lines. This design resembles the interlaced scan system of a CRT.

Figure 14 shows the driving principle of the ALIS method. In the odd-line display period, the sustain discharge is generated by applying voltage Vs between electrodes Y1 and X1 and between electrodes X2 and Y2. Since Y1 and X2 are now at the same potential, the cells in the even lines are off. Similarly, in the even-line display period, the switches shown in Figure 14 are switched to allow the even-line cells to discharge.

Figure 15 shows the difference in the glow sizes of the conventional and ALIS methods. Because the discharge area for the ALIS method can be wider than in the conventional method, a bigger discharge space and therefore a higher luminance can be obtained.

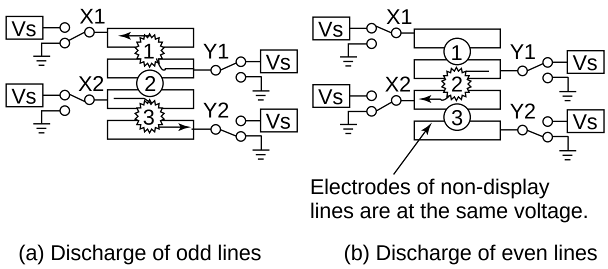


Figure 14
Driving principle.

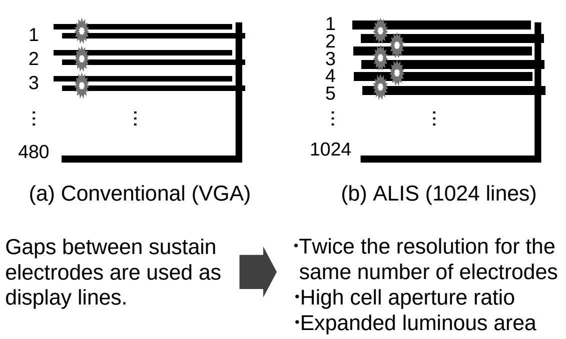


Figure 13
Conventional and ALIS (Alternate Lighting of Surfaces) discharge methods.

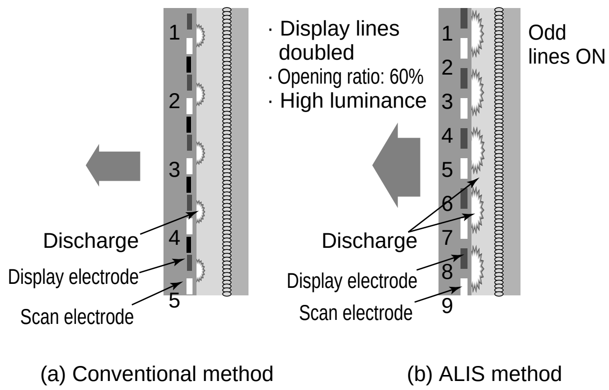


Figure 15
Glow sizes of conventional and ALIS methods.

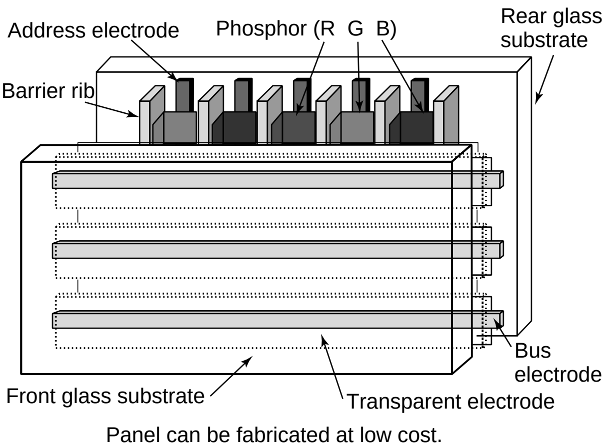


Figure 16
Structure of ALIS panel.

Table 3
Performance of 42-inch high-resolution PDP.

Display area (mm)	922 (H) × 522 (V) diagonal : 106 cm (42-inch)
Resolution (pixels)	1024 (H) × 1024 (V)
Pixel pitch (mm)	0.9 (H) × 0.51 (V)
Number of colors	16 770 000
Luminance (cd/m^2)	500 (white peak)
Contrast ratio (in dark room)	400 :1
Power consumption (W)	250
Weight (kg)	16 (panel module)

Displays a bright, high-quality picture of more than 1000 lines.

Figure 17
42-inch high-resolution PDP suited for high-definition TV.

3.3 Structure of ALIS panel

Figure 16 shows the structure of the ALIS panel. It is almost the same as the structure of a conventional three-electrode surface discharge type. Sustain electrodes, each consisting of a transparent ITO (indium-tin oxide) electrode and a bus electrode at its center, are arranged in parallel on the front glass substrate. The sustain electrodes are covered with a dielectric layer and a MgO film. The rear glass contains the address electrodes, barrier ribs, and phosphor layers. As can be seen in Figure 16, the ALIS panel has a simple structure.

3.4 Product overview

Table 3 shows the performance of a prototype 42-inch ALIS panel. It has a high resolution of 1024 × 1024 pixels and a plane average luminance of 500 cd/m^2, which is about 1.5 times higher than that of a conventional panel. **Figure 17** shows a photograph of the new panel.

4. Conclusion

We have developed a high-resolution PDP for workstations and one for HDTV. The PDP for workstations has a diagonal of 25 inches and 1280 × 1024 pixels, which gives it the highest resolution among PDPs currently available in the world. This high-performance PDP has been made possible by a new fabrication process for forming fine-pitched discharge cells and a high-speed driving method. For the PDP for HDTV use, we have developed a brand new driving method called "ALIS" which enables the PDP to reproduce the interlaced images of HDTV perfectly. The ALIS method not only reproduces HDTV images with high fidelity without the need for scan line conversion, but also advantageously reduces the number of drivers required. Thus, the PDP can be made conformable to HDTV at a low production cost.

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