PDP Manufacturing

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1. Introduction

The markets for large area plasma display panels (PDP) larger than 40 inch diagonal size have been expanded rapidly. The large area flat panel display is demanded for a HDTV and a digital TV which display a real and life-size image in addition to the traditional TV image because of the development of the both computer and network technologies.

The author has proposed and developed the three-electrode surface discharge color PDP (TS-PDP) technologies [1,2] and realized the first color PDP products in the world. These are the three-color PDP in 1989[3,4,5,6,7], the 21-in.-diagonal color PDP with 260 thousand colors in 1993[8], and the 42-in.-diagonal full color PDP with 16.7 million colors in 1996 as shown in Fig.1 [9].

These results have opened the dream of a wall hanging TV. When we look back a history of color PDP, a development of the 21-in.-PDP was the most important step in which the most essential technologies for large area PDPs have been completed. The commercialized 42-in. and 50-in. PDPs have been developed based on the technologies [10,11,12].

This paper will describe the manufacturing technologies for color PDPs. The basic technologies will be explained first, and then the history of the development of the color PDP until the completion of the 21-in.-PDP will be explained. These are very important to understand the reason why the current practical panel structure and the processes are selected. The current manufacturing process will be explained, finally.

2. Principle of color PDP

A color PDP uses the emitted light from phosphors excited by an ultra-violet ray (VUV) in discharge[13,14,15]. The principle is similar as a fluorescent lamp (FL). This means that color PDP is a device that the some millions of miniature FLs about 0.5mm are arrayed inside of the 1 m squared glass plates. Figure 2 shows the principle of the light emission of a color PDP. When the voltages are applied to the gases, discharges are ignited and then both ions and electrons are generated. The ions and electrons make recombination and then emit VUV. The VUV excites the phosphors and then visible light comes from. The primary three-color phosphors, such as red, green and blue, are arranged inside the panel and the luminance levels are changed with controlling the discharge. The human eye detects full color by mixing the luminance emitted from the three primary colors.

The discharge in each cell should be controlled to make a beautiful image on PDP. The principle of PDP operation will be explained with the opposed discharge as shown in Fig 3[16,17]. Each striped X and Y electrodes is on each glass substrate in orthogonal and is covered by a dielectric layer and a protecting layer. The substrates are assembled with a 100 μm gap which is filled with a Ne + Xe mixture. The driving waveform described in Fig. 3(b) is applied to the X and Y electrodes. The waveform is constructed with a write pulse(Pw) which ignites discharge, sustain pulses which sustain discharge to display, and an erase pulse. A discharge is ignited when the write pulse with higher voltage than a discharge ignition voltage is applied to the X electrode. The ions and electrons generated by the discharge are accumulated on the opposite protecting layers on both substrates by an externally applied field. As the accumulated charges reduces the electric field rapidly and then stop the discharge, the discharge is in the shape of pulse. The accumulated charge is called a wall charge. The following sustain pulse is applied to the Y electrode which is the reverse pole to the previous pulse for the discharge cell. Although the sustain pulse voltage is not sufficient to ignite a discharge by itself, the voltage inside the cell becomes higher than a discharge ignition voltage because the voltage is superimposed to the accumulated wall charge. The discharge is then also pulse shape. The discharge are repeated by applying the sustain pulses. Once the discharge is ignited by the write pulse, it is sustained by applying the sustain pulses. The display is usually done by applying the sustain pulses and the luminance is proportional to the number of sustain pulses per sec. To erase the discharge, the narrow erase pulse, Pe, is applied. As a result, the wall charges are eliminated because the pulse width is not sufficiently wide to accumulate the wall charge and then discharge is not supported by the following sustain pulses. The function that the states of the discharge and non-discharge are sustained is called as a memory function of an ac PDP.

There are important indexes called a firing voltage (Vf) and a minimum sustaining voltage (Vsm) to evaluate the function. Each has values of a minimum and a maximum. The minimum firing voltage (Vf1) is defined as a voltage at which an other first cell is ignited with increasing a voltage of the sustain pulse applied all of the display electrodes in whole display area at a state of that a small number of the discharge cells are ignited. The maximum firing voltage(Vfn) is defined as a voltage that a last cell is ignited at the same measuring method mentioned above. The maximum minimum sustain voltage (Vsmn) is a voltage at which a first cell is eliminated when an applied voltage is decreased from a condition that all cells are ignited in the whole panel. The minimum minimum sustain voltage (Vsm1) is a voltage at which the last cell is eliminated with the same measuring method for Vsmn. The difference between the Vf1 and the Vsmn called a static memory margin is an index which shows an adjustable range of a sustain voltage. The memory coefficient (□m) defined the following equation shows the capability to use the memory function.

$$\alpha m = (Vf - Vsm)/(Vf/2)$$

$$\text{where,}\quad Vf = (Vfn+Vf1)/2, \quad Vsm = (Vsmn + Vsm1)/2.$$

A wider operating margin is essential to operate the PDP stable. A large margin is obtained by realizing a large memory coefficient and small differences between Vfn and Vf1, and Vsmn and Vsm1. The author believes this shows the essential point of view to manufacture PDPs. These can be translated into the manufacturing words as follows.

(1) The priority is to design the structural factors to have a sufficient margin.
(2) And the next is to design the structural factors to have an optimum electrical and optical performance.
(3) To design fabrication steps and processes to make uniform characteristics of each cell,
(4) And then manufacture to keep the smallest differences between products.

3. The development of surface discharge color plasma display panel structures

In this chapter, it will be explained why the TS-PDP structure was introduced. Figure 4 summarizes the technical points to realize the practically available color PDPs. There were typical 5 technical subjects to be solved when I stared to develop a color PDP in 1979. How to realize (1) color, (2) a long stable operating life, (3) a high luminance, (4) high resolution, and (5) full color operation. From (1) to (4) related to structure and (5) relates to driving method. To understand the development of the TD-PDP structure will help you to understand color PDP technologies.

3.1 The basic structure to realize a color display

The first issues to be solved for a practical panel were as follows in more detail. (1) a long operating life, (2) a high luminance, (3) a low operating voltage to be operated without a special development of driving ICs

(1) Long operating life

The opposed discharge color PDP structure that had the similar structure of the conventional monochrome PDP has been investigated in the initial stage of a color PDP study. The phosphors deposited on a MgO protecting layer were degraded by an ion bombardment in discharge resulting in a short operating life. The study of a matrix type color PDP with surface discharge technology was focused to solve the issue as shown in Fig. 5 (b). There were two types of surface discharges developed at the stage. One was monochrome PDP with capacitive via structure developed by Dr. Dick of Bell Labs [18]. The other was a color PDP developed for segment type PDP by Dr. Takashima of Fujitsu Labs [19,20]. It had already demonstrated a green color clock, but been unfortunately stopped to study. Both did not succeeded to develop a practically available full color PDP. Fig 6 shows the panel structure tried first to realize the full color PDP [21]. The panel was a two-electrode type surface discharge structure having an unique suppression electrode to prevent the spread of a discharge, phosphors, and He + Xe gases. Figure 7 shows the effect of the suppression electrodes to prevent the spread of a discharge to get a large memory margin. The phosphors of red, blue and green colors were deposited in three areas in a small experimental 5 in.-diagonal panel as shown in Fig. 8. Although a degradation of the conventional opposed discharge was large as that the reduction of a luminance to the half level of the initial stage was within 100 hours, the stable luminance level for the surface discharge was extend more than 2000 hours. This however had new problems. One was a low break down voltage at the cross point of X and Y electrodes and the other was unstable operating voltage for a long operation. Fig. 9 shows the phosphor degradation by an operation. The surface discharge PDP has a long stable luminance comparing to the conventional opposed discharge PDP. Figure 10 also shows the change in the firing voltage and the minimum sustain voltage for a long operation. The solid and dotted lines show the change in the voltage of non-operated cells and operated cells, respectively. Although the voltage does not change for non-operated cells, the voltage of operated cells increases after the operation for some 10 hours. The luminance however does not change. This means that this is due to the degradation of the MgO layer, but not phosphors. The author stopped to develop the two-electrode surface discharge structure because the problem was thought to be essential.

The TS-PDP structure was proposed to solve the problems [1,22]. Figure 11 shows the principal electrode configuration. The display electrodes (sustain and scan electrodes) are parallel and the isolated third electrode, address electrode, is in orthogonal to them to select discharge cells. An address cell is defined at the cross points between a scan electrode and an address electrode and the display cell between the display electrodes. The electrode of PDP has two functions of addressing and display in the conventional two-electrode PDPs. Addressing is that the pulses are applied between selected address electrodes depending on display data and a scan electrode to ignite discharge and then wall charges are accumulate. And display function is that the following sustain pulses sustain the discharge in the display cell where the wall charges are accumulated previously to display. The addressing is repeated for each scan electrode one by one and then the alignment of the wall charges depending on the display data is completed on the panel. The TS-PDP structure was expected to solve the problems of two–electrode structure as follows. A flicker-free TV image can be obtained by displaying 8 sub-flames for 60 times per second because of the image retention characteristics of human eye. The discharges for addressing are ignited for 480 times /second in the address cells. On the contrary, discharges for display are ignited for 60 thousand times / sec (30 kHz). A ratio between addressing and display is 1 to 120. So if we separate the display and address cells, the operating life of address cell was expected to extend 120 times comparing to one of the conventional two-electrode structure.

(2) high luminance

A structure of reflection type has also been introduced. Figure 12 shows the principle cross section of the panel. As a short wave length vacuum ultra-violet does not penetrate into the phosphors, a thin surface of a phosphor layer is only excited. The emitted visible lights go to both directions of a front and a rear. A large amount of the light that goes to the rear plate are reflected by the phosphor layers. As the display electrodes made on a front plate are transparent, the high luminance characteristics is realized because the visible light is emitted to out side of the panel efficiently.

(3) Low addressing voltage for IC driving

The TS-PDP has also another advantage for driving with ICs, Integrated Circuits. The color PDP is driven with a higher operating voltage than one of the commercial monochrome PDPs because the high content Xe in the Ne + Xe mixture gas system. So to realize a commercially available color PDP, a higher voltage driving IC was needed. Especially, the color plasma displays needed three times large numbers of addressing electrodes because a pixel is made of three subpixels. The address electrode of the TS-PDP can be driven with low current and low voltage because only each address driver addresses a cell at a time. It made the color PDP possible to be driven with the conventional IC driver technology.

The first commercially available color PDP was the three-color PDP for a financial display as show in Fig. 13. This displays three colors such as red, green, and yellow by mixing red and green. The development of a 20-in.-diagonal PDP was thought as big challenge for first products. An experience to manufacture the first three-color PDP made our self-confidence to develop a full color PDP in the next step.

4. The panel structure and driving method to realize a high resolution full color PDP

There were two big subjects to realize a full color PDP, such as a panel structure to realize a high resolution and a gray scale driving technology.
These issues have been solved while a developing a 21-in.-diagonal full color PDP.

4.1 A high resolution 21-in.-diagonal color PDP structure[23]

The specification of the developed 21-in.-PDP is shown in table 1. A display addressability is 1920x 480 because a pixel includes three subpixels. The pixel pitch is 0.66 x 0.66 mm, and then the subpixel pitch is 0.22 x 0.66 which was too small to realize with the conventional PDP technologies for both a panel structure and a fabrication process. So we have developed more simple structure over the three color PDP. Figure 14 shows the panel structure of the three-color PDP. Fig.15 compares the subpixel arrangement of the three-color and 21-in.-PDPs. As the financial display did not require a high resolution pixel pitch, the subpixel pitch was 0.8 mm which was possible with a complex structure having the meshed barrier rib structure and the exposed address electrode structure. The subpixel pitch of 0.22 x 0.66 mm which is 4 times higher in resolution than the three color PDP was thought to be not possible with the complex structure. So a new structure with stripe barrier rib has been investigated.

Four types of panel structures were investigated as shown in Fig.16.

(a) Transparent type in which the phosphor is deposited on front plate,

(b) Reflection type with ribs on both substrate and the phosphor is deposited on only rear plate,

(c) Reflection type with both the barrier rib and phosphors on the rear plate, but the phosphor is deposited on only the bottom of the channel that is made with barrier ribs.

(d) Reflection type with both the barrier rib and phosphors on the rear plate, and the phosphor is deposited on both the bottom of the channel and side wall of the barrier rib.

The (d) structure has advantages over other structures that will be discussed later, and then the panel with both stripe rib and strip phosphor structure was finally adopted as shown in Fig.17. The panel is called as a stripe TS-PDP. The parallel transparent electrodes on front substrate and the stripe ribs and phosphors on the rear substrate are arranged in orthogonal to each other. The barrier works for separating the adjacent cells in electrically and optically. The structure finally developed is enough simple for realization of a mass production, a high resolution and a large area display. The manufacturing processes were also completed by the development of 21-in. -PDP.

4.2 Driving technology for moving picture[24,25,26]

There was no appropriate driving method to realize a high gray scale for a moving picture on ac PDPs. The author proposed a new driving method called as address-display-period-separation sub-field method (ADS method) as shown in Fig.18. The method made it possible to display a 256 gray scale picture on the ac PDPs. These technologies developed the full color 21-in-PDP as shown in Fig. 19.

5. The panel design to obtain a practical electro-optical characteristics

5.1 Dependence of optical characteristics on panel structure

The characteristics of luminance, luminous efficiency and viewing angle largely depend on a panel structure. The characteristics for the three structures of (a), (b), and (c) in Fig. 16 were evaluated. Figure 20 shows the luminous dependency on the viewing angle for the three panel structures. The vertical shows the relative luminance normalized by the luminance in normal direction on the panel, and the horizontal shows angle to the normal direction. Line (d) shows that the luminance level in the angle between ±60 degrees is higher than the luminance in the normal direction. The higher luminance than 50 % of the normal direction is obtained in the angle between ±80 degrees, which means the very wide viewing angle. The transparent type of line (a) shows a cosine curb characteristics. The reflection type of line (c) shows a narrower viewing angle that the luminance decreases largely with increasing the angle. Figure 21 compares the luminance of the structures with and without phosphors on the side wall. The luminance level in the normal direction of the panel is 260 cd/m^2 for the structure with phosphors on the side wall contrast to 190 cd/m^2 for without phosphors on the side-wall. And the whole of the emitted luminous flux of with phosphor on the side-wall is twice larger than that of without phosphors on the side wall. The luminous efficiency was sufficiently large to realize a practically available color PDP at that stage. These are the successful results of the development of TS-PDP.

5.2 Relation between rib structure and operating margin

The stripe barrier ribs are formed only on the rear substrate in the stripe TS-PDP. As there are only parallel display electrodes in the front substrate, the discharges can not be separated by only the front substrate. Each cell is separated when both plates are attached and the stripe ribs works to separate the discharge. At the early stage of the stripe TS-PDP, the ribs are formed with printing technology. Figure 22 shows a photograph of the ribs. The top of the barrier rib waves and is round. If there is a gap between top of the barrier rib and a surface of the MgO, the discharges in the adjacent cells make influence to each other through the gap. A discharge previously ignited supplies charges through the space and then reduces a firing voltage of an adjacent cells. Figure 23 shows a relationship between the operating voltages, firing voltage and minimum sustain voltages, and the gap. The width of the top is 15 μm. The firing voltage decreases and the minimum sustain voltage increases with increasing the gap larger than 10 μm resulting in reducing memory margin. This means that the flatness on the top of the barrier rib should be less than 10 μm to keep a sufficient memory margin for practical use. A memory margin more than 60 volts was obtained by controlling the flatness of the top of the barrier ribs. This large memory margin made it possible to manufacture the stripe TS-PDP.

5.3 Electrode design

The electrode design is also important to get good characteristics. Although the stripe barrier ribs isolate the discharges between the adjacent cells on a same display electrode, there is no barrier in the direction of vertical to the display electrodes. Isolation of the discharge in the vertical direction is also important to get a large memory margin and depends on an electrode design. Figure 24 shows the symbol and design factors of display electrodes. P, We, Ws and Wd is a cell pitch, a width of the display electrode, a width between display electrodes, and a width of display, respectively. Wr and Ps is a width of a barrier rib and a cell pitch, respectively. In the case of the 21-in.-PDP, symbols P, Ps and Wr is 0.66, 0.22 and 0.07 mm, respectively. Figure 25 shows the relationship between a ratio of Wd /P and a static operating margin. Vsm increases and Vf decreases with increasing the range of the ratio more than 0.7 resulting in decreasing a memory margin due to the influence between the adjacent cells. The value of Wd/P should be less than 0.7.

5.4 Filling gas condition

There are four important points to select the filling gas.

1. Long operating life
2. No visible light
3. High emission efficiency of VUV

4. Low operating voltage and wide memory coefficient

A He + Xe gas mixture system is investigated in the early stage of color PDP development because of the minimum visible light emission. Although the author also investigated the gas system, it was clarified that the system was not practical because of a short operating life and a high operating voltage. Figure 26 compares the operating life in terms of an operating voltage and a luminance for both Ne + Xe and He + Xe gas mixtures. The operating voltage increases and the luminance decreases gradually. The life is defined at the time when the luminance becomes half of the initial stage of operation and specific number of defects generates. The figure shows that the luminance decreases in half of the initial stage and the operating voltage increases within some hundred hours. The operating life extends some thousand hours for Ne + Xe gas system. This is thought that the energy of the Xe ions may lose their energy by the collision with the mother gases, such as Ne or He gas, before bombarding on the MgO surface. That is, the energy of the Xe ion in Ne + Xe system is reduced and then the damage of the MgO surface is reduced. The Ne + Xe system has been finally selected to investigate.

Figure 27 shows the light emission spectrum from the 21-in.-diagonal PDP. A light of around 450 nm comes from an emission of blue color phosphor. A light of around 500 nm and 600 nm comes from the green and blue phosphors, respectively. A visible light of around 650 nm to 700 nm comes form a Ne gas itself. The light reduces the quality of colors from each phosphor and disturbs the image reproduction. The spectrum of light emission is analyzed to improve the light emission from a Ne + Xe gas mixture. Figure 28 compares the spectrums from the gases with various Xe contents in Ne + Xe system. The figure suggested that the amount of the luminance of around 700 nm will be reduced and then the disturbance for color purity by increasing in the Xe contents. P(X%) means the peak intensity of the luminance for a pure Ne gas. The P(10%) and P(4%) mean that the luminance intensity from the Ne+Xe gas of 10 % and 4 % Xe contents.

Figure 29 shows the relation between the Xe contents and color purity of green phosphors in the CIE chromaticity diagram. The color purity becomes more pure with increasing in the Xe content. The color purity of the He + Xe gas system which does not degrade the color purity is also shown in the figure for a reference. Figure 30 shows the dependencies of the luminance and luminous efficiency on the Xe contents. The upper shows the luminance and the lower the luminous efficiency. Both luminance and luminous efficiency increase with increasing in the Xe contents. This means that the VUV radiation also becomes efficiently with increasing the content. Although Xe contents should be high from these experimental results, operating voltages have to be also taken into account to decide the gas condition. Figure 31 shows the Vfi and Vsmn dependencies on a gas pressure with the parameters of 3, 4, 5%. The Vf and Vsm increased with increasing in the gas pressure and the operating margin also increased with increasing in the Xe content although the operating margin was almost same for the three Xe contents, 3, 4, and 5 %. The operating voltage of 5% was higher than that of 3% about 20 volts. The static operating margin of 50 V was obtained when the gas pressure was about 600 torr. The value is sufficiently large to operate the plasma display panel. Figure 32 shows the chromaticity coordinate of pure three primary colors of red, blue and green comparing with that of NTSC standard and CRT. The width of the region is proportional to the color reproducibility and it is sufficiently wide for a color display application.

6. Panel structure[8]

The practically developed TS-PDP structure of Fig.17 will be explained in more detail. Paired parallel display electrodes, sustain electrode X and scan electrode Y, are formed on the front glass substrate. Each display electrode is composed of a transparent SnO_2 and a narrow bus electrode of multi-layered Cr, Cu and Cr, to emit a luminance effectively through the transparent electrode and reduce the electrode resistance. These electrodes are covered by a dielectric layer which is made of low melting glass materials. These are also covered with a thin MgO layer. On the other rear substrate, striped address electrodes A are arranged. Striped barrier ribs are on both side of the address electrodes to separate the adjacent discharge cells and to eliminate the optical cross-talk between them. Three primary color phosphor materials for red, blue, and green colors are deposited in the neighboring channels made by the ribs to cover both of the side wall of the ribs and the dielectric layer. The structure has realized good performances such as a high luminance, a high luminous efficiency and a wide viewing angle. Phosphor materials are $BaMgAl_{14}O_{23}$:Eu for blue, $(Y.Ga)BO_3$:Eu for red, and Zn_2SiO_4:Mn for green. The substrates are assembled onto each other with about 120 μm gap. A Ne + Xe gas mixture is introduced between the gap. The panel structure developed for the 21-in.-diagonal color PDP is the simplest one of conventionally developed color PDPs. And the fabrication process is also simple enough to mass-produce. So the PDP has advantages such as a low cost process and easiness to manufacture large area panels and high resolution panels.

7. Fabrication process

7.1 Flow of fabrication process

The essential fabrication process as shown in Fig.33 is also completed to develop the 21-in.-PDP. The transparent conductive ITO film is made on the front glass. The plural paired display electrodes are formed by a photolithography technology. The metal electrode film of a Cr/Cu/Cr multi-layer is sputtered on these transparent electrodes. The bus electrode is also formed by a photolithography technology. These electrodes are covered with a frit glass layer with a printing technology and then fired about 600 ℃ to make a transparent dielectric layer. The seal glass layer with a width of about 3 mm is made on the out side of the display area and then pre-fired. A MgO protecting layer is evaporated on the dielectric layer over the display area of inside of the seal layer. The front plate is completed with these processes.

A small hole of a diameter of about 1 mm is made on a corner of the rear plate. The Ag address electrodes are printed and fired. The frit glass is printed on the electrodes in the display area and then fired about 600 ℃ to make a dielectric layer. The barrier ribs are made by printing the frit glass on both side of the address electrodes and then dried. The process is repeated about 10 times and then fired. The red, blue, and green phosphors are printed inside the channel between the barrier ribs. Each color phosphors are printed at a same time and then the printing is repeated three times and then dried. The rear plate is completed with these processes.

Both plates are assembled and fixed with clips. The assembled plates are fired to melt the seal layer and the plates are glued resulting in making a panel. At the next gas filling process, the panel is connected to an evacuation/gas-filling system through the evacuating tube. After the baking, the discharge gas is introduced. Finally, the PDP is completed after cutting off the evacuating tube. The driving pulse is applied to the panel and discharges are ignited in every discharge cells to reduce and make stable the operating voltage.

The rib and phosphor formation and gas filling processes that are unique for PDP will be improved in the future to manufacture efficiently with a low cost.

7.2 The role of each process

7.2.1 Front plate

- **Glass substrate**

A new glass for PDP has been developed to prevent the distortion and the shrinkage of the glass substrate in the firing processes of high temperature. Figure 34 shows the characteristics of a high strain glass substrate. The high strain point glass has about a 100 ℃ higher strain point comparing to the conventional soda-lime glass. This eliminated the distortion and reduced the shrinkage in the process and then made it possible to construct the process with a large process margin.

- **Transparent electrode process**

The ITO (Indium Tin Oxide) or SnO_2 is used for a transparent electrode. Figure 35 compares the processes for SnO_2 and ITO formation. The ITO film is made by a sputtering or an ion-plating and then patterned with photolithography processes. A photo resist is generally coated with a roll-coating machine due to the large area. The expose uses a proximity method with a vertically supporting mechanics to prevent the bending of the glass substrate. As an exchange of a large photo- mask is also big issue, so the direct exposure machine is developed and practically used. The ITO film is etched with a solution of hydrochloric acid with small amount of nitric acid. The performances of the conductivity, transparency, etching ability, the adherence with Cr, resistance to the etching solution of Cr and resistance to the reaction with the dielectric layer while firing should be take into account to make an ITO films.

Although SnO_2 has advantages on the stability of the film quality and conductivity over ITO, it is too difficult to control the etching condition. The film is now patterned with the lift-off process with heat -resistant photo-resist. The development of lower cost patterning method for SnO_2 is expected.

- **Bus electrode**

A bus electrode is used to reduce the electric resistance of the transparent display electrodes. Ag and Cr/Cu/Cr are currently used. An Ag electrode is made with a printing method or a photolithography with photosensitive paste including Ag and frit glass as shown in Fig.36. The Cr/Cu/Cr is made with sputtering method and photo-lithography as shown in Fig. 37.

- **Dielectric layer**

The dielectric layer is made by forming the layer of the low melting frit glass composed of the PbO and then fired at about 600 ℃to make transparent glass layer. The dielectric layer of a front substrate should have high transparency due to affect to the display performance. There are some methods to make the frit glass layer, such as screen printing, slot coating, roll coating, and green sheet.

The screen printing method as shown in Fig. 38 has a long history and good results. The glass layer is made by the way that the paste including frit glass and organic solution is deposited on the substrate through the mesh of screen. It is important to keep a sufficient time for leveling after printing to eliminate the roughness due to the mesh because the thickness uniformity affects on the differences in the discharge voltage of the cells.

The slot coating method is the way that the glass paste is deposited through the slot of about some 10 μm as shown in Fig. 39. The roll coating method is the way that once the layer of a paste is made on the roll and then transcribed on the substrate as shown in Fig. 40. Both methods does not use the screen mesh, there is an advantage of the uniform layer over the printing method. There however remains an issue of that if the drying condition is not controlled sufficiently, the uniformity is not sufficient and/or the crack of the layer generates. The green sheet method is the way that a dried layer made on the base film is put up on the substrate and then fired as shown in Fig. 41. Although this also realizes a good uniformity, a sufficient degas while firing is difficult because much organic binder is included in the glass film.

・ MgO protecting layer formation

The protecting layer is the one of the most important element to realize a good performance. At the early stage of PDP development, a lot of materials were investigated by Prof. Uchiike and Mr. Urade [27,28] and then found out MgO as a most appropriate material for a protecting layer. Although this has been started to employ for the protecting layer in monochrome PDP and there reported many researches to find a new material, other materials than MgO were not successful.

The performance requested for the protecting layer are as follows.

1. Low sputtering rate [29]
2. High transparency
3. Non-conductivity
4. Large ion-induced secondary emission
5. High stability in the PDP fabrication processes

MgO is the most appropriate materials for these requirements.

The MgO layer is generally made with electron beam evaporation method. The new methods are expected to manufacture more efficiently, such as ion plating, reactive sputtering, etc.[30,31]

7-2. Rear plate processes

・Address electrode formation

The address electrode process is almost same as the bus electrode process. As the higher resistance than the display electrode is permitted and the requirement against the reaction with the dielectric layer is not severe, the author expected the lower cost process will be able to develop.

・**White dielectric layer formation**

The white dielectric layer works for protecting the address electrode and reflection of the visible light emitted from phosphors to front plate to get a high luminance. The process is almost same as the dielectric layer of the front plate.

・**Barrier rib formation**

The formation of barrier rib is one of the most unique processes for PDP and largely affects on the cost. The thickness and width of the rib is 150 μm and 70 μm, respectively. There are some fabrication methods, such as printing, sandblasting, lift-off, filling-up, photolithography, and so on.

The first process developed for 21-in.-PDP is printing method as shown in Fig.42 [32]. The screen printing mask with the stainless mesh on which the rib pattern is made with the emulsion is used. As the thickness of rib layer printed through the mask is about 20 μm for each printing, it is repeated for more than 10 times to make thick rib pattern. The shape is controlled by using pastes with appropriate characteristics for each level of the accumulated layers. The most important point is to keep the shape and the flatness of the rib top. So, both keeping the accuracy at the initial printing and preventing shear between each shot to accumulate is important in the printing process. Figure 43 shows a screen for printing. The stainless mesh is coated with the Ni to prevent the distortion of the screen. The process is the most effective if the times of printing to accumulate is reduced because the efficiency of the material consumption is higher than other processes for rib formation.

The sandblasting has advantage to get the high accurate barrier rib due to use the photolithography and is currently used for large area PDPs [33]. Figure 44 shows the process. A thick frit glass layer is formed on the display area, and then covered by a dry photo-sensitive elastic film. The film is exposed through the film with barrier rib pattern and then developed. The small hard particles are sprayed in high pressure. Although the frit glass layer of the area without elastic layer is cut, the area of the layer coated by the elastic film remained because the particles are reflected.   The covered film is removed and then fired resulting in completing the rib as shown in Fig.45. The subject of the sandblasting process is that the 70 % of the materials formed on the plate are thrown away finally and then material cost is expensive. The recycle system of the material should be developed.

The lift-off process also uses the photolithography technology. A thick photosensitive dry film covers the plate and the exposed through the film with a pattern of barrier rib and then developed to make a deep channel. The rib materials are dipped inside of the channel and then removed the dry film. Although the material efficiency of frit glass is high and the pattern accuracy is good, the process tend to be expensive due to the low material efficiency of expensive dry film.

In the photosensitive paste (PS) method, the thick PS layer composed of photosensitive material and frit glass is used [34]. As the glasses in the PS layers reflect and disturb to make accurate barrier rib, thick layer is not possible at once. The processes of formation of PS layer and exposition are repeated two or three times and the developed. It is then fired to make the barrier rib.

・**Phosphor layers**

The printing method is the most practical and efficient method although three methods are investigated, such as the printing as shown in Fig.46, the photosensitive phosphor paste in Fig.47, and the photo adhesive resist methods. The phosphor formation process is unique because the phosphor layer is deposited on the dielectric layer and side wall inside of the channel. The required tolerance of the phosphor deposition with the printing is not severe comparing to the printing processes for electrodes and barrier rib. That is because that as the phosphor paste is filled in the channel through the screen, the pattern of the screen can be designed narrower than the channel width. The filled paste is then dried. The drying condition is important to make uniform phosphor layers. The thickness of the phosphors can be determined by the composition of the phosphors in the paste. The phosphor layer deposited is shown in Fig. 48.

7.3 Panel completion process

・**Assembling**

The front and rear plates are assembled to align the display electrodes and address electrode in orthogonal. The plates are pre-fixed with clips. As the elements of electrode, phosphors, and barriers fabricated are all striped shape and arranged in orthogonal, it is easy to align the both plates each other. This is an advantage of the TS-PDP. The evacuating tube is placed on the hole with frit paste. After the assembling, it is fired about 400 ° C to glue the plate each other by melting the seal layer.

・**Evacuation and gas filling**

The panel is connected with an evacuation and gas filling system through the evacuating tube.

The panel is placed inside of the furnace and baked out about at 350 ° C to evacuate the adsorbed gases on the surface of MgO, phosphors, barrier ribs and dielectric layers. After the sufficient baking, the panel is cooled down to the room temperature and then discharge gas is introduced to the designed pressure. Finally, the PDP is completed after cutting off the evacuating tube. As this process is one of the most important processes to decide the characteristics of PDP, the temperature while evacuation, evacuation system without impurity, purity of filling gas should be controlled carefully.

- **Aging process**

The pulses higher than firing voltage is applied to the all discharge cells to make cleaning and activating the MgO layer. This lowers the operating voltage and increases the uniformity resulting in deducing the difference between the operating voltage.

The paneling process from assembling to aging is unique for PDP. In the individual front and back plate formation process, it should be focus on how to reproduce the designed factors on each element. In the paneling process after the MgO deposition, it should be focused how to not absorb the impurity gases on MgO layer and how to remove the absorbed gases from MgO. So, it is most important to shorten the process time from MgO formation to the evacuation. Then some attempts to combine the firing process of assembled plates and evacuating/ filling process are investigated.

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Item	Performance
Display Area	920mm x 518mm
Aspect Ratio	16 : 9
Number of Pixels	852 (R,G,B) X 480
Pixel Pitch	1.08mm X 1.08mm
Number of Colors	16.7 million
Luminance	350 cd / m^2
Viewing Angle	> 160 degree
Power Consumption	300 W max
Weight	18Kg

Fig.1 A 42-in.-diagonal color PDP

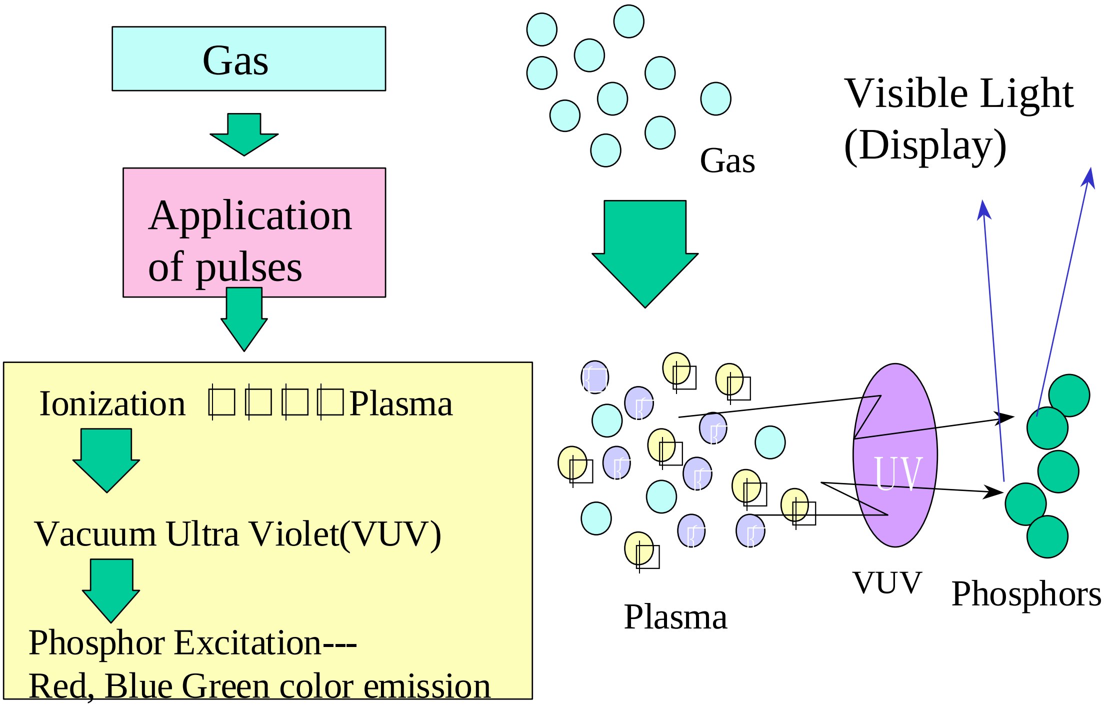
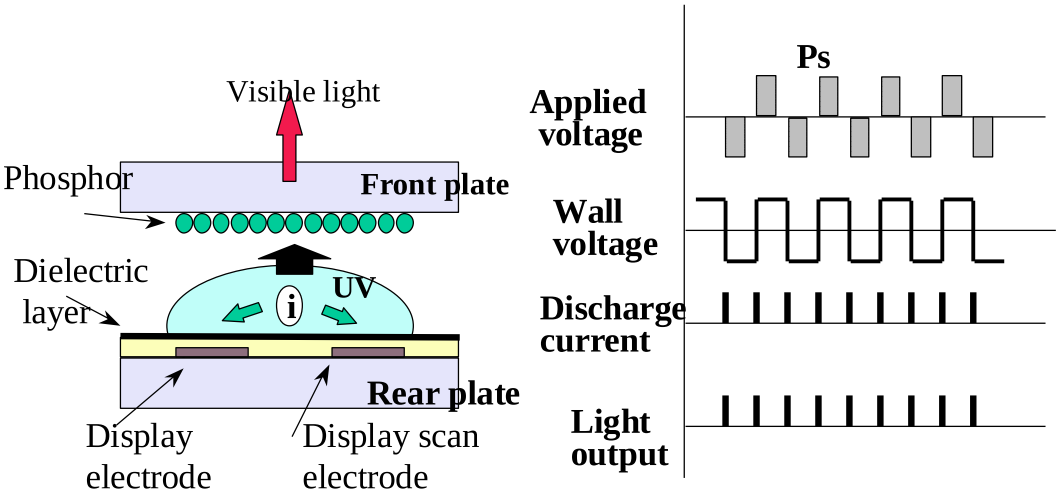


Fig.2 The principle of light emission for color PDP



(a)Cross section of a sub-pixel of color panel

(b) Relationship among Applied voltage, wall charge, discharge and light output

Fig.3@Operating principle of AC-PDP

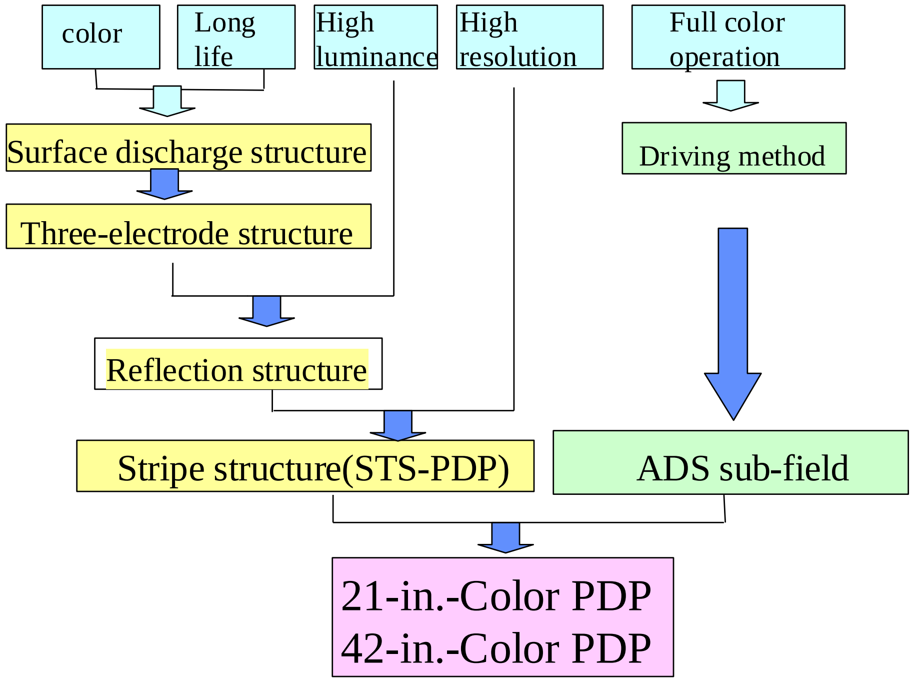
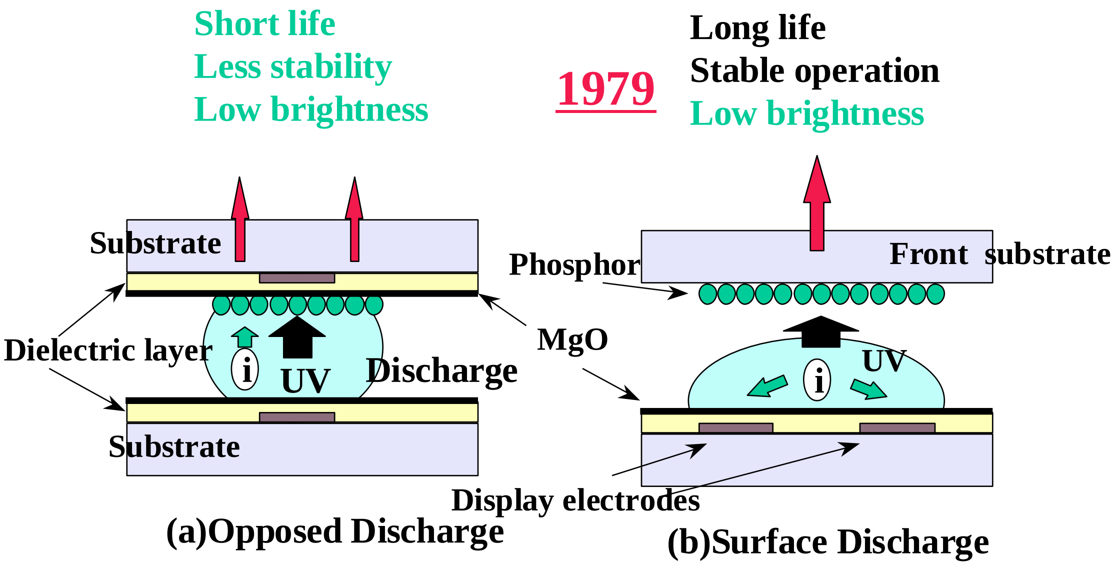


Fig.4 Technical points to develop practical color PDP



Separation between discharge site and phosphor site

Fig.5 Introduction of surface discharge structures

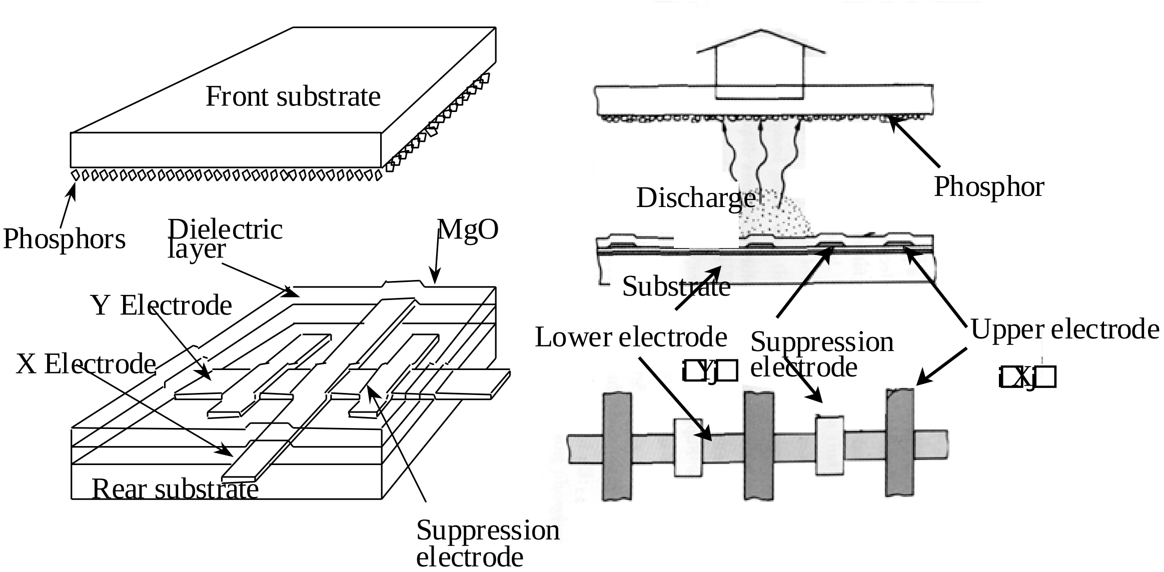
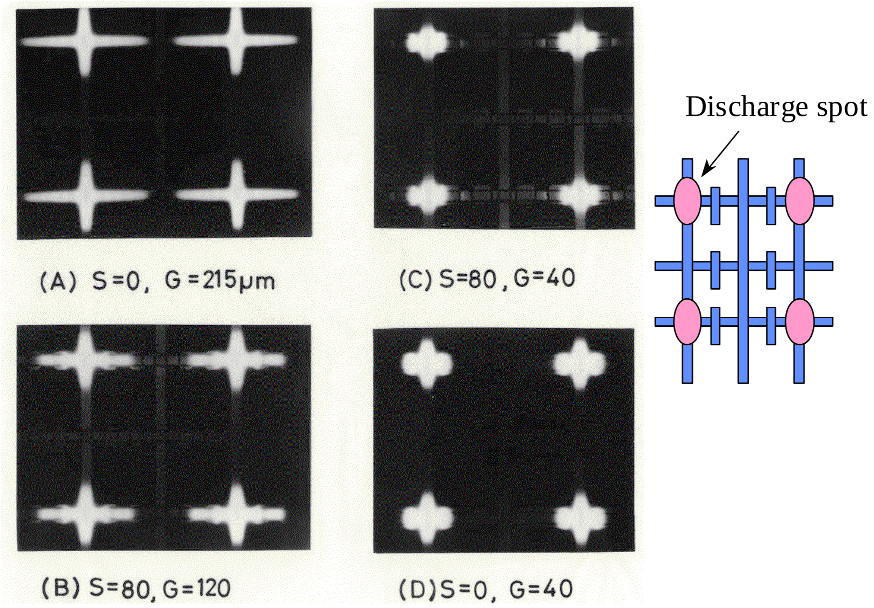


Fig.6 Proposed Two-electrode Color PDP



Discharge shapes for four suppression electrodes

Fig. 7 Effect of suppression electrode

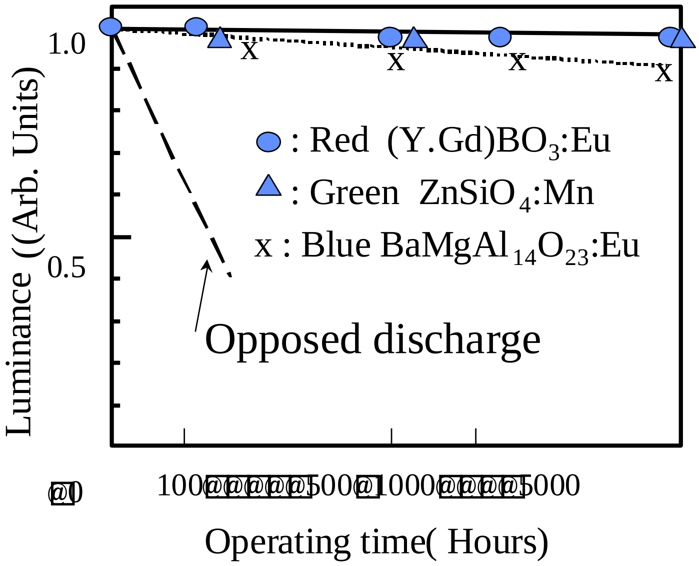


Fig.8 Change in the luminance of the two-electrode PDP

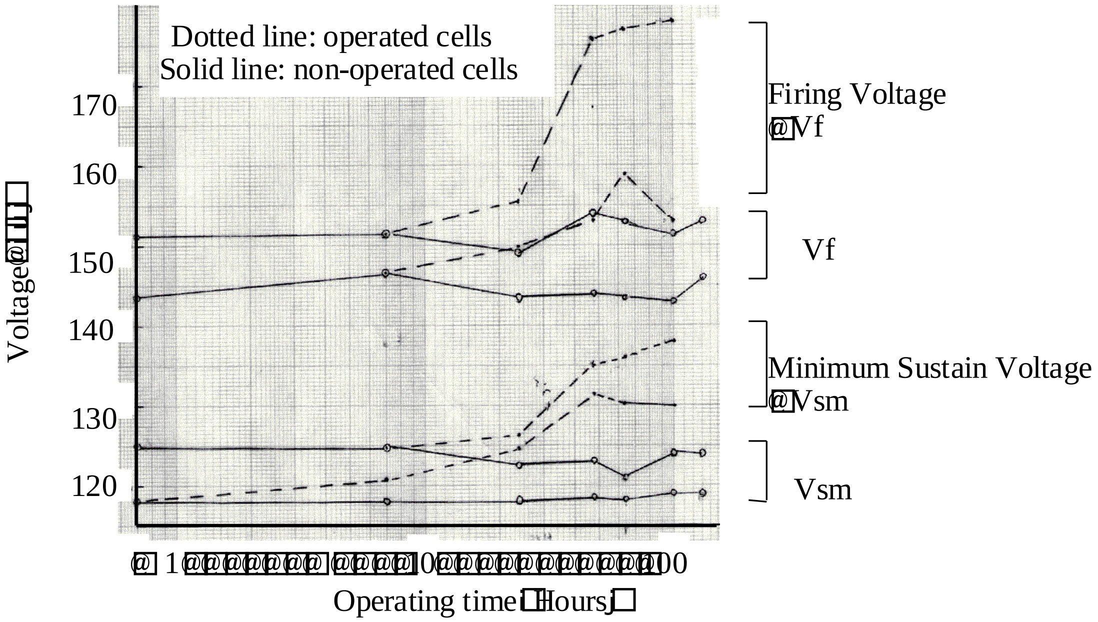


Fig.9 Operating Life of the Tow-electrode PDP

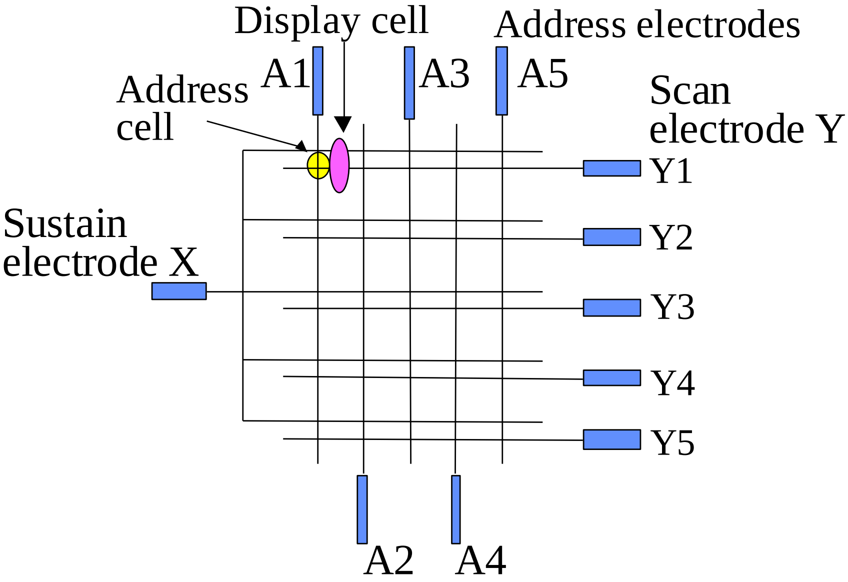
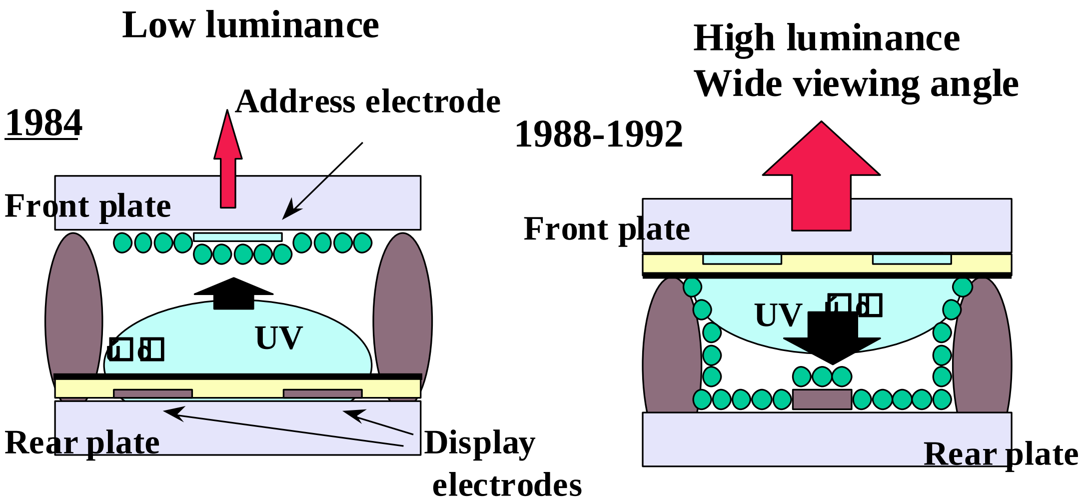


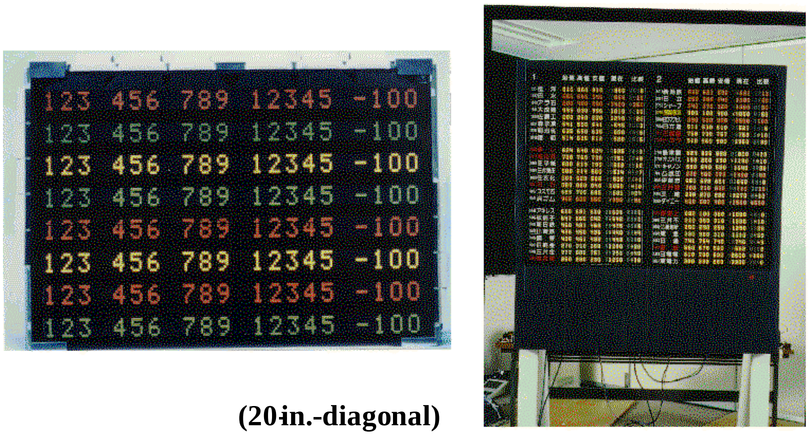
Fig. 10 Electrode configuration of three-electrode color PDP



(a) Transparent type

(b)Reflection type

Fig. 11 Principle structures of three-electrode surface discharge PDP



(20in.-diagonal)

Three-color PDP module

Stock exchange display unit (1989)

Fig. 12 First color PDP product for financial display

Table1. Target of a developed panel.

Items	specification
Active display area	21-in.-diagonal
Display capacity	640 horizontal x 480 vertical
Pixel pitch	0.66 x 0.66 mm
Sub pixel-pitch	0.22 x 0.66 mm
Luminance	□ 150 cd/m^2

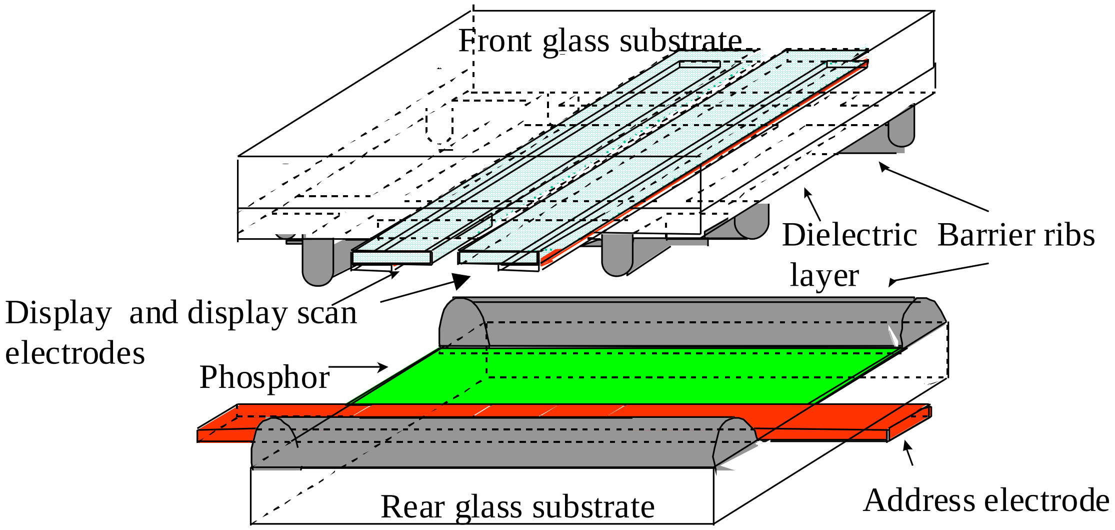
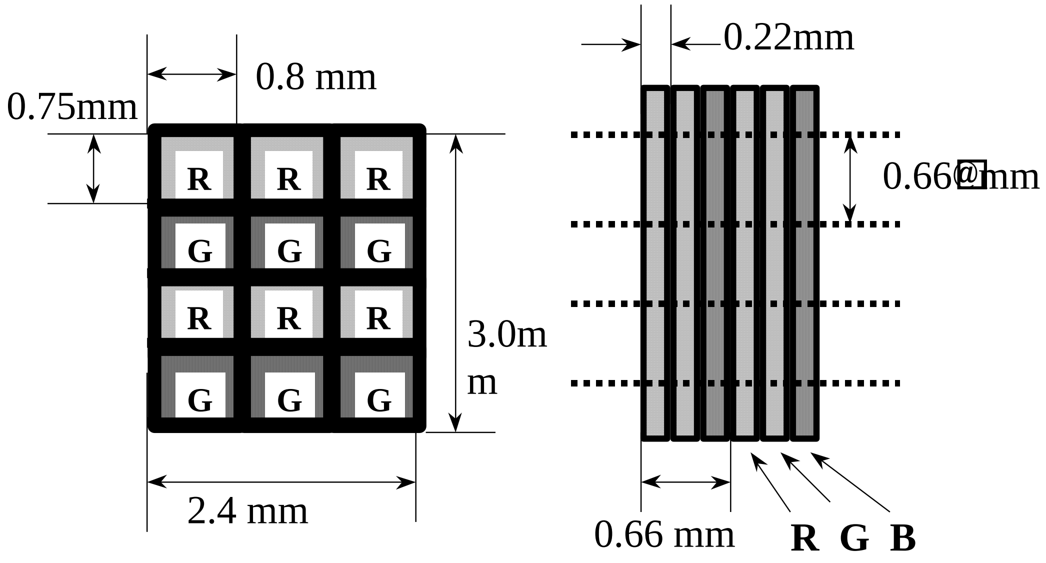


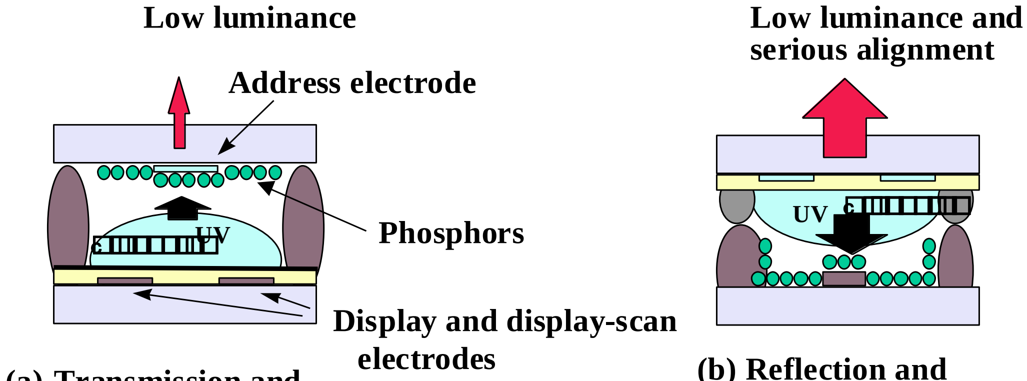
Fig. 13 Panel structure of three color PDP



Three color PDP

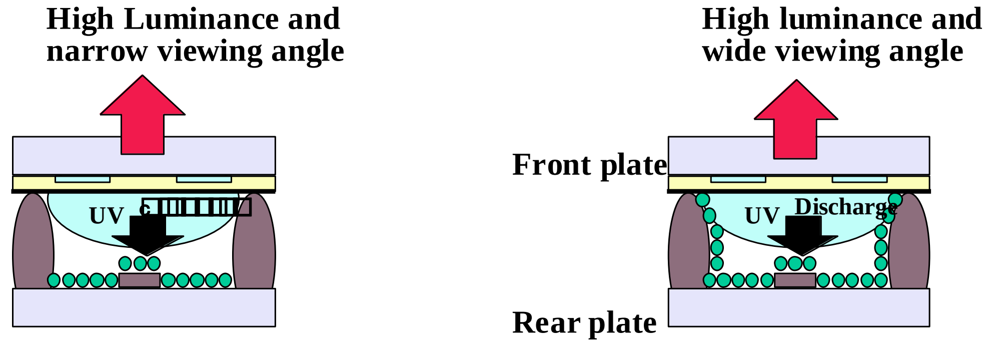
21-inch-PDP

Fig. 14 Comparison between sub-pixel arrangements of three color and 21-in. PDP s.



(a) Transmission and single rib type

(b) Reflection and double rib type



(□) Reflection and single rib type

(d) Reflection and single rib type

Fig. 15 Four types panel structures investigated

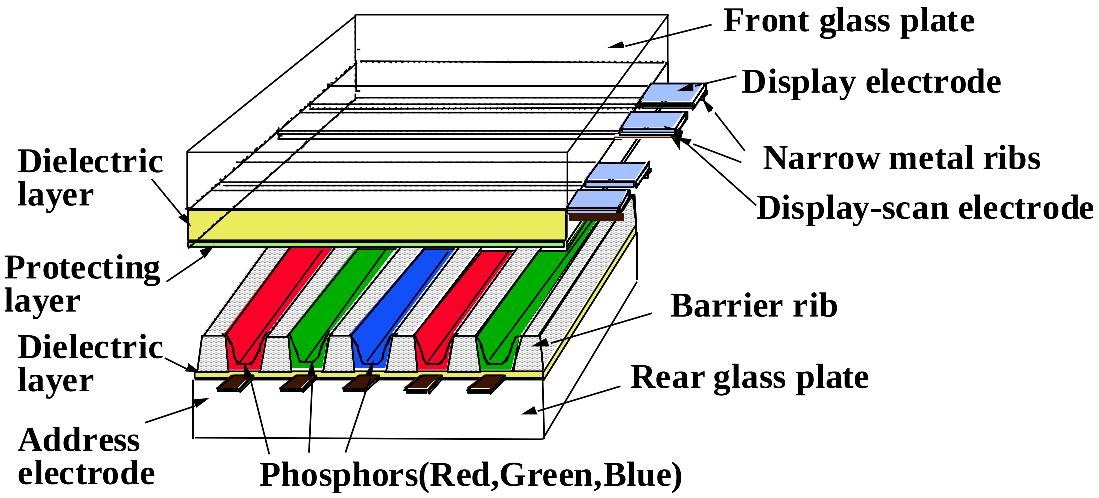


Fig. 16 Stripe TS-PDP with striped phosphor and barrier rib.

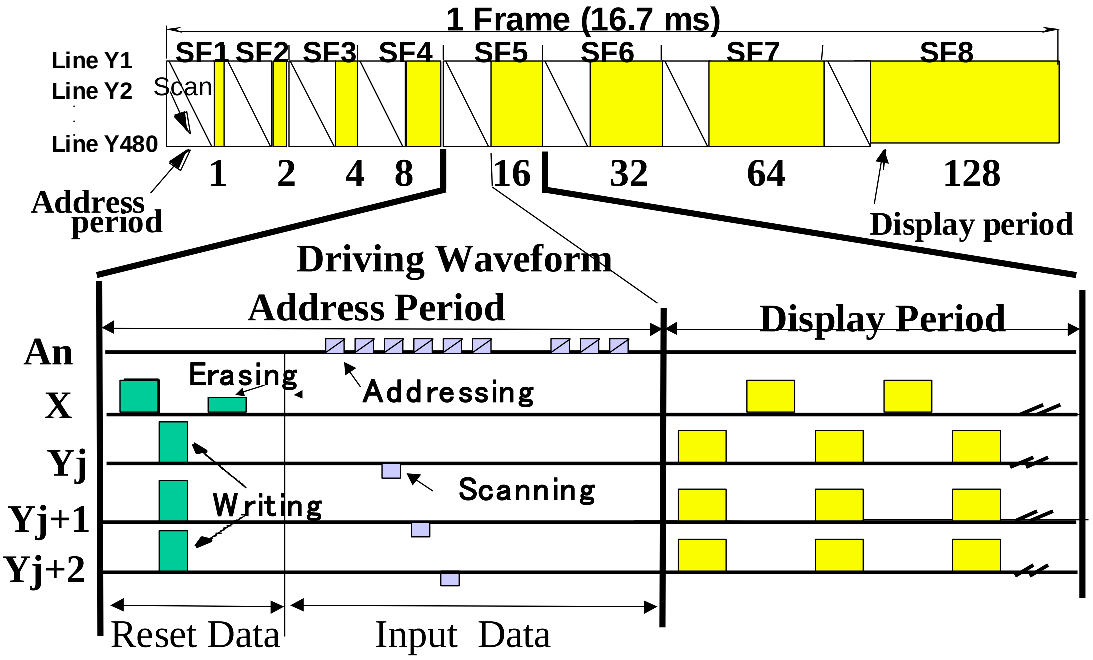


Fig.17 ADS Method for 256 Gray Levels

(1992)

Item	Performance
Display Area	422 x 316 mm
Aspect Ratio	4 : 3
Number of Pixels	640(R,G,B) X 480
Pixel Pitch	0.66mm X 0.66mm
Number of Colors	260,000
Luminance	180 cd / m^2
Viewing Angle	> 160 degree
Power Consumption	100 W max
Weight	4.8Kg

Fig.18 Sample display and performances of 21.-in.-diagonal color plasma display

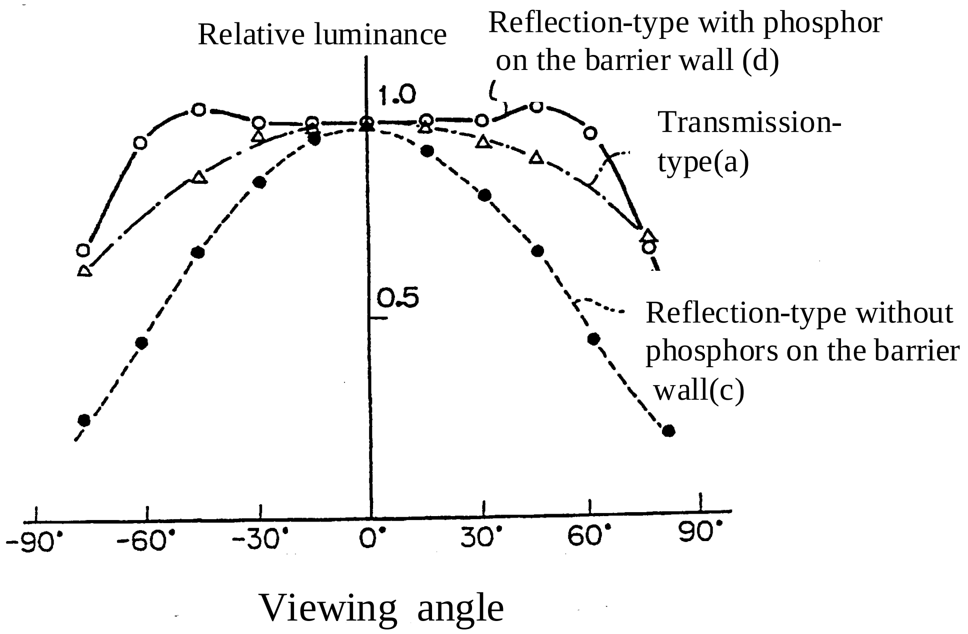


Fig.19 Luminance dependence on viewing angle for three panel structures

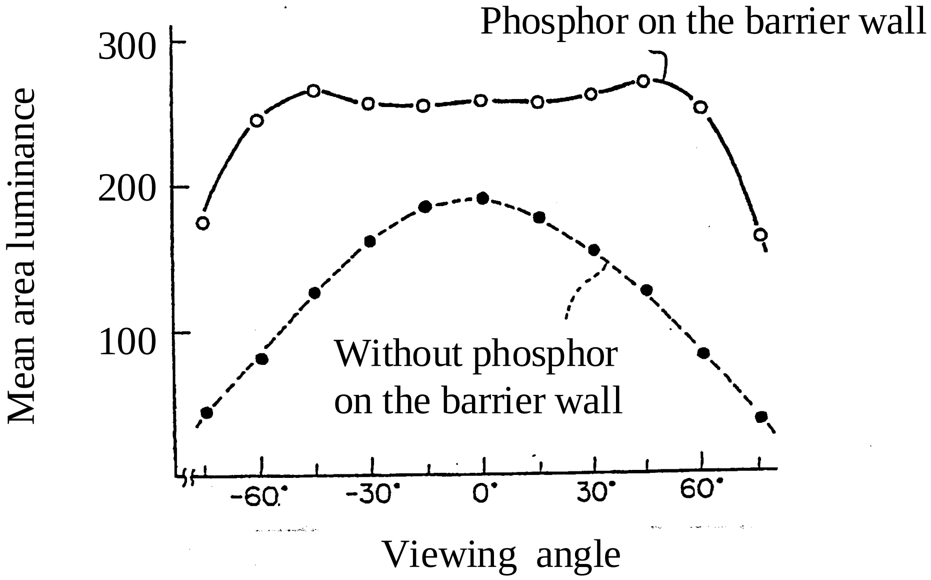


Fig. 20 Comparison of the luminance between the structures with and without phosphors on the side wall of the barrier rib.

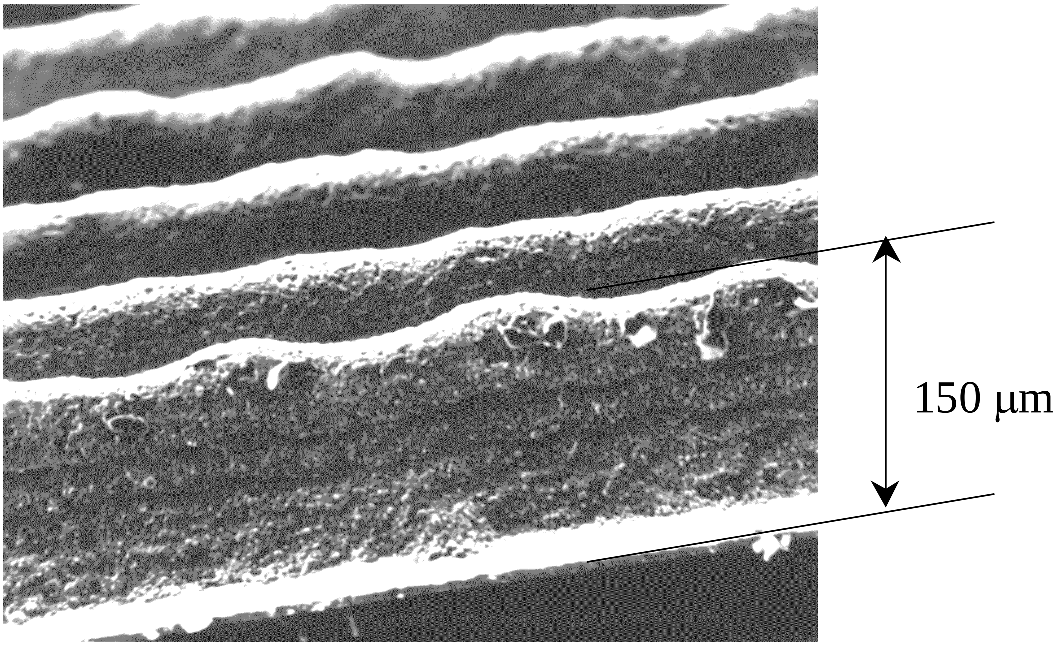


Fig. 21 The photograph of printed barrier ribs

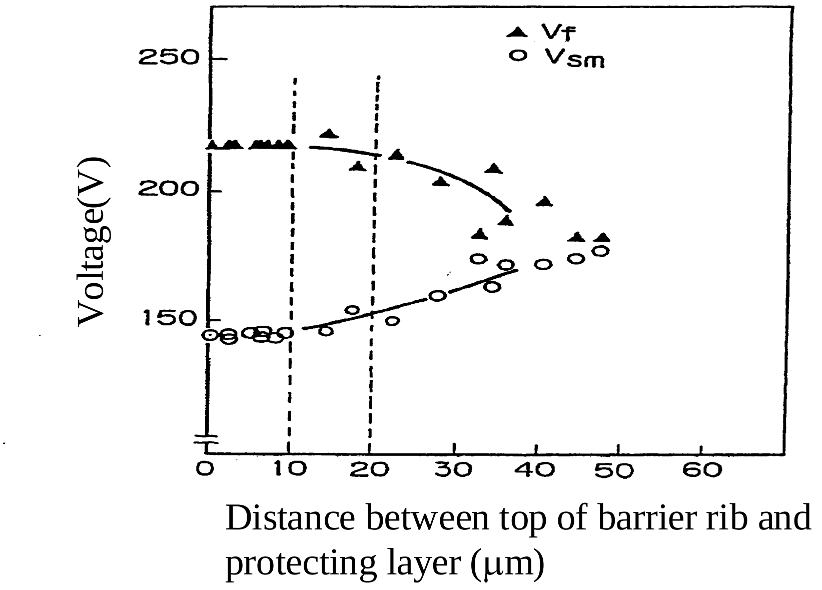


Fig.22 The influence of the gap between top of the barrier and MgO surface on discharge voltages

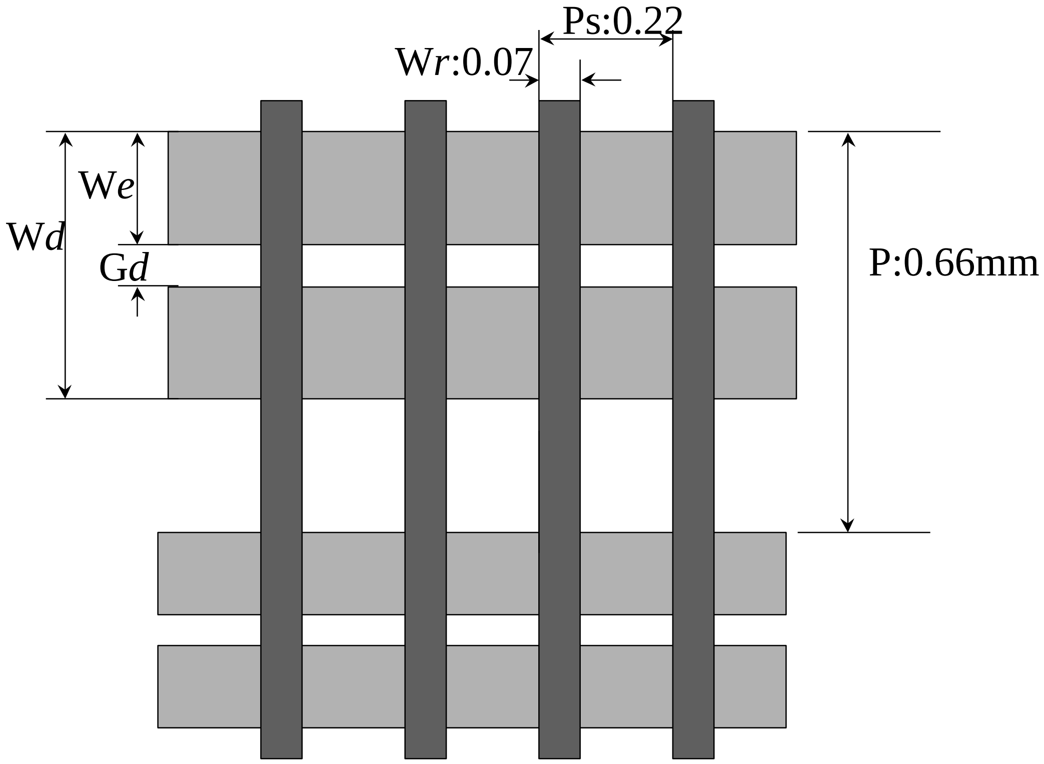


Fig.23 Design Factor of color plasma display

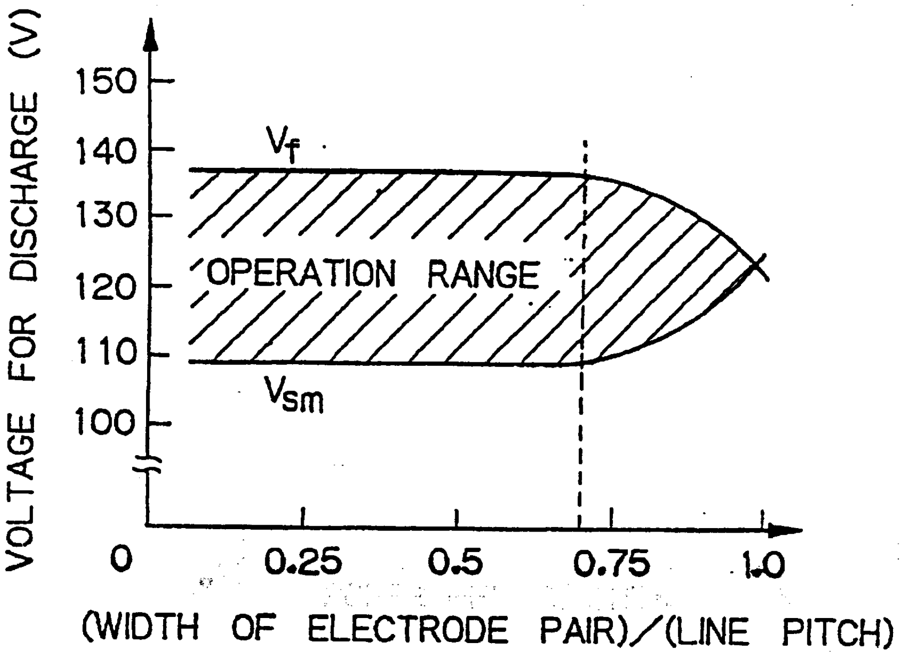


Fig.24 Operating voltage dependency on the ratio between width of display electrode pair and display line pitch

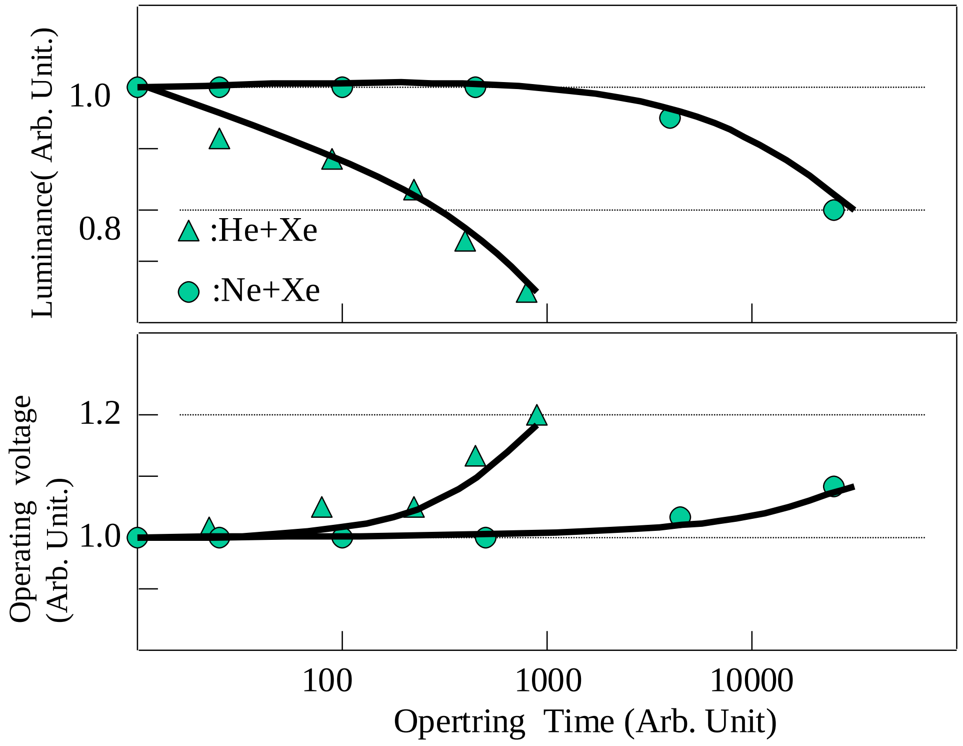


Fig.25 Dependency of changes in operating voltage and luminance on filling gas (He+Xe(3%), Ne+Xe(3%))

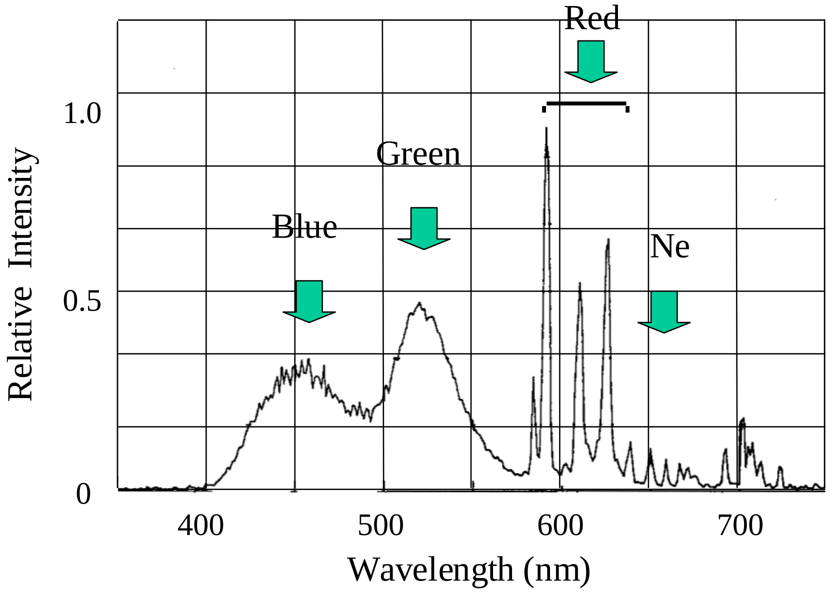


Fig.26 Light emission spectra form
a 21-in.-color plasma display (white color)

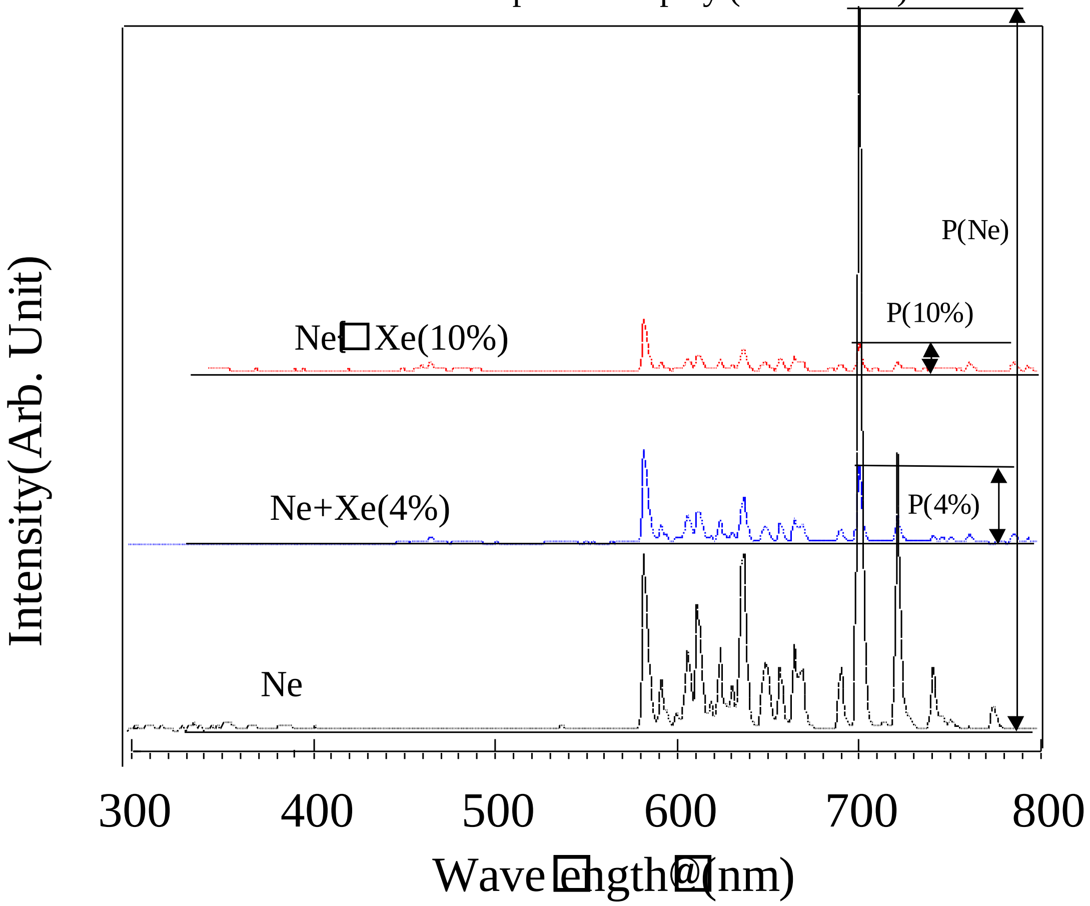


Fig. 27@Emission spectrum from Ne + Xe mixture gases

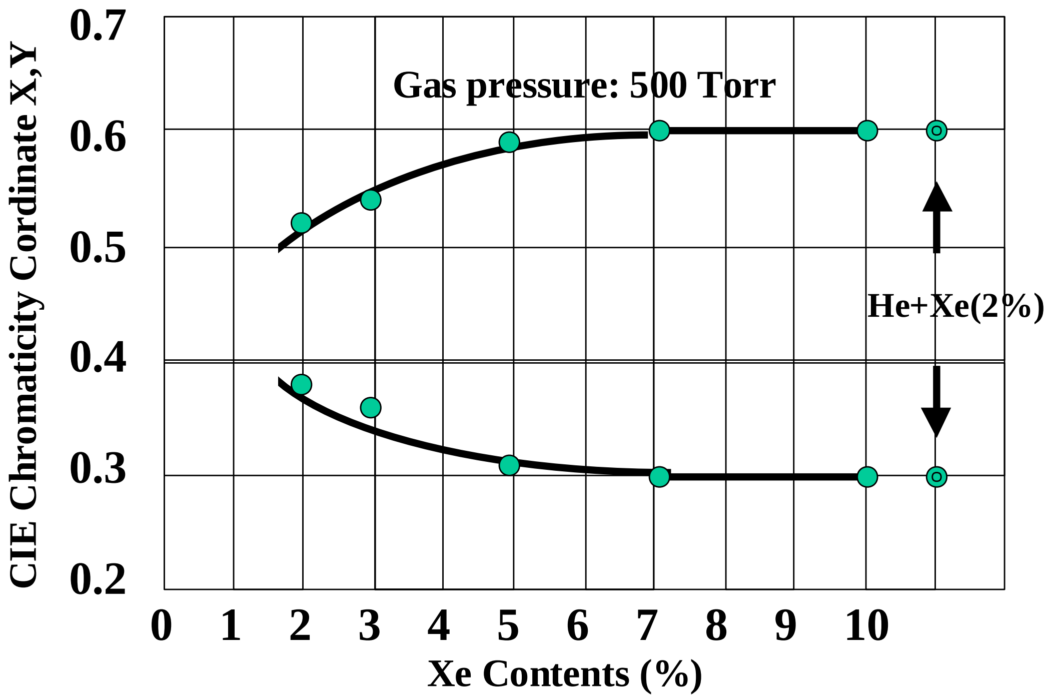


Fig.28 Dependence of CIE chromaticity on Xe contents in Ne + Xe system

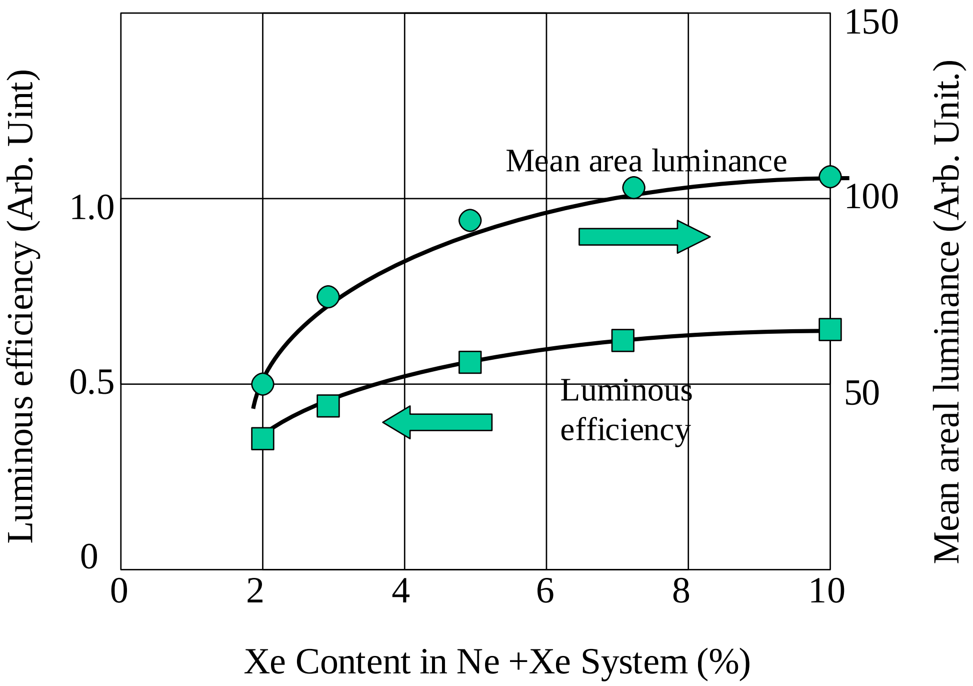


Fig.29 Dependence of Luminance and Luminous efficiency on Xe Contents

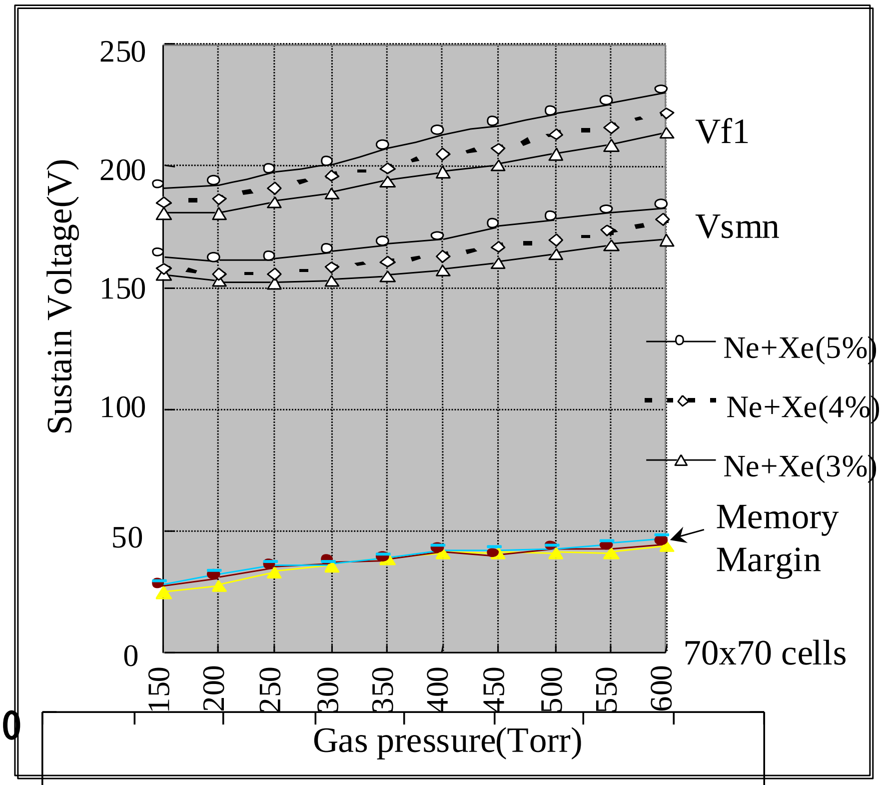


Fig. 30 Operating Voltage Dependence on gases

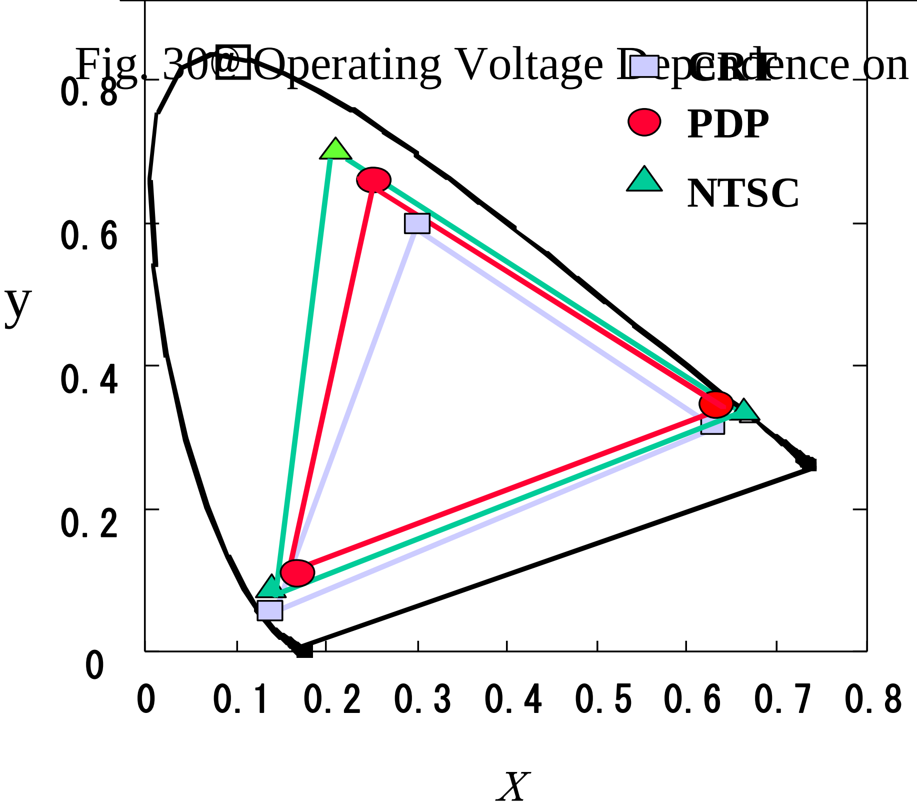


Fig.31 Color coordinate of a 21-in.diagonal plasma display panel developed

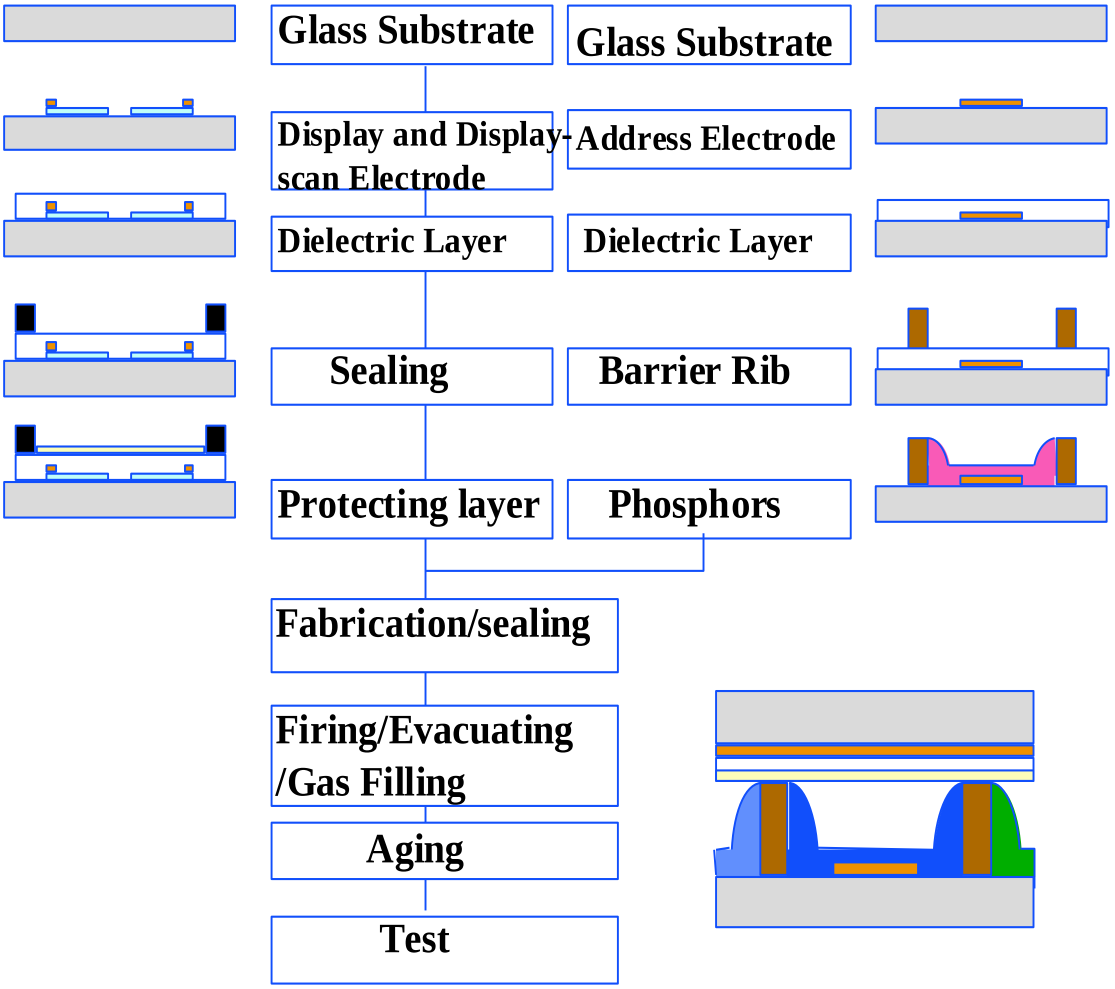


Fig.32@Fabrication Process of color PDP

	Soda lime	High strain point
Specific gravity	2.49	2.74
Thermal Expansion	85	87□10-7/□
Softening point	735□	835 □
Strain point	511□	595□
Cooling point	554□	640□

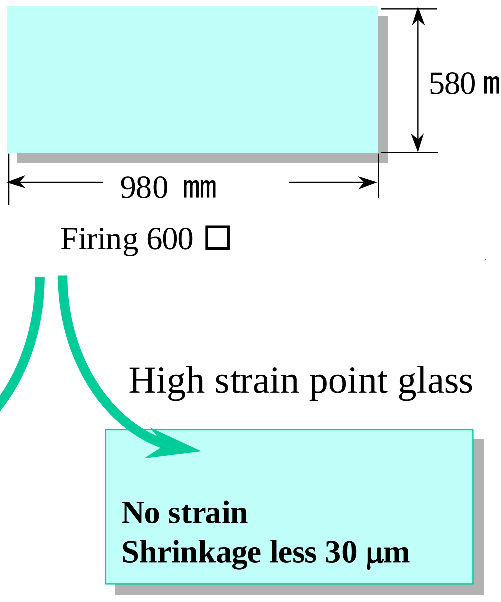
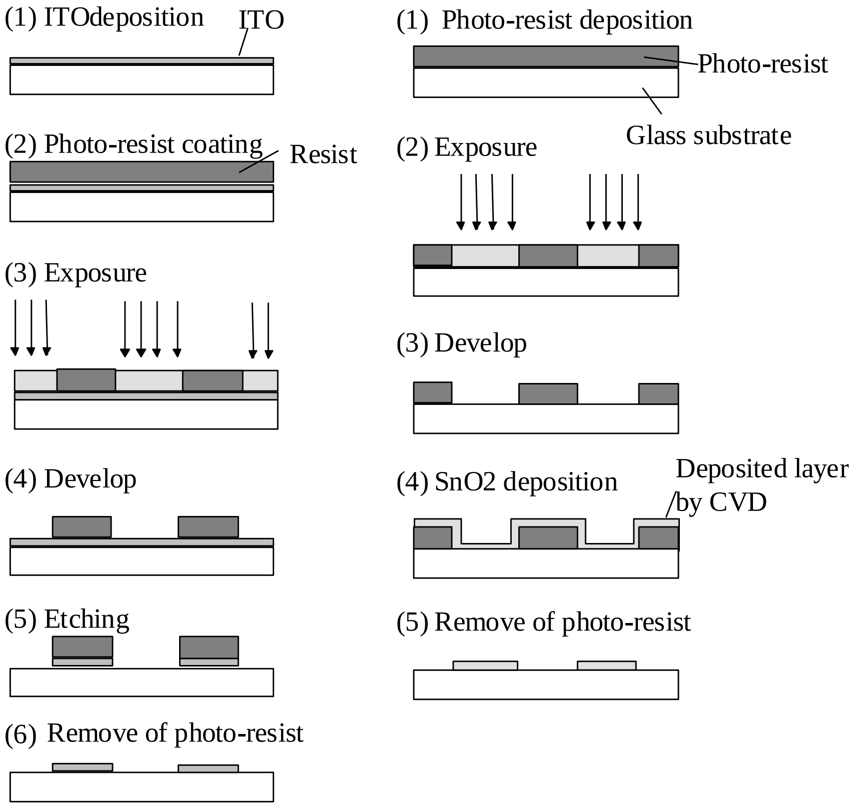


Fig.33 High strain point glass substrate



ITO electrode formation SnO2 electrode formation

Fig.34 Comparison of processed of ITO and SnO_2

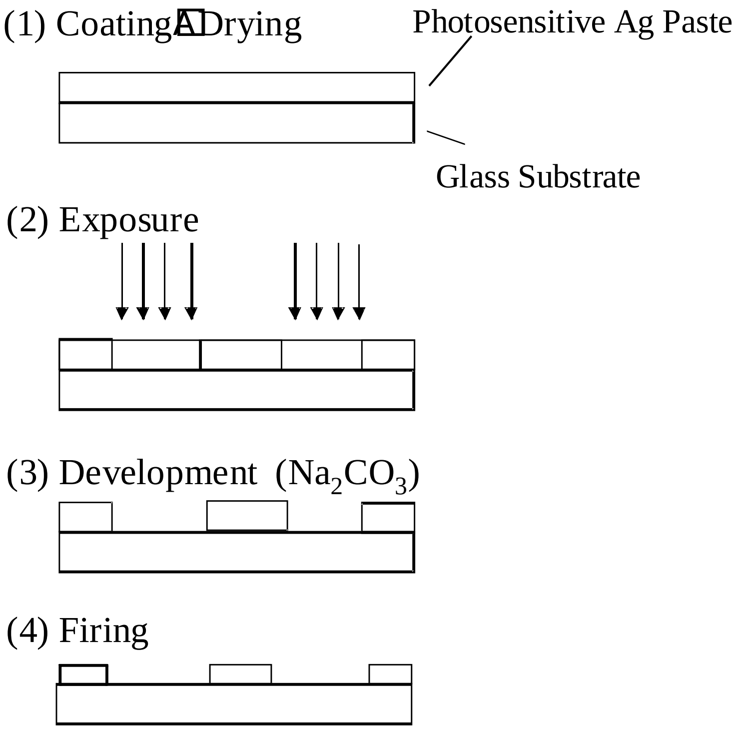


Fig.35 Ag electrode formation by Photosensitive Paste

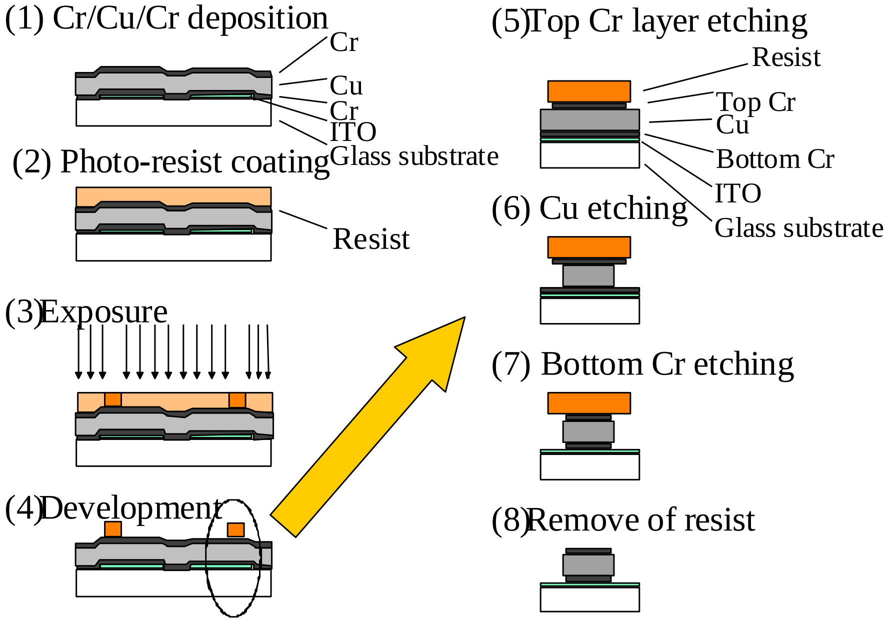
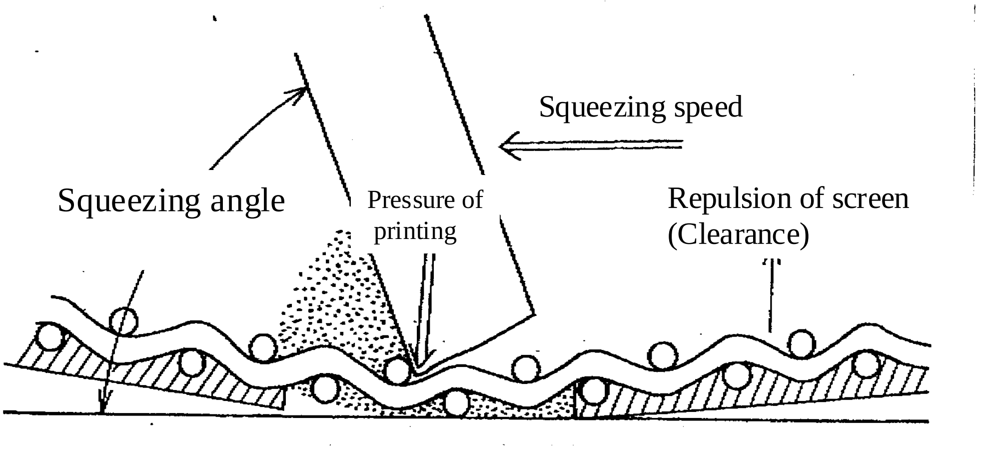


Fig.36 Cr/Cu/Cr@□formation



By the catalog of Micro-tech Ltd.

Fig.37 Screen printing method

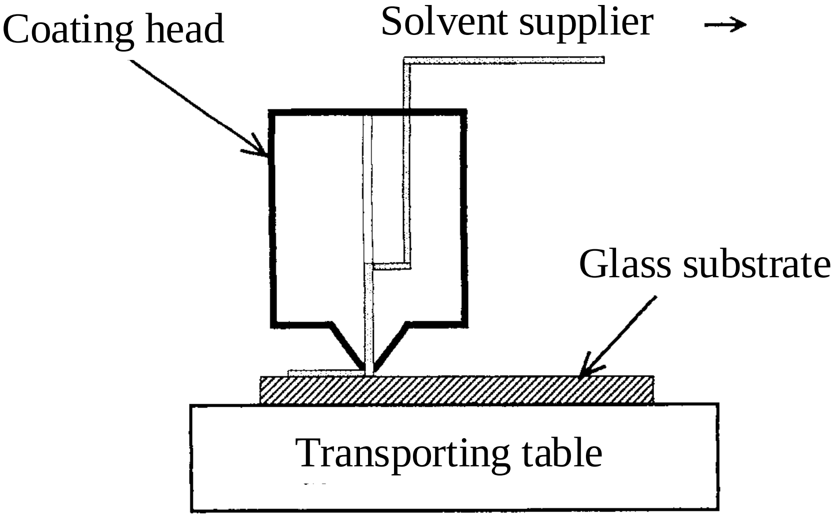


Fig. 38 Slot Coating method

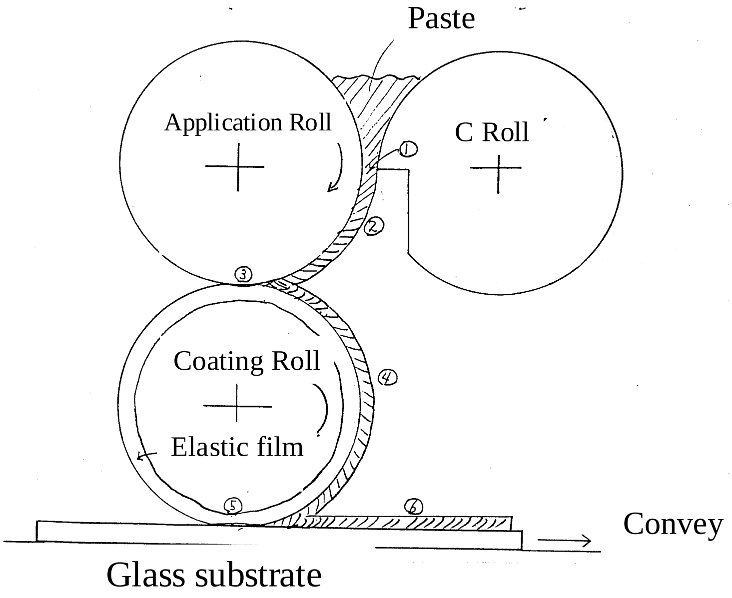


Fig. 39 Roll Coating Method

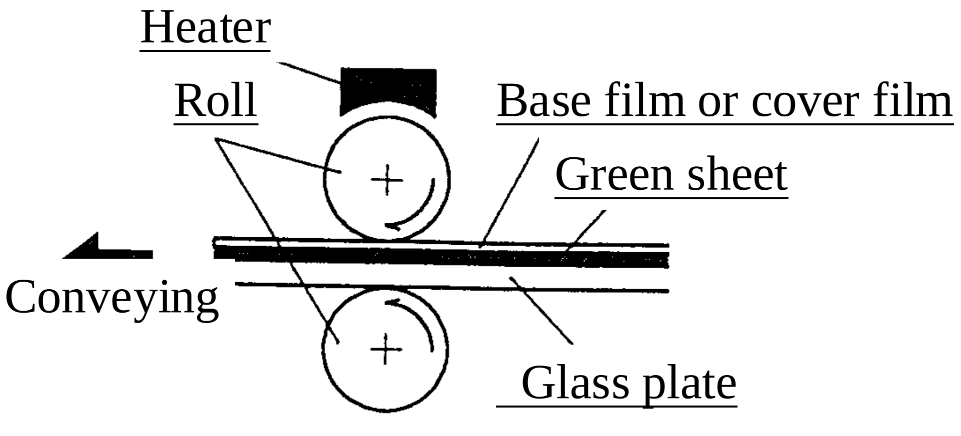


Fig.40 Green sheet method

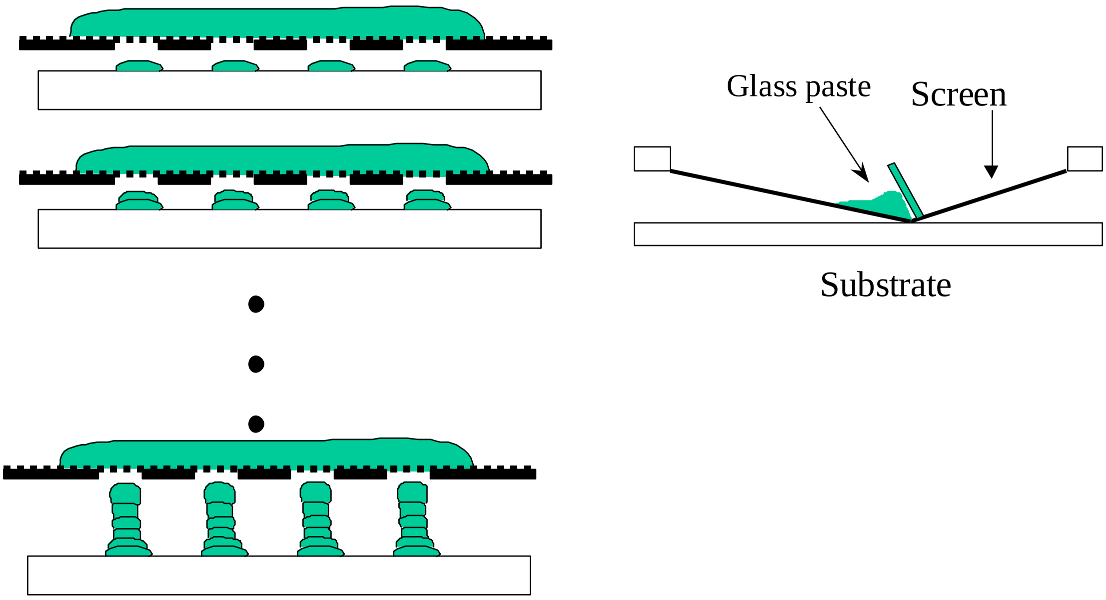


Fig. 41 Barrier rib formation with screen printing

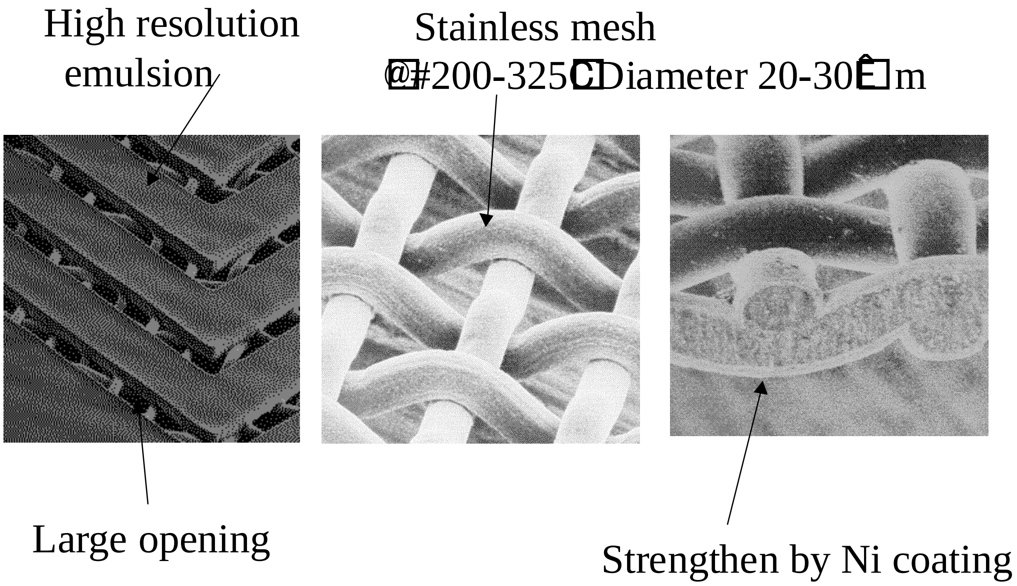


Fig.42 Screen for printing

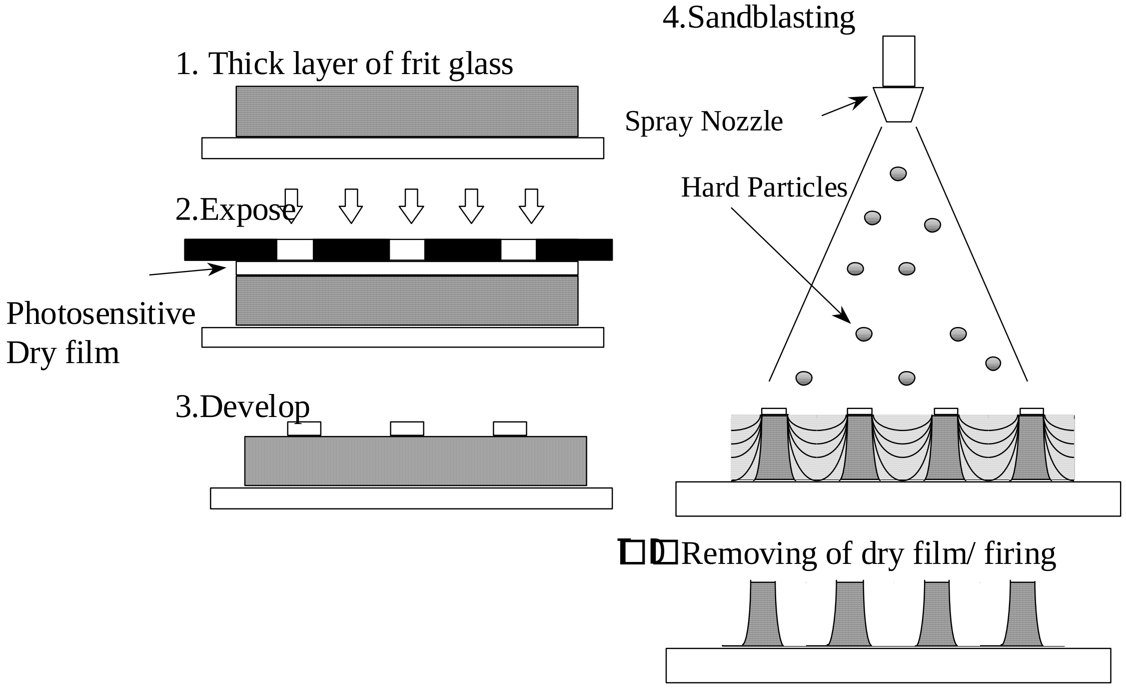


Fig. 43 Sandblasting method

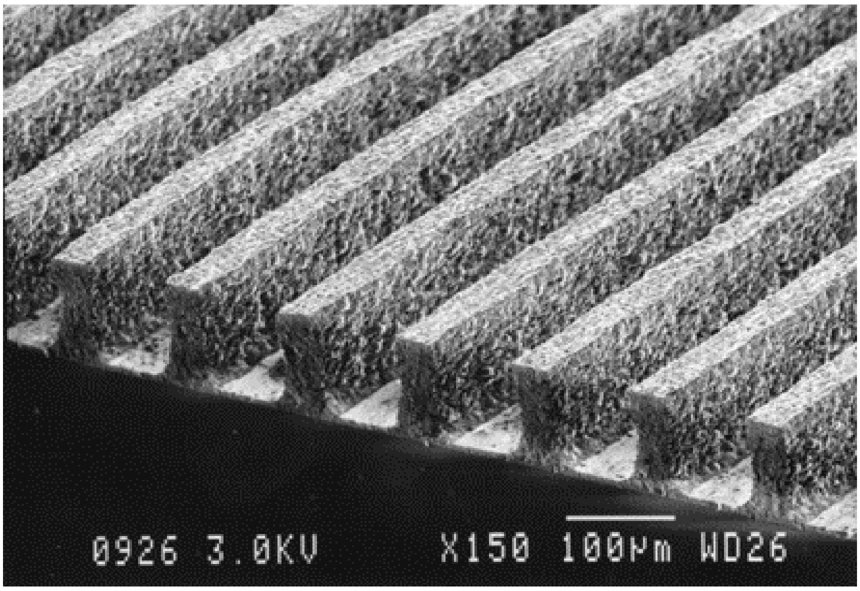


Fig. 44 Barrier ribs made with the sandblasting method
Rib pitch: 130 µm

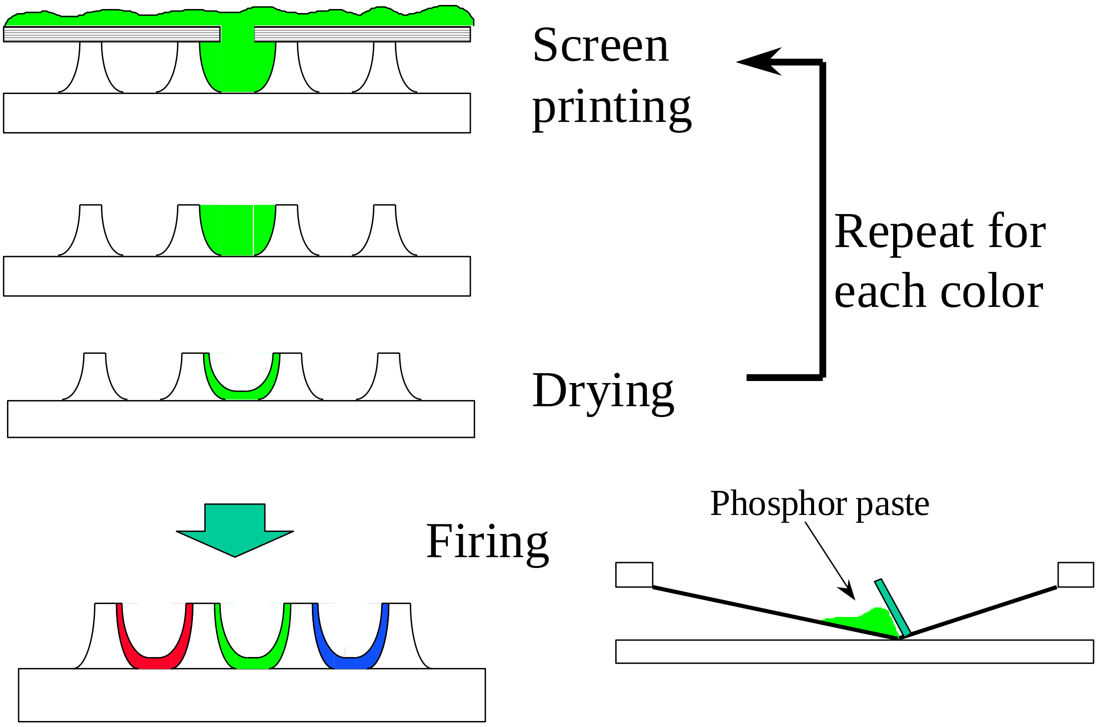


Fig.45 Phosphor formation with screen printing

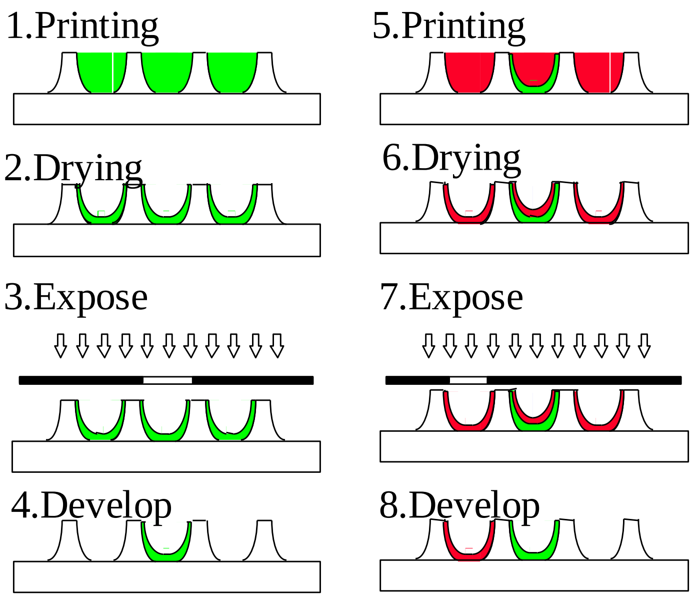
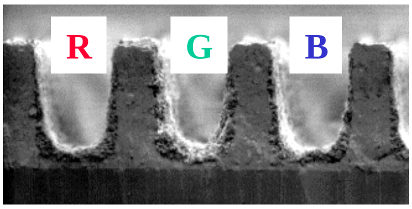
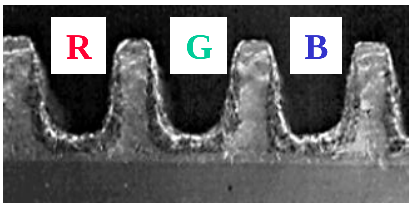


Fig. 46 phosphor layer formation with photosensitive phosphor method



- Simple process
- Low investment for equipment
- High quality screen mask
- Short life of screen mask

Screen printing



- High accurate patterning
- Corresponding to special shapes
- Complex process
- High investment for equipment

Photolithography

Fig.47 Phosphor layers