PLASMA DISPLAYS

The year 1996 may be called "the beginning of a plasma-display era." Billion-dollar investments for mass production of 40-inch–class plasma display panels (*PDPs*) were announced by Japanese and Korean industries (1). The PDP market was forecast to be worth 2 billion dollars in the year 2000. The market growth, however, have been much faster than the expectation. Ten years later in 2006, the world-wide annual sales of PDP-TVs achieved 20 billion dollars with nearly 10 million units for 40-inch and larger.

A plasma display panel is basically an assembly of top and bottom plates (2). The simplicity of the structure makes a rugged, large-area, and light-weight display possible with a set thickness of 10 cm or even less. A display as large as 103-inch-diagonal with 1920 × 1080 pixels has been commercialized (3). Fine resolution of 0.33mm pixel pitch has also been achieved (4).

Chemically stable rare gases are used exclusively in the panels to avoid contamination or reactions with discharge cell walls. Panel life is typically 60,000h. A response time of less than 1 μs for each discharge cell allows the panel to be used for expressing 1080-horizontal-line, progressive-scan, high-definition television (*HDTV*) images with 16 subfields.

A sharp threshold of a discharge current rise with respect to an electrode voltage allows a use of a time multiplexing technique for 2048 horizontal lines (5). Also, nonlinearity of the voltage-current characteristics is utilized to acquire an internal memory operation for the purpose of increasing luminance. The major drawbacks of the plasma displays are low luminous efficiency and high operating voltage. The efficiency is further reduced when the pixel size is made smaller for obtaining a high resolution performance.

GLOW DISCHARGES IN PDPS AND LIGHT EMISSION

Color plasmas use vacuum ultraviolet (*VUV*) radiation, whereas monochrome plasmas use visible radiation, both from low-pressure glow discharges (6). In color PDPs, radiation from both the negative glow and positive column is converted to visible emission by using phosphor.

Requirements for the gas in color plasma displays are that it should have an intense VUV radiation capability, that the radiation energy should be low to reduce phosphor damage, and that visible emission should be weak so as not to degrade color purity of the display. Xenon is found to be the most favorable gas.

One of the major factors that determines the panel life is sputtering of a cathode material by ion bombardments. The sputtering rate is approximately proportional to $p^{-2.5}$ (p = gas pressure), implying an importance of admitting high pressure gas. Increasing of Xe pressure, however, raises the discharge voltage. Instead, it is a common practice to add buffer gases (*e.g.* He or Ne) to Xe. For the purpose of reducing the sputtering rate, the buffer gas atoms should be heavy enough to repel the ejected atoms back to the cathode. Ne is desirable in this respect, although it emits visible red-orange radiation and interferes with the phosphor color. A notch filter is used to cut-off the Ne emission.

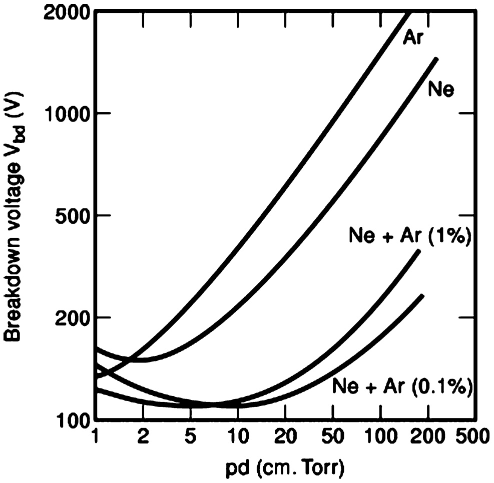

Figure 1. Paschen curves for breakdown voltages.

When voltage applied across a pair of electrodes is increased gradually, a discharge suddenly initiates at the threshold breakdown voltage V_{bd} and discharge current starts flowing between the electrodes. The Paschen curves of Fig. 1 show the breakdown voltages between two parallel plates at a distance d apart as a function of (pd) for Ne, Ar, and their mixtures [6]. The curves indicate that the breakdown voltage is constant at any value of p and d, as long as the product pd is kept constant, a principle called the similarity rule.

For each gas, there is a minimum value, called the Paschen minimum, which gives the lowest operating voltage. An addition of a small concentration of Ar to Ne (the Penning mixture) results in the Penning effect, a lowering of the breakdown voltage below the values for either of the constituent gases. This phenomenon is also found for the glow discharge maintenance voltages. In the Penning mixture, the metastable potential of the Ne buffer gas is slightly higher than the ionization potential of Ar, assisting ionization of Ar. For color displays, an addition of buffer gases, He, Ne, or Ar to Xe results in the Penning effect to some extent.

Light emission from color plasma displays occurs in the following process:

1. production of secondary electrons by bombardment of the cathode with energetic Xe ions
2. multiplication of the electrons by means of ionizing collisions with Xe atoms
3. excitation of Xe atoms by collisions with these electrons
4. emission of VUV radiation from the excited Xe atoms, and
5. conversion of VUV to visible radiation by phosphor.

The production of the secondary electrons from the cold cathode is not an efficient process, and more than 90% of the electric energy is lost as heat at the cathode. A requirement of high-resolution displays reduces the size of

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

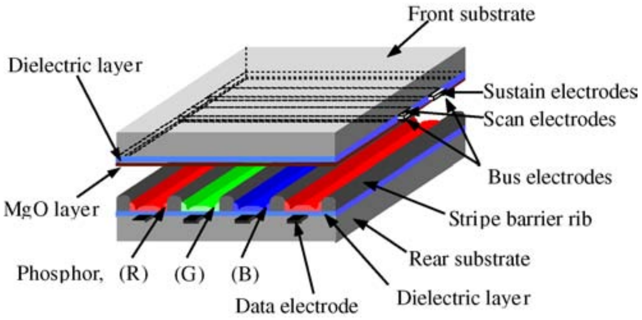

Figure 2. Structure of a three-electrode, surface-discharge ac-PDP.

discharge cells, resulting in an increase of diffusion losses of charged particles to the cell walls, necessitating larger energy input, and hence the efficiency is reduced. The excitation of atoms is also a loss-provoking process, since there are many excitation levels which are inefficient in terms of exciting phosphor.

Loss of resonance VUV photons arising during the process (5) is significant in color displays. Since the resonance photons are easily absorbed by the parent gas, multiple absorption and emission are required for these quanta before reaching the phosphor on the enclosure wall, a phenomenon called imprisonment. Because of their effectively long lifetime, the excited species are likely to be de-excited by electronic collisions. This causes saturation of output light and reduction of efficiency as the discharge current is increased. The saturation does not occur for excimer radiation from Xe_2^* molecules, which are produced under relatively high Xe pressures.

STRUCTURES AND FABRICATION TECHNIQUES OF PLASMA DISPLAY PANELS

Figure 2 shows a typical structure of the three-electrode, surface-discharge, alternating current (*ac*), color display (7, 8). A use of float soda-lime-glass for the front and rear substrates is one of the choices because of low cost. Its chemical instability can be overcome by coating the glass surface with a Na-free dielectric layer such as SiO_2. Glasses with higher working temperatures are used for panels that require high accuracy for high resolution displays.

Transparent Indium-Tin-Oxide (*ITO*) sustain and scan electrodes are formed on the front substrate and run parallel to one another. The electrical conductivity of the ITO electrodes is enhanced by opaque Cr/Cu/Cr three-layered bus electrodes which are formed using sputtering and photolithography techniques. The set of the electrodes are then covered with a transparent thick-film dielectric layer, 25 μm thick. On the surface of the layer is a 0.5 μm thick MgO coating formed by such a technique as an electron-beam deposition. The MgO layer has low normal cathode fall (approximately 95V), resistant to ion bombardments, highly transparent to visible radiation, and has relatively intense exoelectron emission.

Silver data electrodes run vertically on the rear substrate. In order to avoid electrical/optical cross-talks between the neighboring cells, thick-film barrier ribs are formed between the address electrodes. Some of the PDPs have closed type barrier ribs which separate the cells in both horizontal and vertical directions. The height of the barrier ribs, typically 120 μm, determines the separation of the substrates.

The barrier ribs can be made by a multiple printing of thick-film pastes, in which height-to-width ratio of 3 is realized for panels having relatively low resolutions. Figure 3 shows a process of making the barrier ribs by a sand blasting technique (9). First, a thick-film barrier rib paste, 120 μm thick, is coated on the rear glass substrate (a). Then a photoresist film is laminated or coated on the rib paste (b), and patterned by the ordinary photolithographic process (c, d). The film is used as a protecting layer for the sandblasting in which glass or plastic powders are blown by pressurized air (e). The rib paste is fired after stripping off the protecting layer (f).

Full-color representation can be accomplished by incorporating red, green, or blue phosphor into each discharge cell, and controlling the emission intensities from these three primary colors. A typical combination of the three primaries are, $(Y,Gd)BO_3{:}Eu$ (red), $Zn_2SiO_4{:}Mn$ (green), and $BaMgA_{11}O_{17}{:}Eu$ (blue). A Xe + Ne Penning mixture of 67 kPa (500Torr) is admitted into the panel.

DRIVING OF PLASMA DISPLAY PANELS

Addressing of each discharge cell in a matrix panel can be performed using the multiplexing technique. Data pulses V_d are applied to the vertical data electrodes, while scan pulses V_s are sequentially applied to horizontal scan electrodes, one line at a time. These pulses are adjusted to satisfy the conditions $V_d < V_{bd}$, $V_s < V_{bd}$, and $V_d + V_s > V_{bd}$. The voltage across the electrodes at the intersection exceeds V_{bd}, and a discharge initiates.

The PDP provides inherent memory characteristics as explained in a simplified example of a two-electrode panel shown in Fig. 4. Positive and negative sustain pulses are constantly applied across the gap, Figs. 4(a), (d), (e), and (f). The voltages of these pulses are adjusted so that they do not initiate discharges. If the data and scan voltages are applied simultaneously so that the condition $V_d + V_s > V_{bd}$ is met, then a discharge (an address discharge) ignites, (b). Space charges created by the discharge diffuse to the cell walls and deposited there, reducing an effective voltage across the gas. The address discharge ceases after a short moment, (c). When the polarity of the sustain pulse is reversed in (d), the field across the gas becomes larger than that of (a) by an amount determined by the wall charges, and a new discharge (sustain discharge) initiates. The buildup of the wall charges again terminates the discharge, (e). The next discharge starts when the polarity of the sustain pulse is reversed again, (f). In this manner, once the sustain discharge is ignited, the data and scan pulses are no longer needed to sustain the discharges. This is called an internal memory operation.

An address-, display-period separation (ADS) driving scheme is widely used (10). The vertical axis of Fig. 5

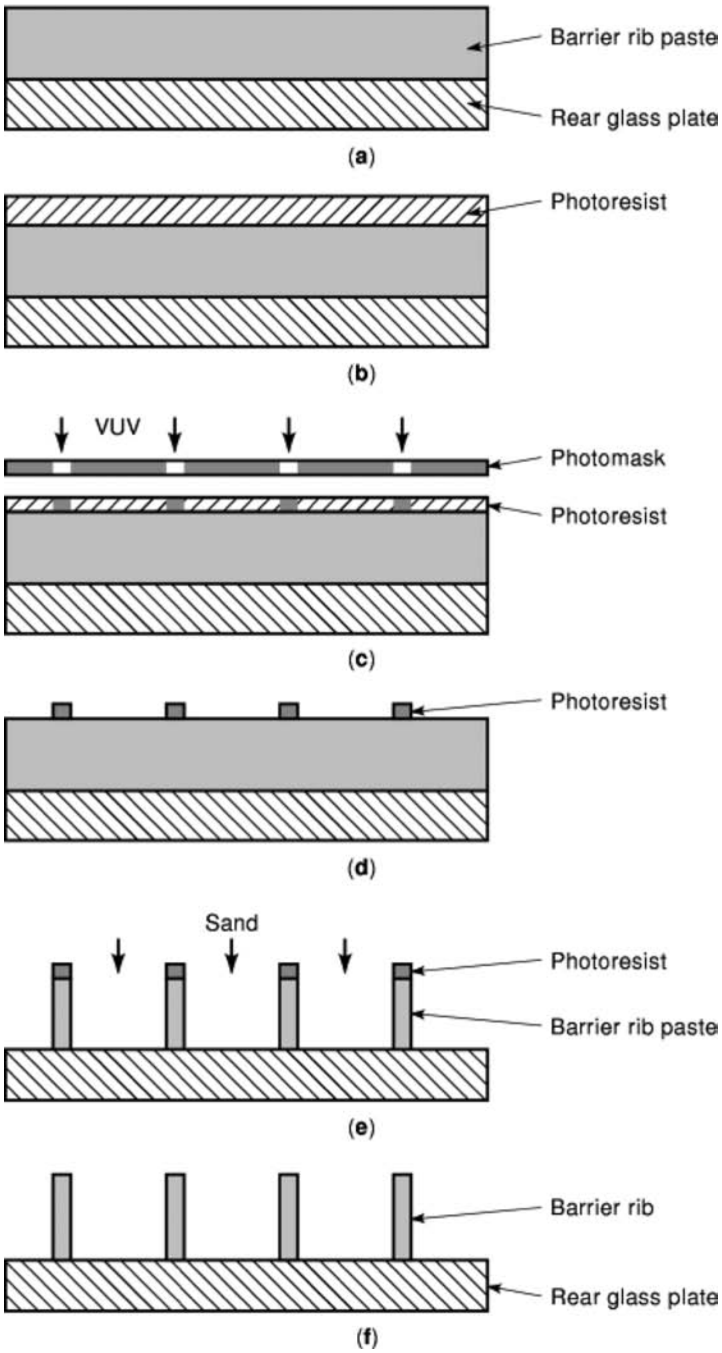

Figure 3. Fabrication process of barrier ribs using sandblasting technique.

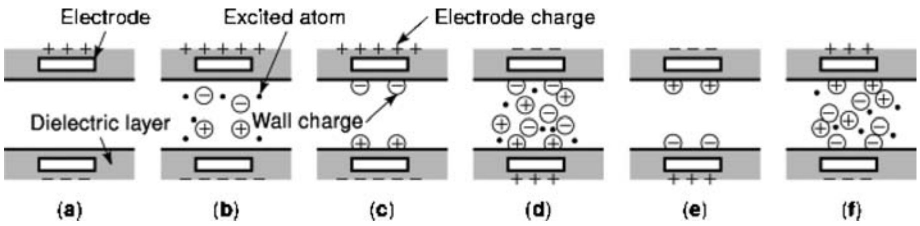

Figure 4. Wall charges in ac display cell.

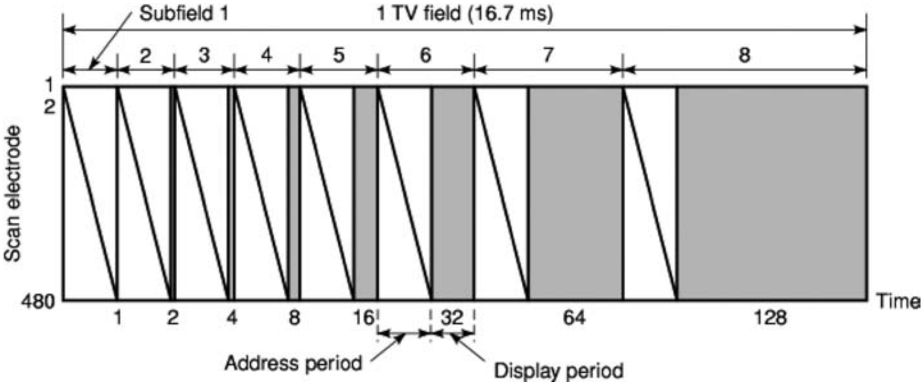

Figure 5. Gray scale expression for Address-Display-Separation drive scheme.

indicates the sequential number of the scan electrodes, and the horizontal axis denotes time. One TV field of 16.7ms is divided into 8 subfields in the figure, each subfield consisting of an address period and a display period. Slanted lines in the address periods indicate timings when the scan pulses are applied. The display periods are filled with trains of sustain pulses. The numbers of the pulses in these periods are arranged according to the binary sequence, 1:2:4:8:16:32:64:128, with which $2^8 = 256$ gray levels can be expressed by combining appropriate subfields.

All the sustain electrodes of Fig. 2 are bussed together and connected to a sustain pulse generator. The scan electrodes receive the sustain pulses on which the scan pulses are superposed. The scan pulses, together with the data pulses, control the amount of wall charges on appropriate discharge cells.

Figure 6 explains the voltage waveforms of the ADS scheme in a subfield. The subfield consists of an address period and a display period. The address period has a reset step and an address step. In the reset step, discharges are ignited in all the discharge cells in the panel by bulk write pulses. The wall charges accumulated with the bulk write discharges are then erased by applying the bulk erase pulse. As a result, an identical condition of wall charges for all the discharge cells is obtained, independent of the on/off states of the display discharges in the previous subfield.

During the address step, the negative scan pulses are applied sequentially to the scan electrodes. The positive data pulses are applied to the data electrodes simultaneously so that the address discharges in the selected cells are generated and wall charges are accumulated on the dielectric layer. The sustain address bias and scan bias may be applied during the address step to assist forming the appropriate amount of wall charges. During the display period, the sustain pulses ignite discharges between the sustain and scan electrodes in the selected cells. The first sustain discharge accumulates the wall charges which triggers the second sustain discharges. Thus the sustain discharges continue as long as the sustain pulses are applied.

In the ADS scheme, the clock rates for the address and display periods can be chosen independently, enabling the rate to be optimized for each operation. This provides wide operating voltage margin. During the address period, however, there is no light emission and hence the peak luminance is limited. The light-emission duty factor is about 30%. This can be doubled by dividing the panel into upper and lower halves and driving them simultaneously, but at the expense of increasing the number of data electrode drivers. Luminance can also be improved by increasing the sustain pulse frequency. This, however, is associated with luminance saturation and efficiency reduction.

Although stray capacitances of the plasma panels do not consume energy, charging and discharging of these capacitances result in energy dissipation in the switching transistors. If a power supply V_0 is connected to a capacitor C *via* a resistor R, the voltage across the capacitor approaches V_0 asymptotically. During the charging process, energy

$$E_{R\text{-}C} = CV_0{}^2/2$$

is dissipated in the resistor. When discharging the capacitor, another energy dissipation in the resistor takes place whose amount is identical to the value shown above. One cycle of the charge/discharge process therefore consumes energy $CV_0{}^2$. Suppose that a PDP with a stray capacitance of 1 μF is powered by 100V pulses of frequency f = 100kHz. The power dissipated in the on-resistance of the switching transistor then becomes $fCV_0{}^2$ = 1000W, which is too large and not acceptable for home-use TVs.

The energy loss can be reduced by inserting an inductance L in series with the panel to form an $L\text{–}C$ resonant circuit (11). Energy dissipation in the resistor during the charging is,

$$E_{L\text{-}R\text{-}C} = (\pi V_0{}^2/8)(C/L)^{1/2}.$$

A typical value of the ratio $E_{L\text{-}R\text{-}C}/E_{R\text{-}C}$ is 1/40, a substantial reduction of the energy dissipation. The energy recovery circuit is used in most of commercially available PDPs.

PICTURE QUALITY OF PLASMA DISPLAYS

A goal for the peak area luminance of TV displays is 1,000cd/m^2 for white. This high luminance is necessary to express appealing images. For better picture quality, however, it is more important to achieve high contrast in an ordinary ambient light; a contrast ratio higher than 100:1 under 200 lx is desirable. An improvement of the contrast can be made by increasing the emission intensity from the display discharges. The contrast can also be made higher

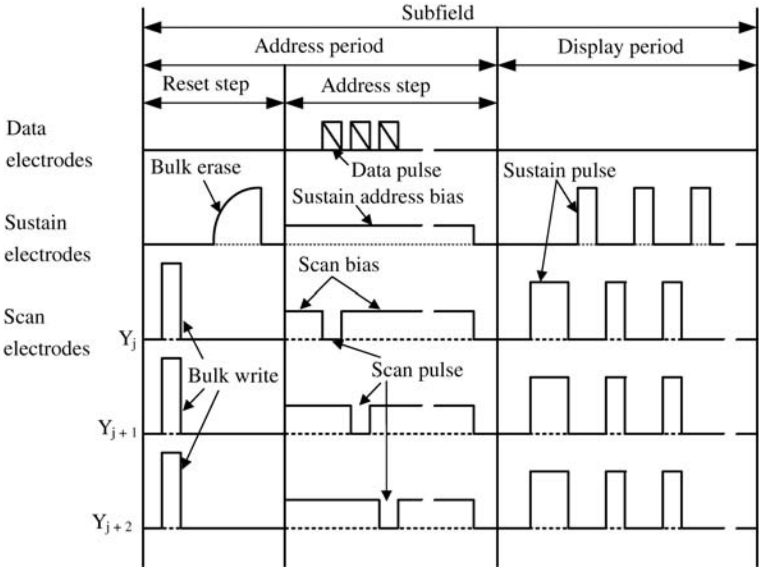

Figure 6. Drive voltage waveforms for Address-Display-Separation scheme.

by placing color filters in front of the discharge cells; for example, a red-transmitting filter in front of a red cell. The filter reduces reflection of ambient light at the surface of the front glass plate. A use of a neutral density filter or a polarizing filer which is uniform across the entire screen is less costly but effective, although it reduces the output luminance. If the transmission of the neutral density filter is 50%, for instance, the contrast ratio is improved by a factor 2 while luminance is reduced by a factor 2.

The dark room contrast can be improved by reducing the emission from the bulk write and bulk erase discharges in the reset step of Fig. 6. This is done by using a ramp waveform (12) instead of the square waveform. If a square pulse is applied whose voltage exceeds the breakdown voltage of the gas, then the discharge current jumps to the value which is determined by an external circuit, and intense radiation is associated. This is due to the nature of negative resistance of the glow discharge.

If the ramp waveform is used with the voltage increase rate of several volts per micro seconds or less, then the discharge exhibits a nature of positive resistance and the discharge current becomes controllable by varying the externally applied voltage. In such a case the light emission becomes weaker by more than an order of magnitude. By employing the ramp waveform a dark room contrast of 10,000:1 has been realized.

Due to differences in light emission mechanisms, various problems arise when the signal-processing techniques developed for CRTs are adopted to PDPs. The CRTs use the 2:1 field interlace in which the odd horizontal lines are addressed line-by-line from the top to bottom of the screen, and then the even horizontal lines. Although only one horizontal line is addressed at a time, the electron beam spreads to the neighboring horizontal lines, resulting in light emission not only from the addressed line, but also from the lines just above and below the addressed line. Therefore, although the addressing frequency is 30Hz, light emission frequency is 60Hz, which is higher than the critical flicker frequency of retina. The interlacing cannot be adopted to matrix displays such as PDPs, since the light emission frequency from each pixel is 30Hz, causing flickering. Since the beam spots of high resolution CRT monitors are smaller with less spread to the neighboring lines, they utilize the progressive scan at 60Hz, as PDPs do.

Also as a screen size becomes larger, another factor called a large-area flickering appears. This is originated from the eye characteristics that peripheral region of retina has higher temporal response compared to the central region.

As mentioned above, the beam spot of CRTs spreads to the neighboring pixels. Due to this as well as to the interlacing, the vertical resolution of CRTs having 480 horizontal scanning lines, for instance, is reduced by a factor approximately 0.7. As the image becomes brighter, the beam spot size increases, leading to further loss of resolution. By contrast, the vertical resolution of matrix displays that have 480 pixels vertically is 480. The pixel structure of matrix displays, however, causes degradation of picture quality because of its high spatial frequency components.

CRTs adopt the raster scan with which the phosphor excitation time is typically 0.1 μs/pixel. Due to intense emission of phosphor which is excited by high-speed electrons, such a short excitation time is enough for obtaining adequate luminance. PDPs, on the other hand, excite phosphor with 8.4eV VUV which yields much weaker emission. In order to obtain luminance comparable to that of CRTs, PDP utilize an inaternal memory operation in which phosphor excitation extends to one TV field, as illustrated in Fig. 5.

Gray scales are obtained by using the pulse-number modulation of Fig. 5. Although this technique is quite adequate to express still images, disturbances of gray scales and colors appear when moving images are expressed. The disturbance becomes more pronounced as the speed of the observation point with respect to the panel becomes higher (13). This phenomenon is explained in an example of Fig. 7, in which (a) shows an intensity variation of a dis-

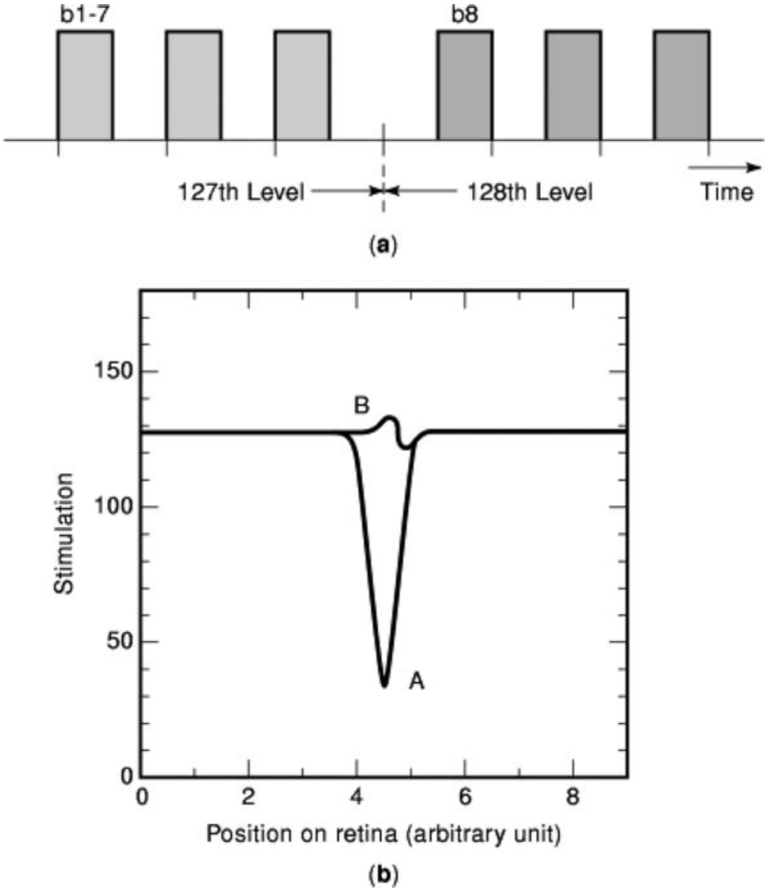

Figure 7. Motional artifact on PDPs. (a) Nonuniformity of light emission with respect to time, (b) gray-level disturbances perceived by the eye.

charge cell that experiences the 127th level (which consists of bits 1 through 7) during the first three TV fields, and then the 128th level (bit 8 only) for the next three. The retinal stimulation of the image is expressed by line A of Fig. 7 (b) in which the after-image effect of the eye as well as blurring of perception are taken into account. It can be found that a dark disturbance is created at the boundary. This is because the horizontal axis of (a) is transformed from time to position on the retina due to relative motion of the eye with respect to the pixels. If the light emission intensity changes from the 128th to 127th level, then a bright disturbance results.

Various methods of reducing the disturbances have been investigated. Reduction of the temporal non-uniformity of light emission patterns of Fig. 7 (a) can be achieved relatively easily by reassigning the subfields from the conventional 1-2-4-8-16-32-64-128 to, *e.g.*, 48-48-1-2-4-8-16-32-48-48, although the number of subfields has to be increased from 8 to 10 for this case. This requires a higher switching speed of the discharge cells by a factor 1.25. The disturbances can be made less perceptible by using an error diffusion technique that is widely adopted in hard copies, but with a sacrifice of resolution. Also, an application of a dither matrix to the original image scatters the contour noise. An alternative method is to add or subtract light emission from the original signal, provided that the speed and direction of motion is known. Line B of Fig. 7(b) shows the improved result with the method (13).

PRESENT STATUS AND FUTURE TRENDS OF PDPS

In 1996, a typical ac-PDP had the following characteristics. Format: standard definition (SD) TV, screen size: 42-inch diagonal, screen area: 920mm (hor.) × 518mm (vert.), aspect ratio: 16:9, number of pixels: 852 (hor.) × 480 (vert.), number of discharge cells: 2,556 (hor.) × 480 (vert.), pixel pitch: 1.08mm (hor. and vert.), discharge cell pitch: 0.36mm (hor.) × 1.08mm (vert.), peak white luminance: 300cd/m^2, dark-room contrast ratio: 400:1, number of gray levels: 256 (8 bits), panel luminous efficiency: 1.0 lm/W, panel power consumption: 300W, set power consumption: 350W, viewing angle: 160 deg, panel weight: 18kg, set weight: 40kg, set thickness: 65mm, and life expectancy (50% luminance): 10,000 hours.

Ten years later in 2006, these characteristics have been improved as follows. Format: full-specification progressive-scan high-definition (FHD) TV, screen size: 50-inch diagonal, screen area: 1,106mm (hor.) × 622mm (vert.), aspect ratio: 16:9, number of pixels: 1,920 (hor.) × 1,080 (vert.), number of discharge cells: 5,760 (hor.) × 1,080 (vert.), pixel pitch: 0.576mm (hor. and vert.), discharge cell pitch: 0.192mm (hor.) × 0.576mm (vert.), peak white luminance:

1,000cd/m^2, dark-room contrast ratio: 4,000:1, number of gray levels: 4,096 (12 bits), set power consumption: 620W, viewing angle: 160 deg, set weight: 42kg, set thickness: 95mm, and life expectancy (50% luminance): 60,000 hours.

One of the major remaining issues for PDPs is to lower the cost so that plasmas can compete with other display technologies such as liquid crystal displays or projection displays. The high cost of PDPs is due mainly to the requirement of a large number (5,760 data drivers and 1,080 scan drivers for FHD) of high-voltage switching elements. To overcome this, reduction of drive voltage and current are essential. As for the panel fabrication, less costly formation techniques of the barrier ribs and phosphor layers should be pursued. The replacement of thin films by thick films may also be effective.

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