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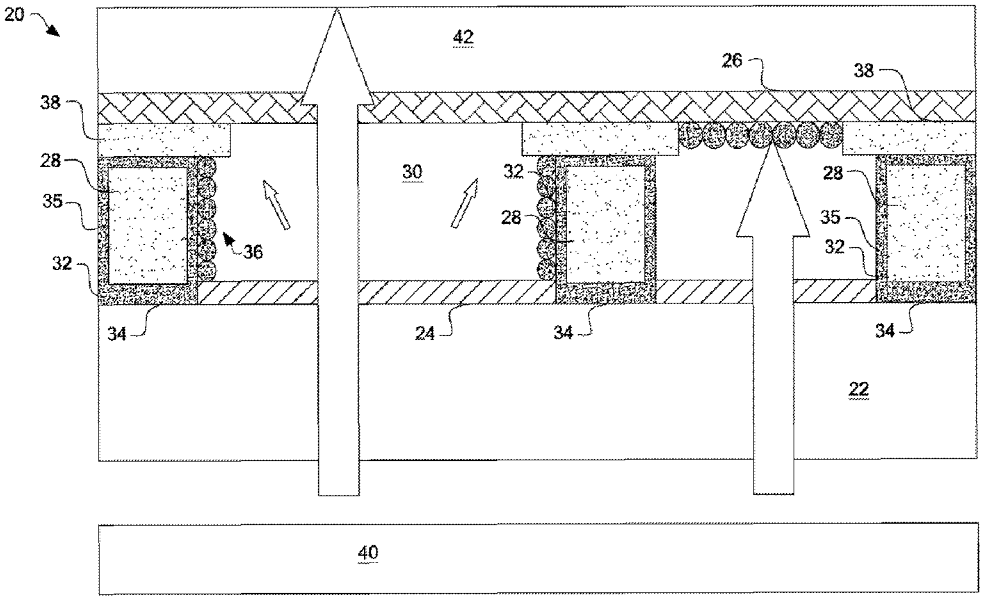

(57) Abstract: In one embodiment, a particle shutter device is provided. The device comprises a color generating material; a transparent planar electrode positioned coaxial with the color generating material; and side electrodes positioned in relation to the transparent planar electrode, the device having an off-state wherein black particles obscure the transparent planar electrode to prevent a passage of light through the transparent planar electrode and an on-state wherein the black particles are laterally displaced relative to the transparent electrode under electrostatic forces to allow the a passage of light through the transparent planar electrode.

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PARTICLE SHUTTER DEVICE AND ASSOCIATED DISPLAYS

FIELD

Embodiments of the present invention relate to electronic shutters and to displays.

BACKGROUND

Electronic displays are known using electro-optical materials between planar electrodes such as liquid crystals that control the passage of light as a shutter in transmission or reflection, or emissive materials such as inorganic phosphors or organic light-emitting films that emit light when subject to an electric field. Other shutter methods include electro-wetting displays using minute droplets of oil containing black dyes or organic fluorescent materials that can be made electrically to cover all or part of a pixel to provide off to on states.

Many such displays have various limitations, including slow response speed using liquid crystals, short life at high brightness for emitting displays using organic fluorescent molecules or polymers in organic light emitting diodes (OLEDs), and low efficiency requiring high power. Furthermore, few are bistable to allow no power at all during either the on or off state for use in electronic books, labels and signs.

Other disadvantages include a limited color gamut arising from a broad rather than narrow emission spectrum, except in a few cases such as OLEDs using phosphorescent dopants, or electrically excited quantum dots (QDs) which have lower efficiency than for excitation by radiation.

Other displays are based on electrophoresis using two color particles suspended in a liquid, but are not shutters and again use the particles themselves as a reflecting element. These have very slow response times and also require expensive thin film transistor (TFT) addressing switches at each pixel. Thus, E-Ink uses a film of small suspended spheres housing black and white charged particles, and color filters facing white particles to give full color but at low brightness due to absorption within the filter. Similarly, SiPix use white particles at the back of an array of micro-cups containing colored liquid but the same absorption losses occur within the filter.

Thus, there is a need for an improved display combining the advantages of wide viewing angle and color gamut, fast response speed, bistability for low power, high efficiency or brightness, and inexpensive addressing by multiplexing rather than use of TFTs, and long life.

SUMMARY

Various embodiments of particle shutter devices (PSDs) may be fabricated using black particles that are laterally displaced from a side electrode to a transparent planar column electrode to produce a shutter effect. In some embodiments, single color black particles, occupying up to 15% of a gas-filled cavity, control light excited by a backlight or incoming ambient light to excite color-generating materials, or to control light from visible light-emitting diodes (LED) backlights passing through a color filter as the light generating film. The color-generating materials may include fluorescent materials comprising transparent particles having a diameter of less than 20 nm. Examples of such materials include quantum dots (QDs) and nanophosphors (NPs). The PSDs of the present invention may be used to realize a full color display having a wide color gamut and long life characteristics.

The transparent column electrode may comprise indium tin oxide (ITO), or mixtures of this with metals, organic conductive films or carbon nanotubes. For each display picture element (pixel) orthogonal side electrodes are arranged perpendicular to the transparent conductor/electrode. Between the transparent and side electrodes, black particles with an electrostatic charge respond to an applied voltage so that they move in a gas either to cover the transparent electrode or side electrode, thus obscuring the passage of light or allowing it through respectively. On either the transparent electrode or the opposing transparent substrate are QDs or NPs able to emit visible light at longer wavelengths than is exciting them (such as UV or near -UV light from an LED or UV lamp as a backlight, or from sunlight). QDs are well known to be very efficient at converting UV into visible light depending on their composition and size.

Dimensions are chosen so as to allow all particles on the transparent electrode to be transferred onto the side electrodes without undue obstruction of the aperture through which light is to be transmitted. This includes limiting the size and number of particles, as well as the height of the side electrodes to avoid excessive cut-off of light at large viewing angles.

Furthermore, excitation light can be generated behind the display, using mercury or inert gas discharge lamps, or light emitting diodes as is well known for LCDs. Where necessary when using color filters, diffusing elements can be included adjacent to the lamps or LEDs, to ensure wide viewing angles, again well known for LCDs. Using color generation film on the front substrate allows even wider angle viewing by using shorter spacer electrodes with less parallax.

QDs and NPs may be used for each sub pixel to generate the narrow emission bands of red, green and blue light enabling a wide color gamut and high brightness or efficiency, using ultra violet (UV) or near-UV lamps or LEDs at the rear, or ambient light from the front. Quantum dots are becoming available through suppliers such as Evident Technologies, Nanosys Inc., American Dyestuffs Inc., Oxonica and Applied NanoWorks. Materials for such quantum dots can be elements such as carbon and silicon, or compounds with or without dopant ions including those of the II-VI, II-IV and III-V elements in the Periodic Table. Other fluorescent materials include organic dyes but generally these do not have such long life under UV excitation nor such narrow emission spectra.

In one embodiment, horizontal rows are patterned of adjoined side electrodes orthogonal to columns of the transparent planar electrode on the other substrate. Combined with the side electrodes are insulating spacers rendered conducting on their surfaces perpendicular to the transparent electrode. The conducting regions are connected to an underlying patterned thin film of metal such as aluminum, forming the rows. Above the spacer on the opposing substrate is a similar pattern of insulating film such as baked photoresist to ensure no short circuit to the columns.

This pattern of orthogonal rows and columns, in conjunction with the voltage threshold effect of response by particles to an electric field, enables passive matrix multiplex addressing without need of thin film transistors (TFTs) to switch each sub pixel of red, green or blue. This reduces cost, and also avoids obscuring of light by such TFTs and their associated storage capacitor. However, if required, the display can also be addressed using active addressing with use of TFTs.

Particles may be of any black insulating material amenable to electrostatic charging, either by contact with other materials, friction, induction or adsorbing ionized gas molecules arising from any means including a separate corona, or ionization by the electric field of any encapsulation gas such as air, nitrogen, argon, neon or carbon monoxide in the shutter cavity. Ideally, their size should be uniform and spherical, both for ease of flowing movement, opaque coating of the transparent electrode, and for uniform charging consistent with lower electric field strength and hence lower applied voltage.

In another embodiment, the side electrodes are replaced by rows of a conducting film perforated by holes to allow at least the same fill factor of apertures as in the method just described. These rows can comprise insulating sheets such as ceramic, glass or polymer coated with a patterned conducting film and containing holes made by a laser or photographic etching including Foturan glass ceramic from Schott. In this case, black particles jump from a uniform distribution on the planar transparent electrode to the opaque metal existing between holes. This configuration allows simple fabrication and high resolution depending on the diameter of holes produced thus allowing high resolution displays.

Other embodiments include electroplated thick film conductors to replace the metalized insulating spacers as side electrodes. Still further embodiments include corrugated snake-like geometry for the spacer side electrodes, and also mid-pixel spacers, to allow shallow height and hence wider viewing angles for use in a display. Also, precautions are mentioned against particle adhesion on the opposed substrate using additional conductive and insulating films or electrets. Finally, a co-planar electrode embodiment is mentioned also using laterally moving particles.

Other aspects of the invention will be apparent from the detailed description below.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a schematic drawing of a pixilated display in accordance with one embodiment of the invention.

Figure 2 shows a schematic drawing of a transmissive particle shutter device (PSD), in accordance with one embodiment of the invention.

Figure 3 shows a schematic drawing of a reflective particle shutter device (PSD), in accordance with one embodiment of the invention.

Figure 4 shows a schematic drawing of a corrugated side electrode for the PSD, in accordance with one embodiment of the invention.

Figure 5 shows the side electrode of Figure 4 in greater detail.

Figure 6 is a graph illustrating the relationship between spacer height and viewing angle, in accordance with embodiments of the invention.

Figure 7 shows a schematic drawing of a snake-like side electrode for the PSD, in accordance with one embodiment of the invention.

Figure 8 shows a plan view of a pixel constructed using the PSD of the present invention.

Figure 9 shows a plan view of a pixel constructed using the PSD of the present invention and having a mid-pixel spacer.

Figure 10 illustrates the viewing angle for a particular construction of a PSD, in accordance with the invention.

Figure 11 schematically illustrates an embodiment of the PSD of the present invention with thick electroplated side electrodes.

Figures 12 and 13 show electrode configurations for a PSD, in accordance with embodiments of the invention.

Figure 14 shows a schematic drawing of a particle shutter device (PSD) with a conductive layer on the rear substrate to assist in the sideways deflection of the black particles, in accordance with one embodiment of the invention.

Figures 15 and 16 show exemplary process flows for fabricating embodiments of the PSD of the present invention.

Figure 17 shows an insulator configuration of a PSD, in accordance with on embodiment of the invention.

DETAILED DESCRIPTION

In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It will be apparent, however, to one skilled in the art that the invention can be practiced without these specific details. In other instances, structures and devices are shown only in block diagram form in order to avoid obscuring the invention.

Reference in this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearance of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments. Moreover, various features are described which may be exhibited by some embodiments and not by others. Similarly, various requirements are described which may be requirements for some embodiments but not other embodiments.

Although the following description contains many specifics for the purposes of illustration, one skilled in the art will appreciate that many variations and/or alterations to said details are within the scope of the present invention. Similarly, although many of the features of the present invention are described in terms of each other, or in conjunction with each other, one skilled in the art will appreciate that many of these features can be provided independently of other features. Accordingly, this description of the invention is set forth without any loss of generality to, and without imposing limitations upon, the invention.

Embodiments of the invention disclose a particle shutter device (PSD) comprising single color micron -scale particles that can be displaced under electrostatic forces to open and close the PSD. The electrostatic forces required to move the particles are provided by electrodes configured to move the particles laterally, rather than up and down. One of the electrodes may be a transparent planar electrode that can be selectively covered with the black particles and then uncovered so that in the one case light can reach and pass through the planar electrode and in the other case the black particles prevent light from reaching the planar electrode. The PSD of the present invention may be used to define pixels in a pixilated display. As will be described in different embodiments, the displays may be reflective or transmissive. For color displays each pixel may comprise a Red, Green and Blue sub-pixel each being defined by a PSD.

Figure 1 shows a schematic drawing of a pixilated display 10 in accordance with one embodiment of the invention. The display 10 may, for example, be a matrix flat panel display. The display 10 comprises an array or plurality of pixels 12 (only two of which have been shown in Figure 1). Each pixel comprises three sub-pixels 14 (triad pixels) for emitting red (R), blue (B), and green (G) light, respectively. Each sub-pixel 14 is defined by a PSD in accordance with embodiments of the invention.

As will be seen, the display 10 comprises a repeating pattern of vertical column electrodes 16 that are orthogonal to horizontal row electrodes 18. In use, a sufficient voltage and electric field is established at the intersection of each row and column electrode to cause the micron -scale particles of a PSD located at said intersection to be laterally displaced under an electrostatic force thereby to expose light-emitting materials of the PSD such as inorganic or organic fluorescent materials that respond to shorter wavelength excitation radiation from a light source located at the rear of the PSD.

Referring now to Figure 2, there is shown a schematic drawing of a PSD 20, in accordance with one embodiment of the invention, which may be used in the display 10.

As will be seen the PSD 20 comprises a rear substrate 22 which supports an emissive color generating material such as quantum dots (QDs) 24. A transparent column electrode 26 is separated from the rear substrate 22 by spacers 28. Thus, the rear substrate 22, the spacers 28, and the transparent column electrode 26 together define an enclosure or cavity 30. Each PSD 20 thus defines a sub-pixel with an aperture of fixed dimensions. Each PSD has two row spacers 28 and two column spacers 28 as can be seen from Figure 8 of the drawings which shows a plan view of pixel design based on the PSDs of the present invention. Side electrodes 32 are formed adjacent to the spacers 28, as shown. Each spacer 28 is connected to a metal layer 34. For descriptive convenience, the combination of a spacer 28 and a side electrode will be referred to herein as a spacer electrode 35. In one embodiment, the cavity 30 is gas-filled and includes black particles 36 that, in use, are electrostatically displaced to provide a shutter effect, as will be described. Reference numeral 38 indicates an insulator to prevent shorting the electrodes 26 and 32. In one embodiment, the insulator 38 may be a 3 to 4 micron dielectric insulator such as a baked photoresist extending laterally into the cavity some 2 to-3 microns to decrease the electric field for gas breakdown.

The PSD 20 also includes a backlight assembly 40 and a front substrate 42.

Corresponding to an off state, the black particles 36 are resident on the transparent column electrode 26. Thus, in the off state, the black particles 36 cover up the transparent column electrode 26 so that light from the backlight assembly 40 is prevented from reaching the emissive color generating material 24. When the side electrodes 32 are energized an electrostatic force is generated. The black particles 36 then migrate under the influence of the electrostatic force towards the side electrodes 32 thereby to uncover the transparent column electrode 26. This corresponds to an on-state in which light from the backlight assembly 40 can pass through the transparent column electrode 26 to reach the in emissive color generating material 24. The result is that the emissive color generating material 24 undergoes excitation to produce light of a desired color which can then be viewed by a viewer. As one of ordinary skill in the art would appreciate, the display 10 may include a driving mechanism (not shown) comprising a power supply, a pixel addressing scheme etc. to selectively energize the planar and side electrodes to drive the pixels.

The PSD 20 described above is a transmissive device. Embodiments of the present invention also disclose a PSD that may be reflective. By way of example, a schematic drawing of a reflective PSD 50 is shown in Figure 3 of the drawings. Referring to Figure 3, the same reference numerals used in Figure 2 have been used to indicate the same or similar components. In the PSD 50, the cavities 30 may be filled with a dry gas such as air. As can be seen, the PSD 50 does not include a backlight assembly. In use, in the off-state the black particles 36 cover up a transparent column electrode 26 thereby to prevent ambient light from reaching the color generating material 24. In the on-state, when the side electrodes 32 are energized, the black particles 56 migrate under the influence of an electrostatic force to adhere to the side electrodes 32 thereby to uncover the transparent column electrode 26. Thus, in the on-state, ambient light passes through the transparent column electrode 26 to reach the color generating material 24. The result is that the color generating material 24 undergoes excitation and emits s light of the suitable wavelength back to a viewer.

In one embodiment, high brightness and color gamut may be achieved using a colored reflective coating 44 disposed on the rear substrate 22 and sandwiched between the substrate 22 and the color-generating material 24 which in the instant embodiment takes the form of quantum dots. The QDs due to their small particle size do not scatter ambient incident light, but instead allow that light to reach the reflective coating 44. Being transparent, the QDs allow both reflection of appropriate colored light from the coating 44, and also reflection of backward moving emitted light from the QDs. Thus, the problems of color desaturation caused by the by scattering of white light as for most conventional phosphor particles is avoided. For this embodiment, the narrow spectrum of emitted colors from the quantum dots allows a wide color gamut and the stronger the ambient incident light the greater is the emissive light. This overcomes the poor visibility of emissive displays in strong sunlight having a limited emissive brightness and competing reflection from reflective powder phosphors.

The materials and fabrication techniques used to produce the PSDs of the present invention will now be described.

In general, the PSDs of the present invention may be fabricated using photolithography techniques involving a series of mask and etch steps.

In accordance with different embodiments, the backlight assembly 40 may comprise cold or hot cathode fluorescent, incandescent, or cathodoluminescent lamps emitting red, green and blue visible light, or LEDs emitting spectrally narrow band red, green and blue light. In some embodiments, the backlight assembly may also be a source of near-UV light such as a gas discharge backlight assembly using mercury and various inert gases including Ar, Ne and Xe, or UV emitting diodes.

In one embodiment, collimation films may be disposed between the backlight assembly 40 and the rear substrate 22 to collimate light from the backlight assembly 40. In some embodiments, the light source of the backlight assembly may be selected to produce collimated light. In such cases, the backlight light assembly 40 may include cold cathode fluorescent tubular aperture lamps.

The rear substrate 22 may be of glass or a thin polymer including flexible films such as, for example, polycarbonate and acrylic sheets, and films such as Solacryl SUVT, and Aclar 22C etc. The polymers may be substantially transparent to any UV light used for exciting the color-generating materials 24.

In one embodiment, the spacers 28 may be fabricated using photo-definable materials such as photoresists ideally capable of defining high aspect ratio structures. Examples of photo-definable materials that may be used include dry film polymer resists such as the MX Series from Du Pont. In some embodiments, non-photo-definable materials such polymers may used for the spacers 28. These materials may be shaped and dimensioned using embossing and micro-replication techniques.

To realize the side electrodes 32, the spacers 28 may be coated with a conductive material such as aluminum using various vacuum coating techniques including sputtering, chemical vapor deposition, or laser ablation.

It is important to ensure that there is sufficient room on the side electrodes for at least a monolayer of particles coating the transparent electrode. In one embodiment, this may be achieved by matching the areas so that $2t(a+b) = ab$ where t is the spacer height, a and b are the sub-pixel sides. For a 0.360 mm triad (360 microns) each sub-pixel is spaced 22 microns so $ab = 316 \times 98$, $a+b = 414$ microns, so $2t = (316 \times 98)/414 = 74.8$ and so $t = 37.4$ microns. Using corrugated spacers 28 (described below) reduces this down to $37.4/1.41 = 26$ microns. However, if the height of the spacers 28 is too great then viewing angle, especially in the horizontal, is decreased by parallax cut-off (see Figure 6). In one embodiment, spacers with a spacer height of 14 microns may be used. In this embodiment, for 1 micron diameter black particles and for a single monolayer on the transparent electrode 36, the particles will form in two monolayers rather than a single monolayer to coat the side electrodes 32 when in the on-state. Increases in the number of black particles on the transparent electrode 26, for say greater opacity, will require a concomitant increase in the number of monolayers on the spacer electrodes 35. However, too many particles on the spacer electrodes 35 may reduce the aperture size and hence brightness. Also, with too many particles the adhesion forces keeping particles in place will weaken.

In some embodiments, the spacers 28 may be shaped and dimensioned to provide an increased surface to which the black particles can adhere. Increasing the height of the spacers 28 in order to provide the increased surface in not desirable, as it can have a detrimental effect on the viewing angle of the display 10, as noted above. Advantageously, in one embodiment, the spacers 28 have corrugations to provide the increased surface. Figure 4 of the drawings illustrates a spacer 28 having a side with corrugations 54.

Figure 5 illustrates in more detail the corrugated spacers 28 where additional surface area is created for accommodating particles from the transparent electrode 26. The gain in surface area is $2r/w = 1.41$ x. This embodiment of the spacers 28 helps to keep the spacer height to a minimum allowing greater angles of viewing for versions with the color film at the rear substrate, as shown in Figure 6.

In one embodiment, a mask for the non-corrugated version may also used to pattern the underlying metal rows 34, and the insulators 38. In one case, the insulators 38 may comprise a baked photoresist. A metal film 58 is deposited over the corrugations 56. In this way, the spacers 28 made of insulating material can be rendered conductive on their surfaces and connected to the underlying metal row 34 via the metal film 58 exposed between corrugations. During metallization, the sub-pixel aperture areas may be protected by photoresist that is subsequently removed in a lift-off process to remove the metal coating formed during the metallization of the spacers 28. In one embodiment, the metal rows 34, and the metal film 58 may be of aluminum.

In one embodiment, the spacer electrodes may have a snake-like geometry in order to provide more area to accommodate the black particle in the on-state, while reducing the height of the spacer electrode, thus increasing the viewing angle.One embodiment of a spacer electrode 60 with snake-like geometry is shown in Figure 7 of the drawings. The electrode 60 has the same width w as the rectangular spacer electrodes 35 described thus far. For a given length of spacer, L, its total vertical area is given by $\{L/[2(s+t)\}x\ 4h(w+s)$ where s is the spacing of the gap in the S-shape, t is the width of the snake, w is the width of the snake track side to side, and h is the height of the spacer walls. This is derived from wall area for a unit cell and calculating the number of unit cells within the length L; $4h(w+s)$ is the unit cell wall area.

Hence, as just one example, $L = 360$ microns, $s = 5$ microns, $t = 3$ microns, $h = 11$ microns, and $w = 11$ microns, gives the wall area as $44\ L = 15{,}840$ sq microns. Compared to a simple rectangular spacer of length L, height h where the vertical wall area is 2 Lh the area of the snake spacer is 2 x greater.

For example, in a sub-pixel size 360 x 113 microns the area is 40,680 sq microns. Spacers on all four sides will have an area of half that given above, as only one side can be accessed by the particles coated on the planar pixel surface. Hence we have:

Spacer area = 2(22 x 360) + 2(22 x 113) = 15,840 + 4,972 = 20,812 sq microns. Thus, for this example pixel area is 1.95 x spacer wall area and so one layer of particles on the transparent column electrode 26 will form about two layers on the spacer walls having this small height, or virtually all of the particles for twice the spacer height.

An example of particle movement is indicated in Figure 8 of the drawings. In one embodiment, dimensions are chosen such that the distance between the particles 36 on the transparent electrode 26 are less than some 200 microns of a nearby side electrode 38 depending on a threshold voltage required to switch the PSD from the off-state to the on-state. With this limit of 200 microns, threshold voltages are well under approximately 250 volts, and very much less for the swing of addressing voltages between rows and columns for on- and off-pixels. Other factors may also affect the threshold voltage including the uniformity of charge distribution over particles, and the total charge initially received by particles that causes them to adhere to an electrode. For example, in a 0.360 mm triad pixel with sub-pixels of 98 x 316 microns, particles would need to hop no more than 79 microns vertically from the center line in the top half, and 45 microns horizontally to the vertical side electrodes as illustrated in Figure 3.

Referring now to Figure 9 of the drawings there is shown a pixel 62 comprising a triad of sub-pixels 64, each defined by a PSD of the present invention. As can be seen the sub-pixels 64 may include a mid-pixel spacer electrode 66 (only one of which has been shown in Figure 12) which serves to reduce the traveling distance for the black particles thereby reducing the voltage necessary for the required electric field but without significant impact on optical transmission reflection, or viewing angle.

In one embodiment the mid-pixel spacer electrodes 16 have similar dimensions to the spacer electrodes 35 described above and thus increase the area by 44 L which in the example given is 15,840 sq microns (using both side walls now accessible by particles). Hence total spacer wall area is now 36,652 sq microns accommodating 90% of particles transferred from the planar electrode and permitting a largely unobstructed passage of light. To obtain exactly equal areas and accommodate all particles from the pixel electrode the spacer height can be increased by 40,680/36,652 = 12.2 microns, with negligible effect on viewing angle.

As examples, for triad pixel pitch p, size a, spacer width w, sub-pixel size d, particle flying distances are x1 or x2 as follows for dimensions in microns:

a) Pitch p = 360, w = 22, 3d + 3 x 22 = 360, so d = 98, d/2 = x_1 = 49, x_2 = 19.0
b) Pitch p = 360, w = 11, 3d + 3 x 11 = 360, so d = 109, d/2 = x_1 = 54.5, x_2 = 24.5
c) Size a = 360, w = 22, 3d + 2 x 22 = 360, so d = 105, d/2 = x_1 = 52.5, x_2 = 20.75
d) Size a = 360, w = 11, 3d + 2 x 11 = 360, so d = 112.7, d/2 = x_1 = 56.3, x_2 = 25.4

where x_2 = (d/2 –w/2)2

For example, the preferred geometry is (d) with a mid-pixel spacer for both decreased particle flying distance of about 25 microns, compared to over twice without a mid-pixel spacer, so operating voltage is also reduced by about a half. There is also least reduction of device transmission or reflection due to obscuration by spacers as indicated by the fill factor, FF, which is the percentage of lit area compared to the whole triad pixel as shown below.

Unit Cell shown in bold lines:

Unit Cell Area $= p^2$
Triad Pixel Area $= a^2 - 2wa$

Fill Factor (no mid pixel spacer) $= FF =$ Pixel lit area/total unit cell area
$= (a^2 - 2\ wa)/p^2 \times 100\ \%$
$= [(a/p)^2 - 2\ wa/p^2\ ] \times 100\ \%$

Fill Factor (with mid pixel spacer) $= [(a/p)^2 - 5\ wa/p^2\ ] \times 100\ \%$

Note $p = a + w$

Option	FF %	
	No mid-pixel spacer	With mid-pixel spacer
a	76.6	59.4
b	88.0	79.1
c	83.2	61.7
d	91.3	79.7

In terms of display viewing angle, this is unaffected by the addition of the mid-pixel spacer as it is surrounded on both sides by the same pixel color, and so only the sub-pixel brightness is affected by the fill factor calculations listed above.

One example is the use of configuration (d) above, for which FF = 80%, transparent column electrode transmittance is 85%, 91% transmittance for the opposite substrate, and the aperture transmittance is 95% allowing for obscuration by particles lining the cavity side walls, so the total is approximately 59%, which is over 11 x that of a TFT LCD.

As another example using configuration c) above has FF = 62%, 85% transmittance for the transparent electrode, 91% for the front substrate, and 73% due to lining of spacer side walls by two layers of particles of 2.8 micron diameter, so the total transmittance is 35%, which is about 7 x that of a TFT LCD giving much better brightness and /or efficiency. Although transmittance is less, so are voltages to side and planar electrode being some 5 V less at +22 V, and -22 V respectively for the particle size and charge mentioned. This assumes also, certain preferred values of nanosize aerosil particles used to keep the black particles from aggregating or exerting excessive Van der Waals' forces with the electrodes and cover plate; sizes for such aerosil particles range from 4 to 16 nm.

For the horizontal viewing angle, taking the example (d) above we can take spacer height as 12.2 microns, plus 3 microns of dielectric insulator, with viewing to half brightness as the parallax cut-off beyond half the sub-pixel width of 112.7 microns and this gives an included viewing angle of 150 degrees (see Figure 10). Also, by trigonometry, the vertical viewing angle is 90 – tan-1 15.2/ 180 = 170 degrees.

It can be calculated that over 85% of the aperture remains for up to 5 monolayers of one micron diameter particles on the side electrodes 32 which is equivalent to filling 10% of a 0.360 mm triad pixel cavity volume. More optimally, a 5% filling allows 95% of the aperture for transmission. Depending on the exact dimensions of particle size and cavity volume, PSDs may be fabricated where the particles occupy 2 to 20% of the cavity volume.

In one embodiment, the PSDs of the present invention may have thick film electrodes instead of the spacer electrodes described above. The thick film electrodes comprise electroplated metal film deposited over a photolithographically etched thin metal film.

Figure 11 shows a PSD 70 with thick spacers 72. Referring to Figure 11, the same reference numerals used in Figures 1 and 2 have been used to indicate the same or similar components. In the embodiment 70 of the PSD, the rear substrate 22 is coated with the unpatterned conductive film 74 such as ITO on its inner side to deflect any upward moving stray particles as will be described later with reference to Figure 14. A thin insulator 76 of about 3-6 micron thickness is formed on the film 74. On the insulator 76 is deposited a thin film 78 some 0.5 to 1.5 microns thick of suitable metal, including copper or gold, that can be etched into the desired pattern for the side electrodes. The film 78 is used to enable electrodeposition of a thicker metal film having a thickness of 10 -25 microns to define thick spacer electrodes 80. In one embodiment, the spacer electrodes 80 are 19 microns thick in the case of straight sided walls. As will be appreciated the thick spacer electrodes 80 do not have and an insulating core as did the spacers previously described. The dielectric insulator 38 may be deposited as a photoresist or ink jet deposited film on the thick spacers 80. In one embodiment, the insulators 38 project some 2 to 5 microns laterally into the pixel aperture area to prevent discharge of the cavity gas close between neighboring electrodes. In one embodiment, an additional safety includes the use of carbon monoxide as the cavity filling gas which has a slightly higher breakdown voltage. Another preventive measure against gas breakdown would be to fill with gas at 50% above atmospheric pressure. After filling with the charged particles, desiccant and sealing adhesive the front and rear substrates are brought together to produce the encapsulated shutter or display.

As will be appreciated, fundamentally the PSDs of the present invention includes a transparent planar electrode and corresponding side electrodes positioned in relation to the transparent electrode so that black particles which normally cover up the transparent planar electrode corresponding to an off-state are electrostatically attracted in a sideways movement to the side electrodes thereby to uncover the transparent planar electrode corresponding to an on-state in which light may enter or leave the device. In configurations of side electrodes described thus far, the black particles form in one or more monolayers along a side of the side electrodes in the on-state. However, as in the case of the embodiments described below, the side electrodes may be such that the black particles reside on top of the side electrodes in the on-state.

Referring now to Figure 12 of the drawings reference numeral 82 indicates an electrode configuration seen in plan view for a PSD in which the black particles reside on top of side electrodes when in the on-state. As will be seen the electrode configuration 82 comprises inter-digitated coplanar electrodes comprising side electrodes 84 that are black. In one embodiment, the side electrodes 84 can occupy 50% of the total area leaving 50% between them for transparent planar electrodes 86. In one embodiment, the electrodes 86 are of indium tin oxide (20). This also allows high optical transmission being the product of the transmission for the transparent electrode and the aperture ratio i.e. typically 85% x 50% = 42%. With the electrode configuration 82, in the on-state the black particles reside on top of side electrodes 84 and in the off-state the black particles reside on top of the transparent planar electrodes 86. In use the black particles move laterally across from electrodes 84 to electrodes 86 in response to opposed polarities of the electrodes. Electrode widths may be consistent with the flight distances outlined above and are between 19 to 45 microns. The electrodes may be etched in conductive thin films or printed. Advantageously, a black dielectric insulator may be coated to cover the gap between the sets of electrodes to prevent leakage of light in the optically off-state. Such an insulator would ideally be overlapping the electrodes for say 5 to 10 microns to take care of tolerances.

Figure 13A shows a plan view of an electrode configuration 90 comprising side electrodes 92 that support the black particles on a top thereof when in the off-state. Figure 13B shows a section through the electrode configuration 90 taken at A-B. As will be seen, the side electrodes 92 comprise an insulating portion 94 covered with a metal film portion 96. Gaps or holes 98 occur between the side electrodes as shown. Reference numeral 100 indicates a transparent planar electrode. When in the off-date the black particles are uniformly attracted over the transparent electrodes 100 as is the case with sub-pixel 102. When in the on-state the black particles are attracted to the metal portions 96 of the side electrodes 92 and reside on top of the side electrodes 92 as is the case with sub-pixel 104. In the on-state the gaps 98 are free of black particles and light passes through the 98. Thus, a shutter effect is realized.

To form the side electrodes 92, in one embodiment, patterned rows of conducting thin film such as aluminum or other metals, are coated on an insulating sheet such as glass, ceramic or polymer containing holes of diameter and spacing to allow aperture fill ratios from 50% to 80% and typically 68%. Such holes may be produced by any convenient means including laser and photoetching. Thus, Teosys can laser etch 30-50 micron diameter holes in 34 micron thick Kapton polymer. Other polymers include polycarbonate, and polyester of 15- 150 microns thickness but typically 25 microns. Cell cavity gaps can be 10-50 microns. With a 10 micron thick rear substrate and 10 micron gap a viewing angle of 136 degrees may be achieved using the side electrode 92 formed on the rear substrate. In one embodiment, the side electrodes 92 may be formed on the front substrate and collimating light at the rear allows wider viewing angles as indicated in the other embodiments with a rear collimator and front color generation film as mentioned above. Alternatively, the device could be used in a projection mode. Substrate spacers may be located around pixels enclosing the black particles using photoresist in the conventional manner, or with a polymer film patterned with holes matching the pixel apertures.

In one embodiment the black particles may be of insulating polymer materials using a black dye or pigment and having a monodispersed particle size of 0.01 to 20 microns, e.g. 2.8 microns. The back particles may include commercially available acrylic beads having a very narrow size distribution, with or without charge controlling surface treatments. In one embodiment, up to 10% of aerosols may be added to the black particles for easy flowability with a small angle of repose in a pile of powder between 20 and 39 degrees. The black particle may also include suitable polymer particles available from Soken in Japan via Reade and Esprix in the US, Polysciences, Sekisui Plastics, Zeon Chemicals, Degussa, Tulco Inc. and Cabot or similar. In general the black particles may include any particles capable of electrical charging including black oxides, sulfides, carbon, organic dyes, or toners used in photocopiers, including polymer encapsulated black pigments such as carbon black. White or other colored particles may also be used if coated by black materials such as an adsorbed dye. In one embodiment, by way of example, 12 nm nanoparticles of Degussa aerosil R972 can be coated onto 5 micron diameter lactose particles to prevent agglomeration by Van der Waals' forces, and the aerosil may even be attached by its acquisition of an electrostatic charge opposite to that of the larger particle (as taught by J.H. Werth et al, Powder Technology 133, (2003) pp. 106-112).

In accordance with different embodiments, the transparent electrode 26 may be of any suitable material capable of patterning through printing, etching, scribing or laser techniques. Examples of materials include indium tin oxide, zinc oxide, antimony tin oxide, or similar inorganic oxide materials, as well as organic films such as Orgacon from AGFA or PEDOT etc. In embodiments that require UV light for excitation of the color-generating material 24 the transparent electrode 26 will be of materials and thicknesses compatible for sufficient transmission of UV.

For embodiments that use a fluorescent material as the color-generating material 24 and a UV or near UV source of radiation, the fluorescent material may be composed of quantum dots so that there is no scattering of ambient light that otherwise would reduce contrast. Also, to preserve high quantum efficiency the quantum dots may have both an inorganic shell of inorganic material having a wide band gap such as zinc sulfide for a core QD of say a II-VI compound. In addition, there may be an organic capping material around the shell. In one embodiment, the QDs are attached to a polymer backbone, thus preserving a quantum efficiency of some 60% by preventing quenching through over-close proximity of the QDs. A further method is to maintain a state of dilute suspension within about 0.5 - 3 microns of polymer coating using say deposition within a photoresist material similar to patterning of color filters.

In one embodiment, surrounding the array of triad pixels forming the display 10 is a seal similar to those used in flat panel displays. Examples of sealants used to form the seal include epoxy adhesives. These adhesives are curable by UV and/or heat, and patterned by a dispensing gun or screen printing, to a thickness no greater than defined by the combination of the spacer and the baked photoresist on the opposing substrate. The width may be sufficient to withstand the long term ingress of water by diffusion. If necessary, desiccant materials may be incorporated similar to those used in organic light-emitting diodes to ensure dry conditions for maintaining particle charge. For examples, such materials include those from SAES Getters.

Referring now to Figure 14 of the drawings a further embodiment 110 of the PSD is shown schematically. In Figure 14, the same reference numerals used in Figures 1 and 2 have been used to indicate the same or similar components. One difference between the embodiments 110 and the embodiments described thus far is that the embodiment 110 includes a transparent conductive thin film 112 on the rear substrate 22 opposite to the planar electrode 26. In use the conductive thin film 112 creates a vertical electric field that can deflect the black particles laterally and help prevent their upward migration towards the rear substrate 22. In the embodiment 110 an insulating film coating 114 on the conductive thin film coating 112 prevents short circuits. The conducting film 112 is non-patterned and covers the rear substrate 22. In one embodiment the conductive thin film 112 is coated with a suitable polymer or inorganic insulating dielectric to avoid any dielectric breakdown relative to some + 27 V applied to the side spacer electrodes. The thickness of the insulating dielectric may be chosen to be only a few microns consistent with required dielectric breakdown strength but also permitting sufficient electric field within the cavity to deflect negatively charged black particles.

As an example, for a 14 micron high cavity (11 micron spacer, 3 micron insulator on the planar electrode) with the total split potential difference of – 54 V on the cover plate ITO, and -27 V on the transparent planar electrode respectively, assuming the dielectric coating over this additional conductive film 112 is thin and of sufficiently low dielectric constant but high dielectric strength, this should provide a force on particles charged to say 1fC, of approximately Eq = (54-27)/14) x 106 x 10-15 N = 1.92 nN. This can counteract the imaging force of 0.6 nN and estimated maximum Van der Waal's force of 1.26 nN. In practice, Van der Waal forces can be less, and also the spherical black particles can roll across electrodes towards the side electrode. However, the aforementioned additional thin film 112 is a safeguard for a wider margin of safety.

The conductive transparent film 112 may be inorganic such as indium tin oxide, aluminum doped zinc oxide or other doped and transparent semiconductors. For better flexing properties, the film 112 may also comprise organic semiconductors, carbon nanotubes, or small nanosize metal particles such as silver which also transparent due to their size. Several suppliers exist in the US for these materials including Nanogram Inc, and Eikos Inc. Only an electric field is required so the sheet resistance can be quite high up from say 100 to 1000 Ohms/sq, and hence corresponding high transmittance for optical throughput, say 90 to 95%.

The insulating film 114 over the conductive film 112 may comrprise an inorganic dielectric such as SiON or similar material having a high dielectric breakdown strength to withstand any possible breakdown versus the adjacent side electrodes. Some polymers may also be suitable at 3 - 4 microns thickness, or a flexible composite of polymer and inorganic films such as Barix films from Vitex Systems, Inc., San Jose, California.

In one embodiment, an unpatterned conductive film may be located on the exterior of the rear substrate but this would require much higher voltages creating cost and safety issues.

In one embodiment, an electret polymer may be used as the front or rear substrates. Alternatively, an electret coating may be applied to the front or the rear substrates. Still further, in one embodiment, an electret film may be laminated to either of the substrates.The electret polymer may be poled whilst near its melting point to impart permanent charge, and this can repel any like charged particles from adhering to a substrate. In one embodiment, poling includes the use of imposed high electric fields from electrodes or metal rollers, corona discharges or use of electron beams. Such material is supplied by Electret Developments Ltd. of Broadstairs, Kent, UK, and is used also by Matsushita for and others for microphones etc (US patent 5,536,982). These materials are very well known to those skilled in the art e.g. Ref. 9th International Symposium on Electrets, vol. 25-30 Sept 1996, ISE 9. PET is used extensively, but also PEN [poly(ethylene naphthalene-2,6-dicarboxylate)] for even better charge stability.

In one embodiment, split voltages may be used to achieve lower operating voltages across the planar and side electrodes of the device. This may be done symmetrically or asymmetrically to allow better matching to lower voltage driver ICs. Examples include +22 V, -22 V or + 27 V, -22 V. Ideally, the maximum voltage is up to + 30 V, -30 V.

Referring now to Figure 15 of the drawing, there is shown an exemplary process for fabricating the reflective PSD described above. The process begins with glass for the front and rear substrate. The process steps for the rear substrate are indicated by reference numerals 120 to 130, whereas the process steps for the front substrate are indicated by reference numerals 132-138. In process 140, the front and rear substrates are assembled and cured. Each substrate requires deposition of thin film electrodes. These include metals such as aluminum for the rows, and a conductive transparent film such as indium tin oxide (ITO) for the columns, deposited by vacuum deposition on either glass substrate. Such films, their deposition and patterning by photolithography are standard practice for the manufacture of flat panel displays (FPDs) with techniques well known to those skilled in the art.

In one embodiment the 3 to 4 micron insulating layer separating the transparent planar electrodes from the side electrodes may be fabricated using standard photoresists that are suitably patterned. In one embodiment, for the fabrication of the insulating layer includes a baking step that is extra long and/or performed at higher temperature is performed to ensure a harder film capable of withstanding electrical breakdown.

PSD spacers may be 11 - 22 microns wide depending on the required aperture transmission, and must withstand a maximum of +50V, -50 V for on and off neighboring pixels. Thus, the PSD spacers must withstand at maximum of say 100/11 x 104 V/cm i.e. 0.09 x 106 V/cm so the above data suggests this is quite possible. With optimized materials and configurations, voltage should come down to only about +30 V, -15 V and so then 0.041 X 106 V/cm will be sufficient.

In one embodiment, it is desirable that a dielectric insulator extends sufficiently over the planar electrode to avoid breakdown of the gas in the cavity. The possibility of gas breakdown is greatly reduced due to the Paschen effect. Some 25 to +25 V potential difference is needed to move the particles furthest away from the side electrodes at about 19 microns (2.6 V/micron).

Thus, the dielectric should protrude horizontally away from the spacer. If this protrusion is 2 microns, then for a 3 micron thick dielectric, 5 microns is the shortest path from the planar electrode to the side electrode. At 50 V this would give a field of 10V/micron which is below the

17 V/ micron breakdown of gas following Paschen's Law (a graph of breakdown voltage against the product of pressure and distance).

If there are any sharp edges or dust particles these might intensify the field by say x 2 to give 20V/micron. In that case, the dielectric thickness and protruding distance would need to increase by x 20/17 = 1.17 x i.e. to 3.5 micron thickness and protruding 2.3 microns. Encapsulation in carbon monoxide would also increase the breakdown strength to 4V/micron.

Figure 16 of the drawings illustrates an exemplary process flow for manufacturing the transmissive embodiment of the PSD. The process steps for the rear substrate are indicated by reference numerals 142 to 156, whereas the process steps for the front substrate are indicated by reference numerals 158 to 164. In process 166, the front and rear substrates are assembled and cured.

As previously noted the PSDs of the present invention may comprise an insulator 38 e.g. of baked photoresist of about 3 to 4 microns thick located on the transparent planar electrode isolating it from the side electrode. In one embodiment, the insulator 38 may comprise gaps or recesses 168 (see Figure 17) some 2 microns wide to allow cavity access to desiccants for removing any water from reaching the sub-pixel cavities near the periphery.

Advantageously, in one embodiment the insulators 38 may be patterned to interlock mechanically with the spacers in a snap fit. In one embodiment, a thermoplastic seal may be formed on the mating surfaces between the insulators 38 and the spacers. A further alternative is to have a slight curve on a relatively rigid substrate that flattens out when sealed with epoxy at the edges and thus keeps pressed against the opposing surface.

Particle deposition may be performed in various ways to produce the ideal of two monolayers:

1) Electrostatic attraction from a dust cloud (aerosol dispersion). This may be combined with tribo-charging using a paddle stirrer and container made of suitable materials to impart the desired polarity and amount of charge defined by work functions of such materials, length of time for the dispersion and speed of rotation. Thus, say a positive charge may be given to acrylic particles and so a negative charge on the substrate can attract the positive particles to form the two monolayers. Alternatively, negative charge may be given to the particles in which case a positive polarity is needed for the substrate electrode. A method of attracting tribo-charged particles onto a surface is taught in US Patent 4,780,331. Professor T.B. Jones at the University of Rochester has described a means of paddle charging on the Internet at www.ece.rochester.edu/~jones/demos/powder.html

2) Electrostatic spray coating using a stream of propelled particles past a corona discharge and onto the conductive electrodes held at ground potential. This is standard industrial practice for coating paint particles onto metal surfaces such as in the manufacture of cars. Techniques are mentioned by manufacturers of such equipment such as Jotun, and in patents such as US 5,585,426.

3) Alternatively, a vacuum can suck in particles creating shear forces to prevent aggregation and allow the formation of two monolayers which can then be charged after deposition by a corona

discharge. A suitable vacuum machine for such deposition of particles is the PD-10 made by Ankersmid, and for which the opaque black layers were obtained using the monodispersed 2.8 micron diameter acrylic particles.

4) Another method is to allow upward vertical electrophoretic deposition from a suspension of charged particles in a liquid and then allow the liquid to drain away and evaporate. This has been done for deposition of 1-3 micron diameter phosphor particles as two monolayers and is a known technique for those skilled in the art of CRT, FED and VFD manufacture. For instance: "Photolithographic Patterning of Phosphors Screen by Electrophoretic Deposition for Field Emission Display" Sang Won Kang et al Vacuum Microelectronics Conference, 1997. Technical Digest., 1997 10th International Volume , Issue , 17-21 Aug 1997 Page(s):682 - 686. See also inclusion in article on phosphor screening at http://www.ddc-co.com/articles/39%20-%20Phosphor%20Screening.pdf

Ideally, the particles are insulating polymers, and may be produced by polymerization of a monomer emulsion. Such particles can have a narrow distribution of particle size and are available from Japanese companies such as Sekisui Plastics, Zeon Chemicals, Soken Chemical and Engineering Co. Ltd. via Esprix Technologies.

The particles used to obscure or open the shutter may be electrostatically charged using the means mentioned in the description of their deposition. Various types of corona systems are also well known by those skilled in the photocopying industry and include Scorotrons, AC and DC coronas.

The level of charge should be in the range of about 0.5 to 1.5 femto Coulombs per particle, corresponding to some 37 to 150 micro Coulombs per gram for acrylic polymer particles. Preferably, this is 1 femto Coulomb per particle, equivalent to 0.0256 micro Coulombs per sq cm on the substrate.

For greater ease of acquiring and maintaining this charge, the particles should be insulating with high resistivity over 10^{10} Ohm cm, and contain or have a surface coating of charge control agents (CCAs) and./or stabilizing chemicals. Such materials are well known in the photocopying industry and for electrophoretic displays. They are supplied by various companies including Orient Chemicals in Japan, Hubei Dinglong Chemical Co. in Wuhan, China, and reference also E.Michel of Clariant GmbH in J.Electrostatics, 51-52 (2001) pages 91-96.

Particles and their treatment to optimize charging are mentioned in the scientific literature for electrophoretic displays such as Dong-Guk Yu et al, J.Polymer Science, Part A: Polymer Chemistry, Vol. 42, 5608-5616 (2004). Also, mention is made for such displays by J.Hou et al in SID 01 Digest, pages 164-167.

The deposition of colored patterns of reflecting and fluorescent materials for the layer 24 (or filter in the case of white backlighting) may be accomplished in several ways, using known basic processes and commercially available equipment. Pigment particles may include additive types as taught in US Patent 6,517,627, or reflective filters as in US Patent 6,919,151. A holographic flake pigment is disclosed in US Patent 5,415,950. Others are mentioned in US 5,885,752 by Fuji

Pigment Co., Ltd. One method uses patterned laser light to change pigment color as disclosed in US Patent 4,861,620.

1) Printing using ink jet, screen printing or pad printing. The use of ink jet printing has been established as common practice for use in ink jet printers for computers, and now also for deposition of organic light-emitting films to make organic light-emitting diodes, especially at Litrex Corp, Pleasanton, CA, and Seiko-Epsom. Screen printing of OLEDs is known also at Add Vision, Inc., California, but in general screen printing lacks high resolution for smaller displays.

However, pad printing is capable of high resolution and is a common method for printing images even on non flat surfaces. Suppliers include TOSH S.r.l of Italy via Innovative Marketing Systems, Inc. of Massachusetts; another is ITW Imtran also in Massachusetts.

2) Electrophoretic or electrostatic deposition techniques are well known for depositing particles as mentioned as one method of depositing the black particles. Pigment particles for the colored reflector can be deposited also by this means and has the advantage of self alignment onto a conductive electrode. Electrodeposition techniques are known in the industry as taught in US Patents 5,674,369 and 5,917,566 by Sumitomo Chemical Co. Ltd. Other suppliers include Shinto Chemitron. Suppliers of display coloring materials include Dai Nippon Printing and Torray in Japan.

While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative and not restrictive of the broad invention and that this invention is not limited to the specific constructions and arrangements shown and described, since various other modifications may occur to those ordinarily skilled in the art upon studying this disclosure. In an area of technology such as this, where growth is fast and further advancements are not easily foreseen, the disclosed embodiments may be readily modifiable in arrangement and detail as facilitated by enabling technological advancements without departing from the principals of the present disclosure.

CLAIMS:

1. A particle shutter device, comprising:

    a color generating material;

    a transparent planar electrode positioned coaxial with the color generating material; and

    side electrodes positioned in relation to the transparent planar electrode, the device having an off-state wherein black particles obscure the transparent planar electrode to prevent a passage of light through the transparent planar electrode and an on-state wherein the black particles are laterally displaced relative to the transparent electrode under electrostatic forces to allow the a passage of light through the transparent planar electrode.

2. The particle shutter device of claim 1, wherein the side electrodes have an axis that is transverse to the transparent planar electrode, and in the on-state the black particles form at least one monolayer extending along the axis.

3. The particle shutter device of claim 1, wherein the color generating material in on a rear substrate and the transparent planar electrode is on a front substrate, the two substrates and the side electrodes together defining a cavity which is gas-filled and contains the black particles, the device further comprising a conductor on the rear substrate to generate an electric field that pushes the black particles towards the side electrodes when in the on-state.

4. The particle shutter device of claim 3, wherein the side electrodes are electrically insulated from the transparent planar electrode by an insulator that extends laterally partly into the cavity.

5. The particle shutter device of claim 4, wherein the insulator comprises recesses to allow the ingress of a desiccant into the cavity.

6. The particle shutter of claim 1, wherein the transparent planar electrode and the side electrodes are coplanar.

7. The particle shutter device of claim 6, wherein the on-state the black particles reside on a top surface of the side electrodes.

8. The particle shutter device of claim 1, wherein the side electrodes comprise a core of insulating material and conductive sides.

9. The particle shutter device of claim 1, wherein the side electrodes have corrugations to increase a surface area thereof.

10. The particle shutter device of claim 1, wherein the side electrodes have a snake-like profile.

11. The particle shutter device of claim 1, further comprising a back light assembly to illuminate the color generating material.

12. The particle shutter device of claim 1, wherein the color generating material is selected from the group consisting on nanophosphors and quantum dots.

13. A display, comprising:

a plurality of pixels, each comprising three sub-pixels, wherein each sub-pixel corresponds to a primary color and is defined by a particle shutter device comprising a color generating material; a transparent planar electrode positioned coaxial with the color generating material; and side electrodes positioned in relation to the transparent planar electrode, the device having an off-state wherein black particles obscure the transparent planar electrode to prevent a passage of light through the transparent planar electrode and an on-state wherein the black particles are laterally displaced relative to the transparent electrode under electrostatic forces to allow the a passage of light through the transparent planar electrode; and

a driving mechanism to selectively energize the transparent planar electrodes and the side electrodes.

14. The display of claim 13, wherein the side electrodes have an axis that is transverse to the transparent planar electrode, and in the on-state the black particles form at least one monolayer extending along that axis.

15. The display of claim 13, wherein the color generating material is on a rear substrate and the transparent planar electrode is on a front substrate, the two substrates and the side electrodes together defining a cavity which is gas-filled and contains the black particles, the device further comprising a conductor on the rear substrate to generate an electric field that pushes the black particles towards the side electrodes when in the on-state.

16. The display of claim 15, wherein the side electrodes are electrically insulated from the transparent planar electrode by an insulator that extends laterally partly into the cavity.

17. The display of claim 16, wherein the insulator comprises recesses to allow the ingress of a desiccant into the cavity.

18. The display of claim 13, wherein the transparent planar electrode and the side electrodes are coplanar.

19. The particle shutter device of claim 6, wherein the on-state the black particles reside on a top surface of the side electrodes.

20. The particle shutter device of claim 1, wherein the side electrodes and the planar counter electrodes are inter-digitated.

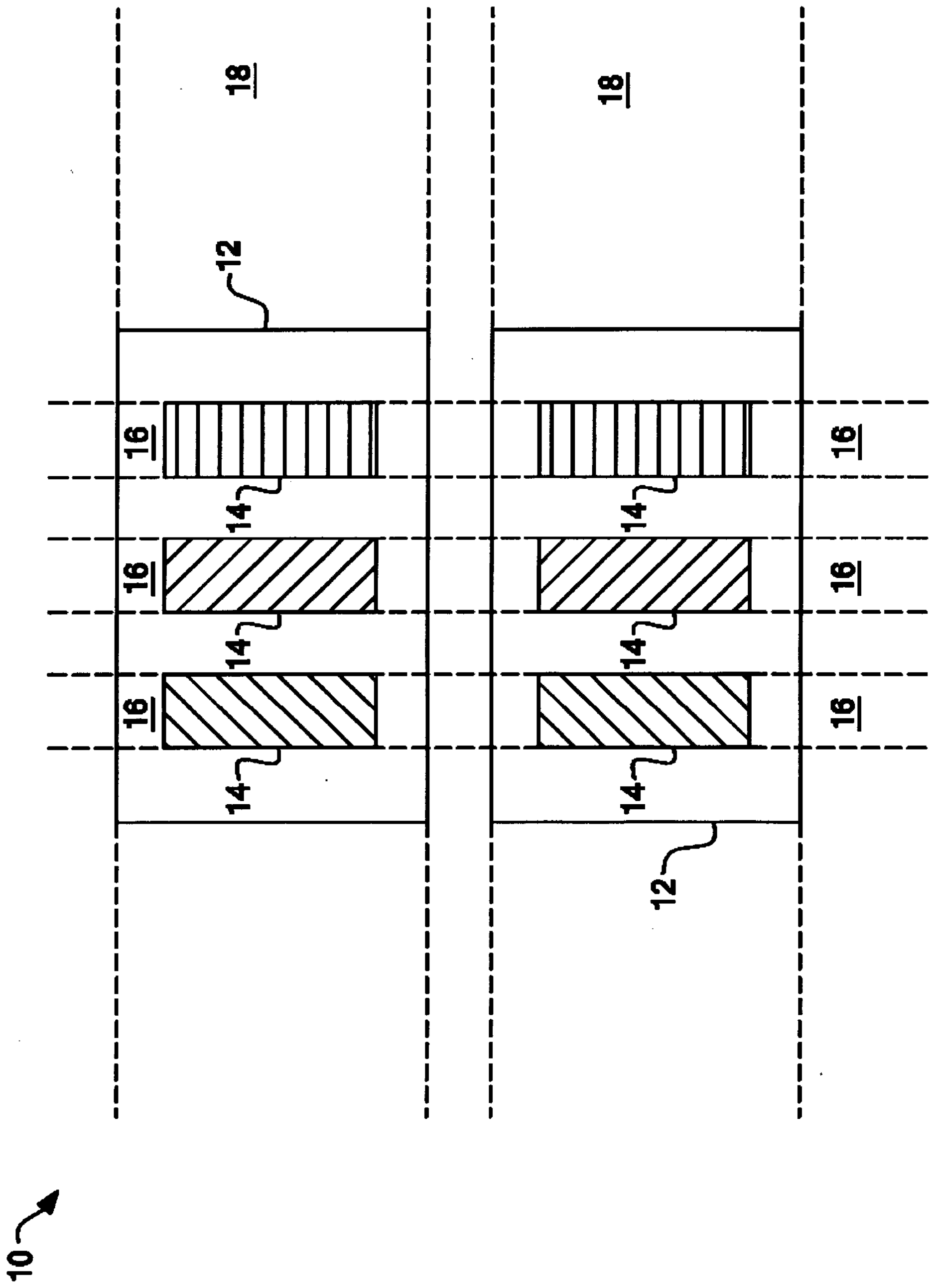


FIGURE 1

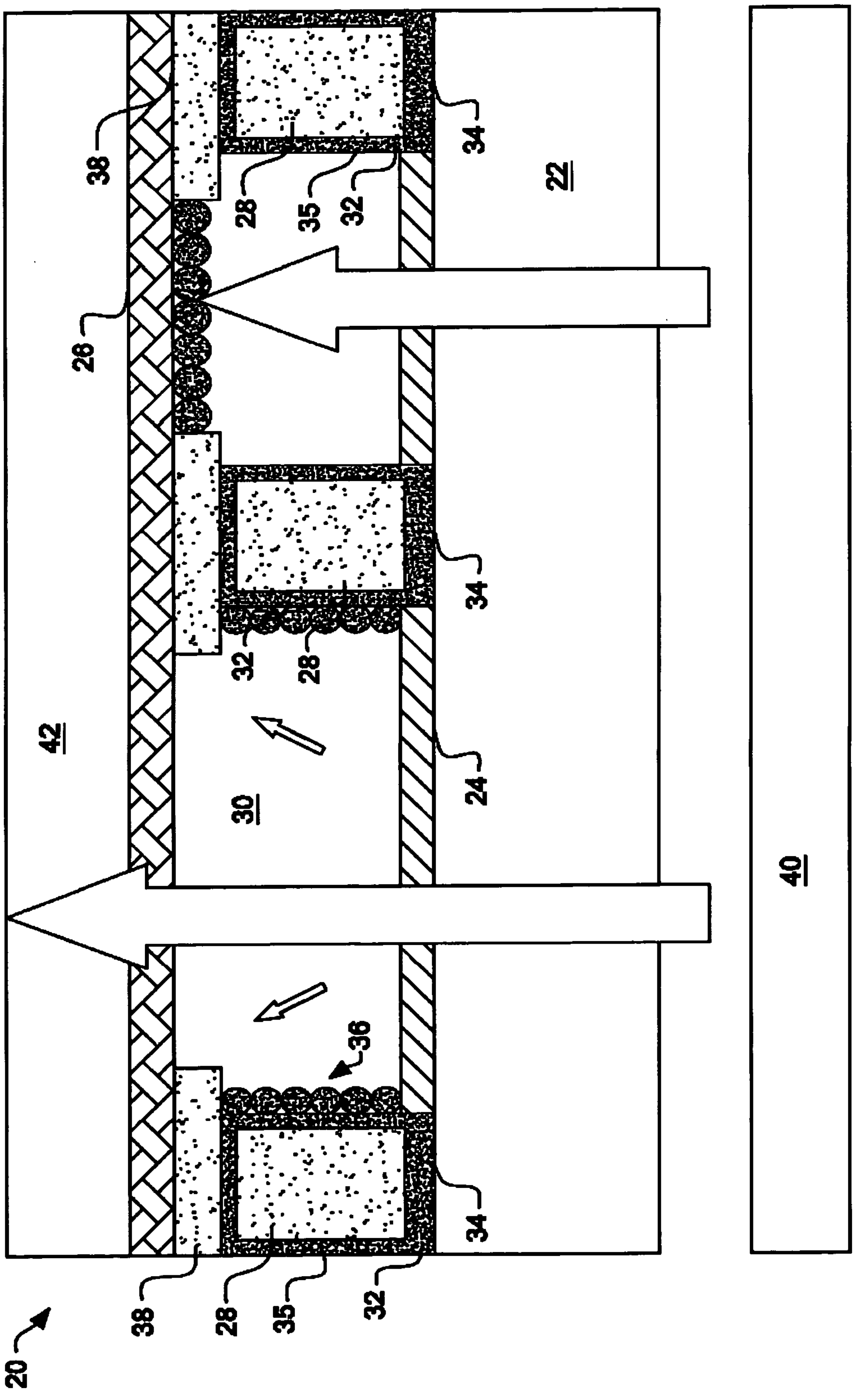


FIGURE 2

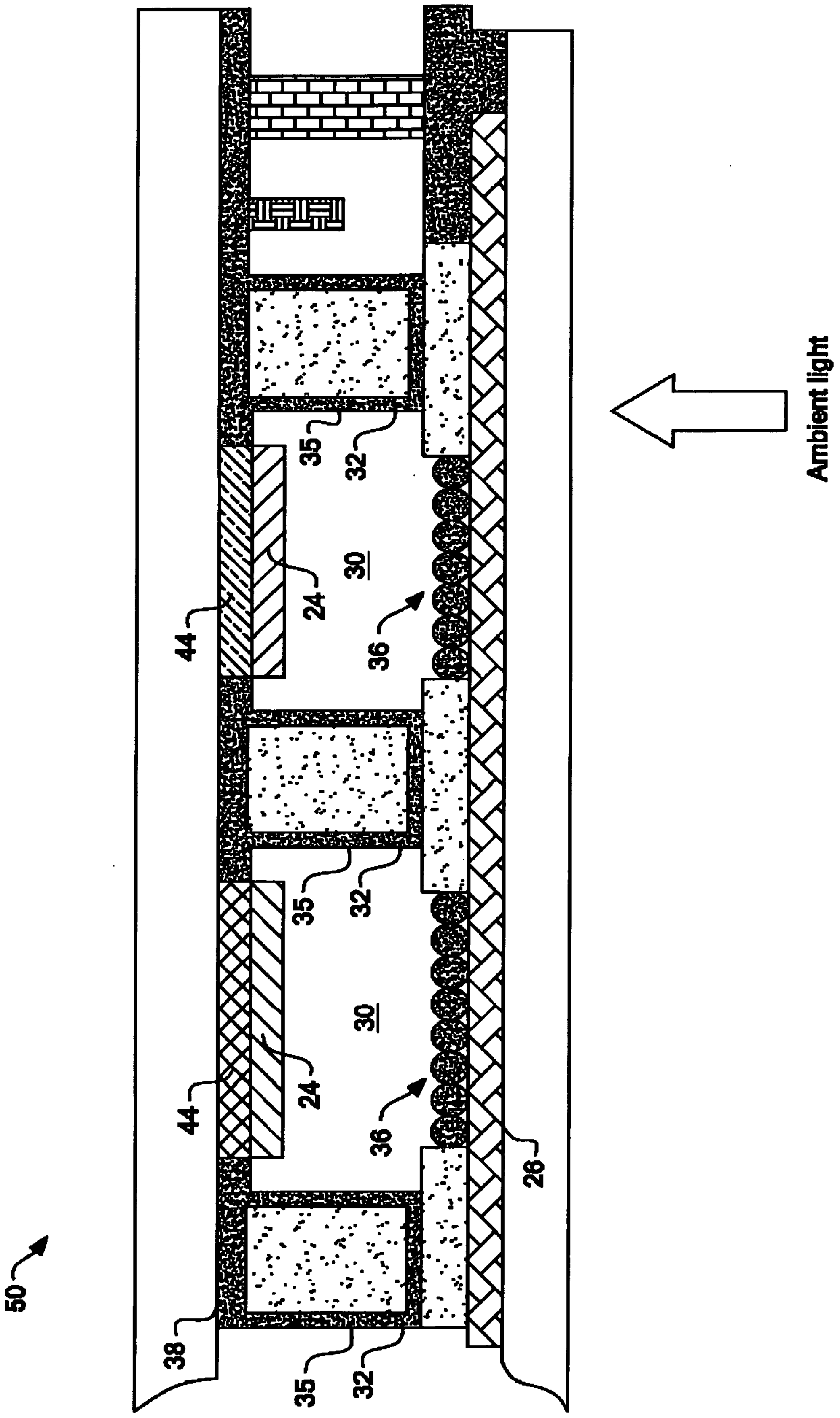


FIGURE 3

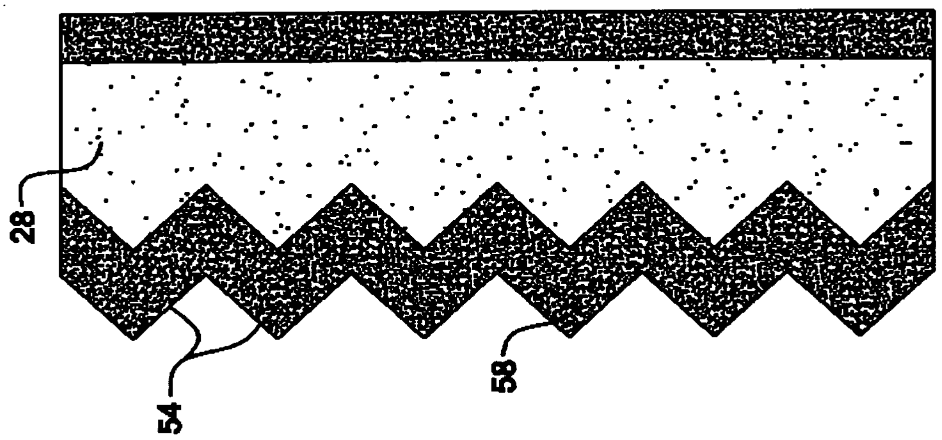


FIGURE 4

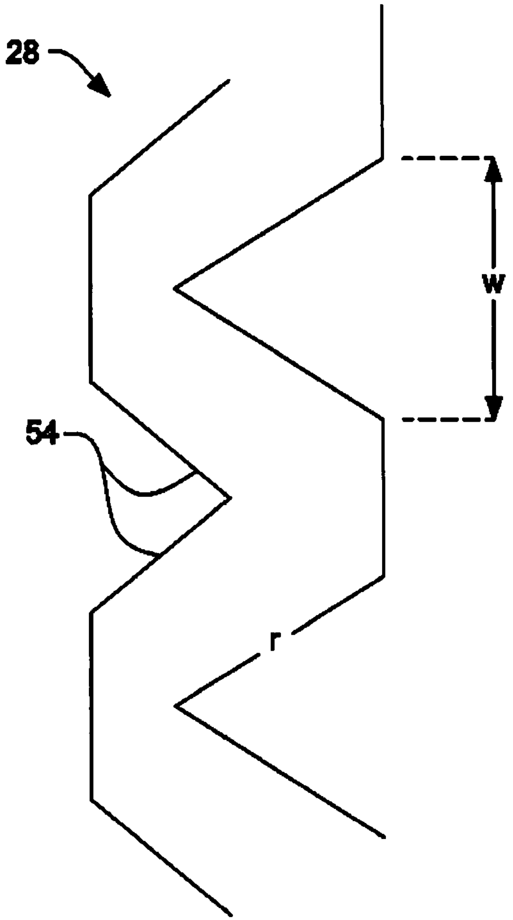


FIGURE 5

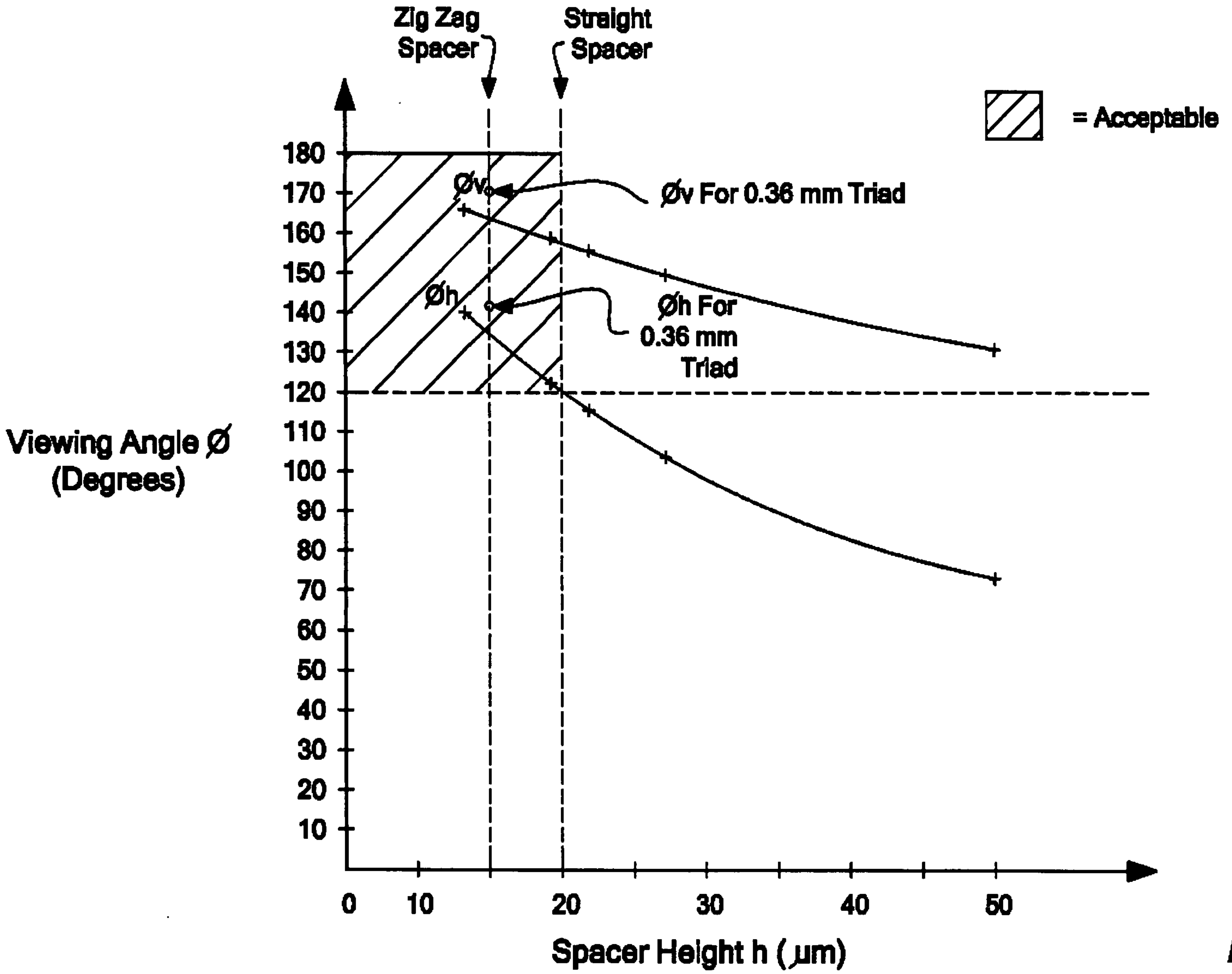

Zig Zag Spacer
Straight Spacer
▨ = Acceptable
Øv
Øv For 0.36 mm Triad
Øh
Øh For 0.36 mm Triad
Viewing Angle Ø (Degrees)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
Spacer Height h (µm)

FIGURE 6

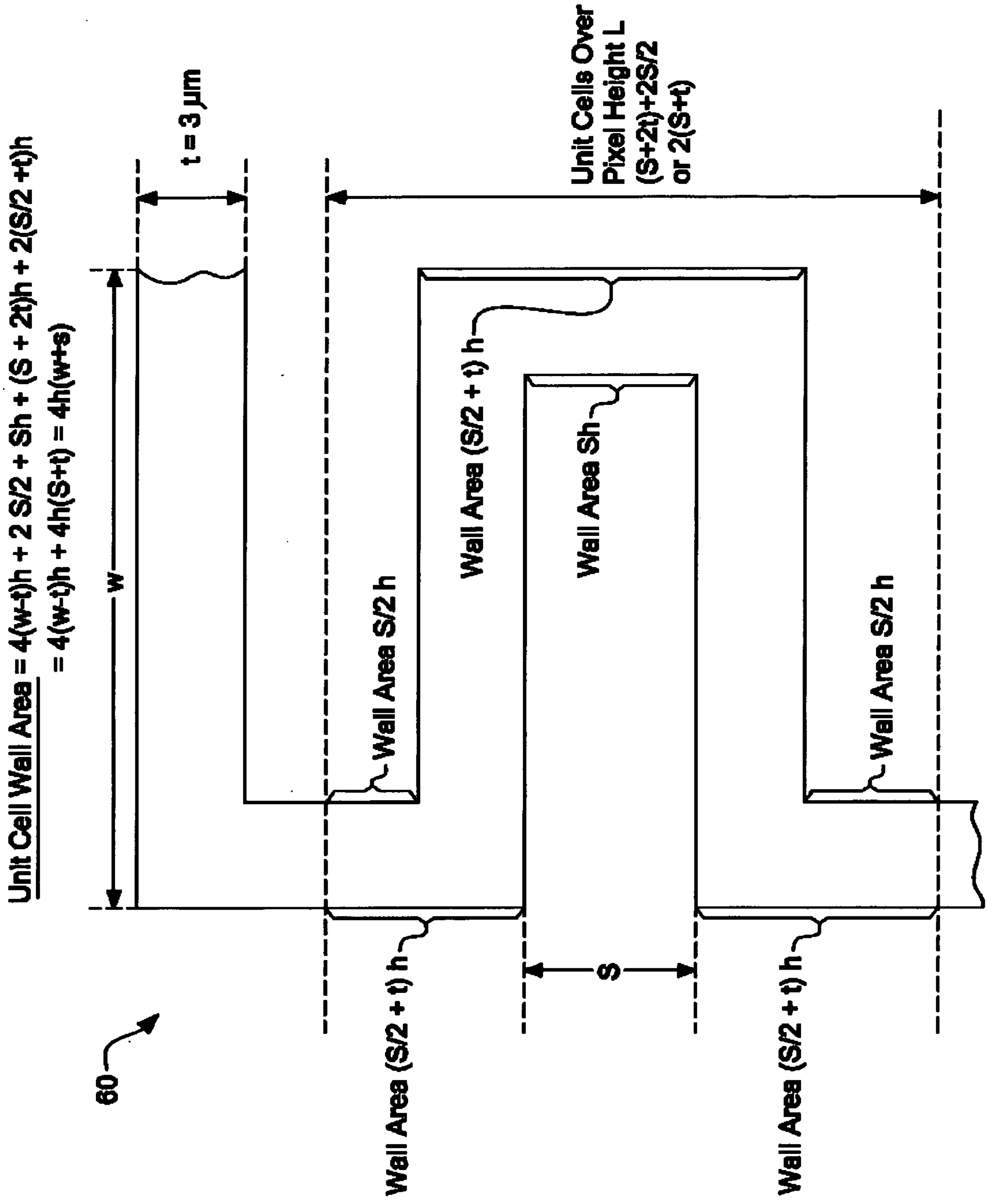

Unit Cell Wall Area = 4(w-t)h + 2 S/2 + Sh + (S + 2t)h + 2(S/2 +t)h
= 4(w-t)h + 4h(S+t) = 4h(w+s)
t = 3 µm
w
Unit Cells Over Pixel Height L (S+2t)+2S/2 or 2(S+t)
Wall Area (S/2 + t) h
Wall Area Sh
Wall Area S/2 h
Wall Area S/2 h
Wall Area (S/2 + t) h
Wall Area (S/2 + t) h
S
60

FIGURE 7

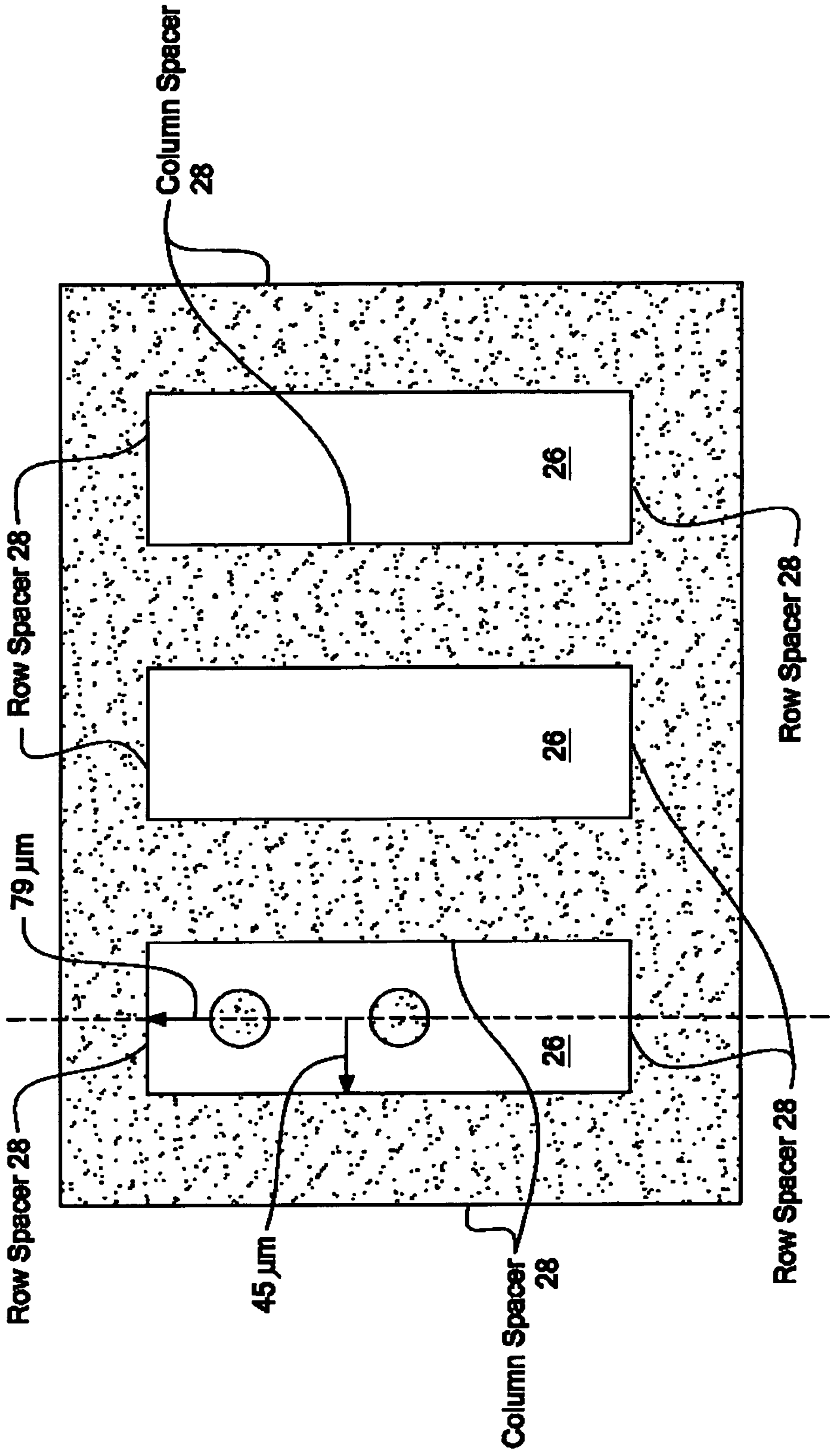

Column Spacer 28
Row Spacer 28
Row Spacer 28
79 µm
Row Spacer 28
45 µm
Column Spacer 28
26
26
26
Row Spacer 28
Row Spacer 28

FIGURE 8

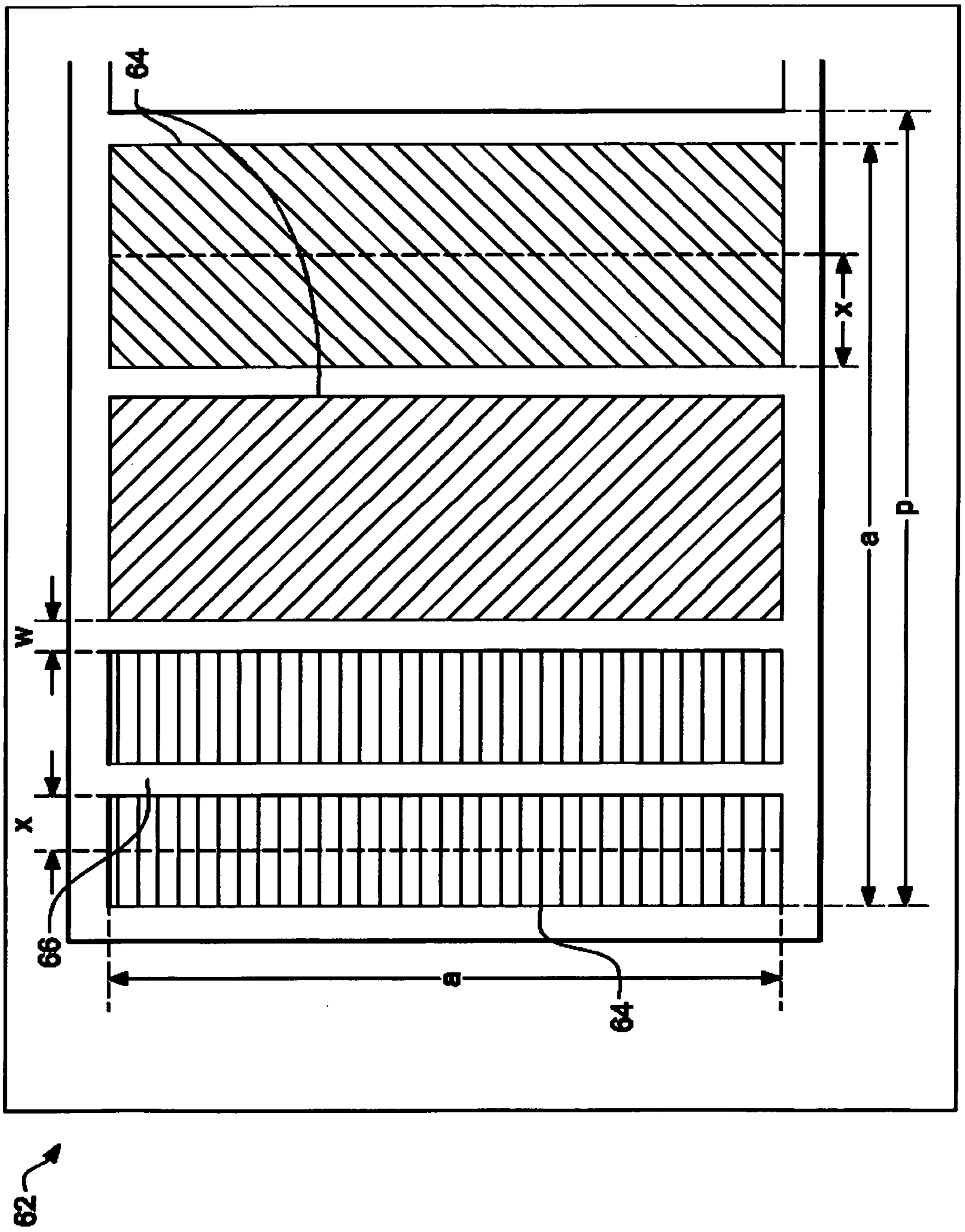


FIGURE 9

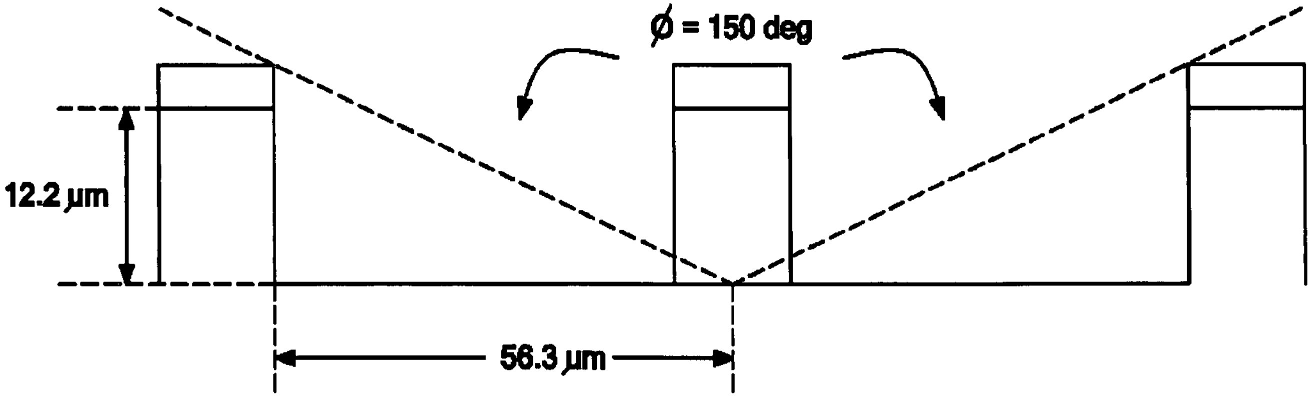
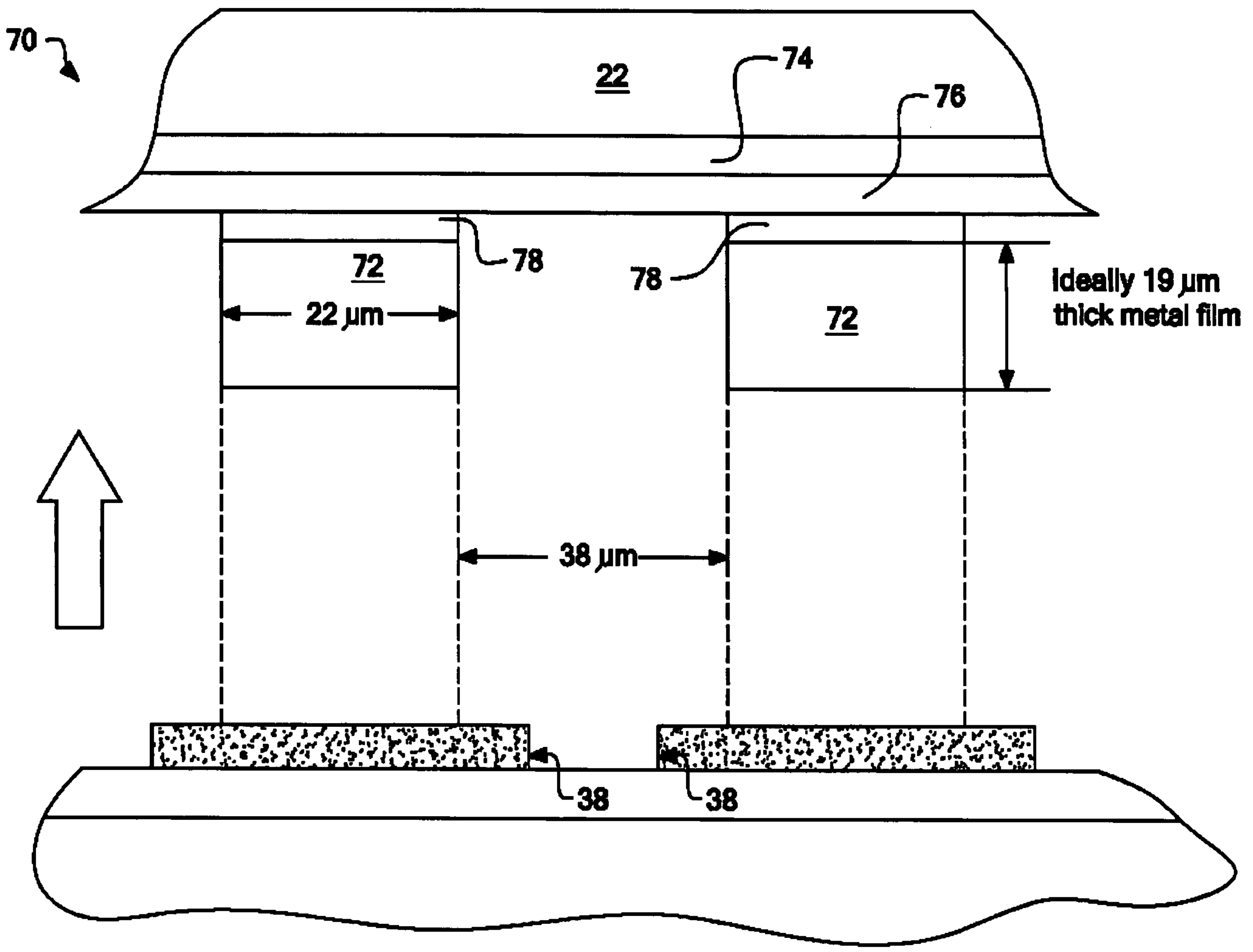


FIGURE 10



Bring substrates together & seal with epoxy at 5 mm wide edge (after device is filled).

FIGURE 11

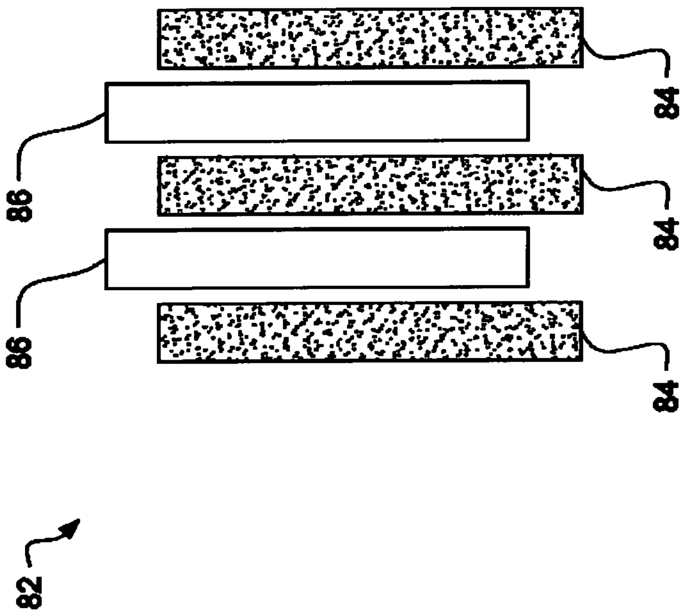


FIGURE 12

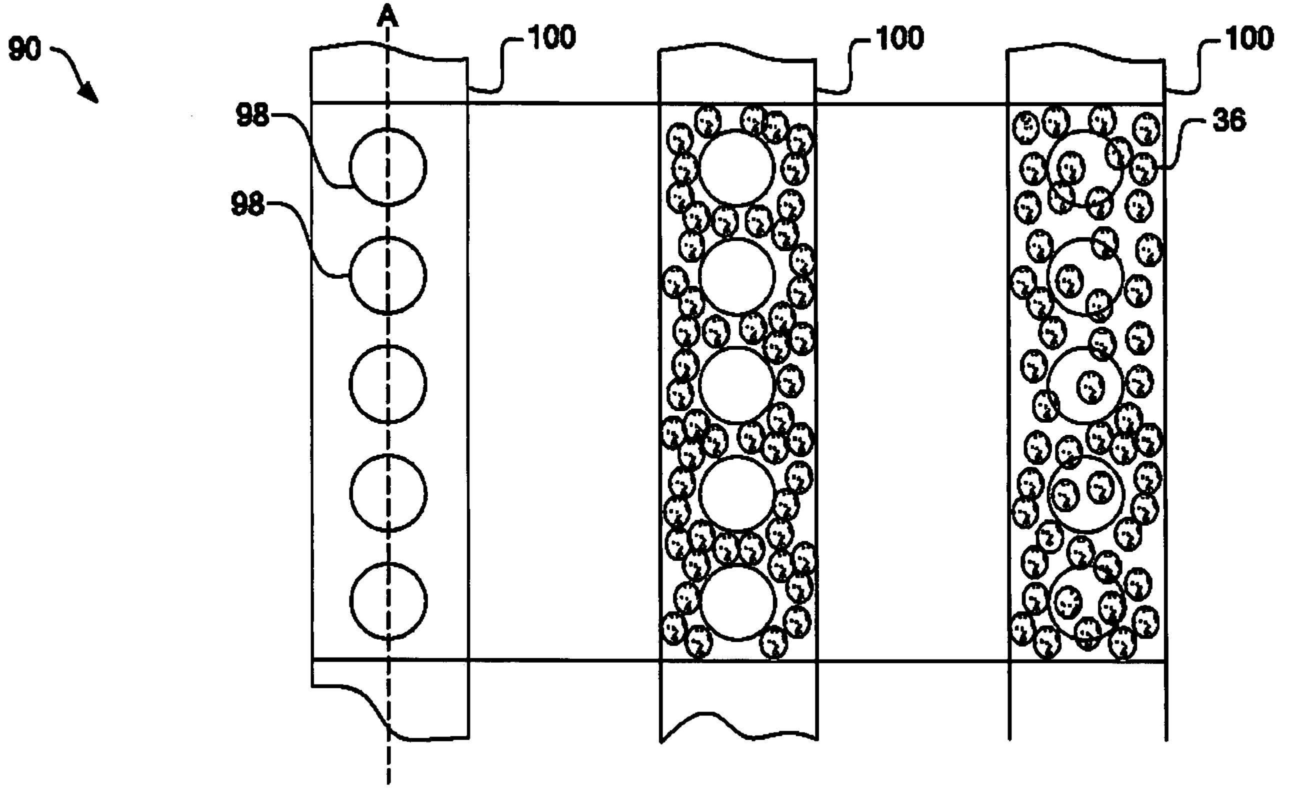


FIGURE 13A

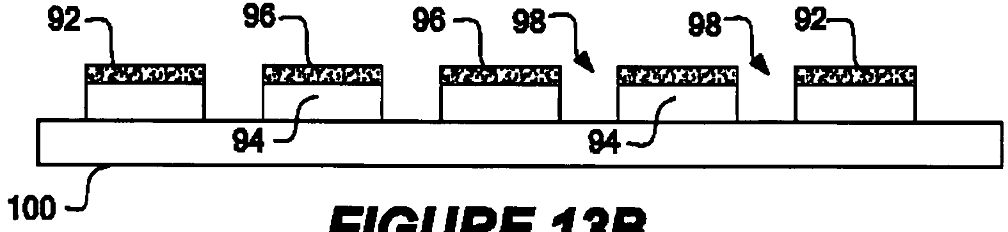


FIGURE 13B

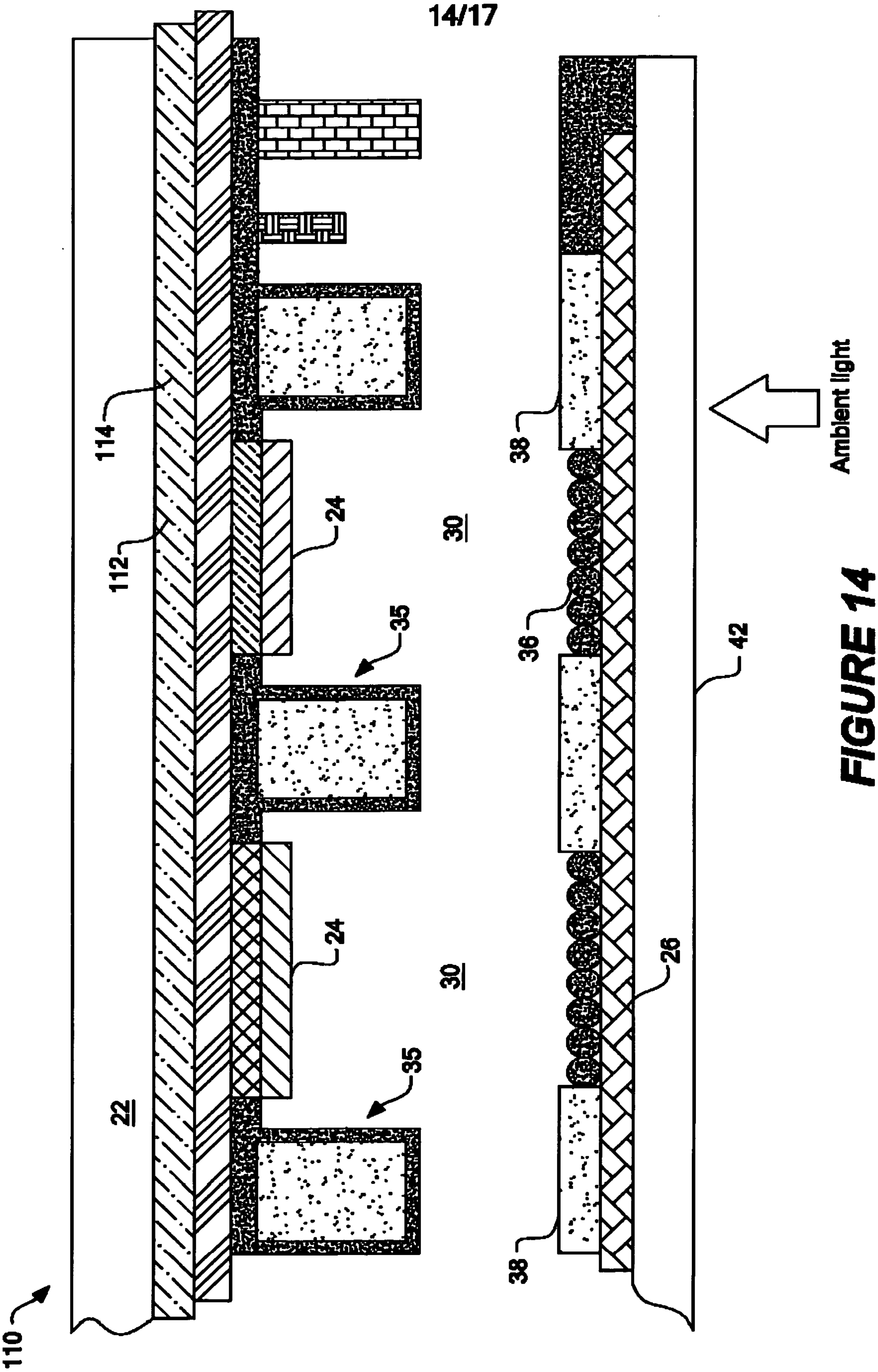


FIGURE 14

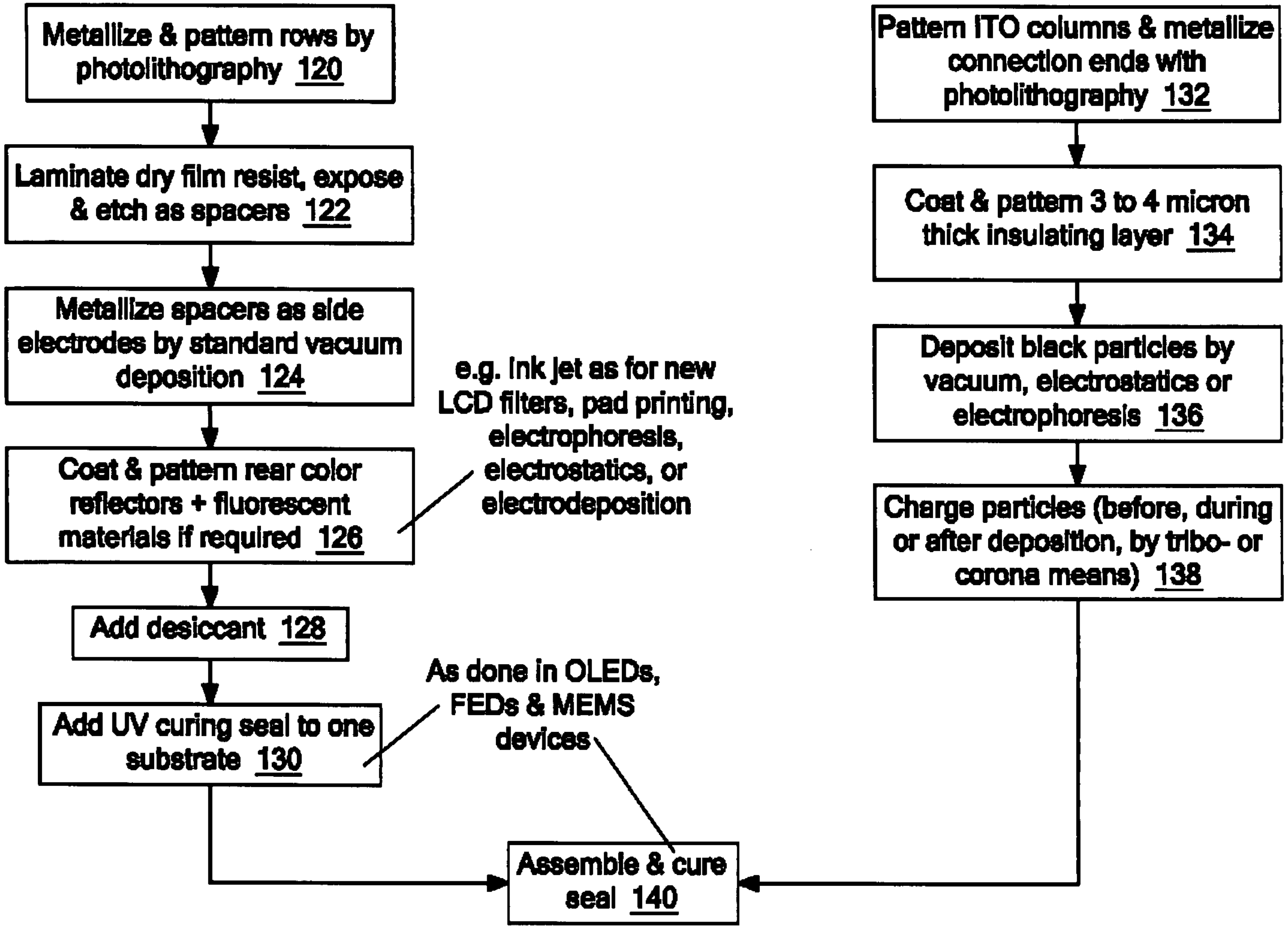

Metallize & pattern rows by photolithography 120
Laminate dry film resist, expose & etch as spacers 122
Metallize spacers as side electrodes by standard vacuum deposition 124
Coat & pattern rear color reflectors + fluorescent materials if required 126
Add desiccant 128
Add UV curing seal to one substrate 130
e.g. Ink jet as for new LCD filters, pad printing, electrophoresis, electrostatics, or electrodeposition
As done in OLEDs, FEDs & MEMS devices
Pattern ITO columns & metallize connection ends with photolithography 132
Coat & pattern 3 to 4 micron thick insulating layer 134
Deposit black particles by vacuum, electrostatics or electrophoresis 136
Charge particles (before, during or after deposition, by tribo- or corona means) 138
Assemble & cure seal 140

FIGURE 15

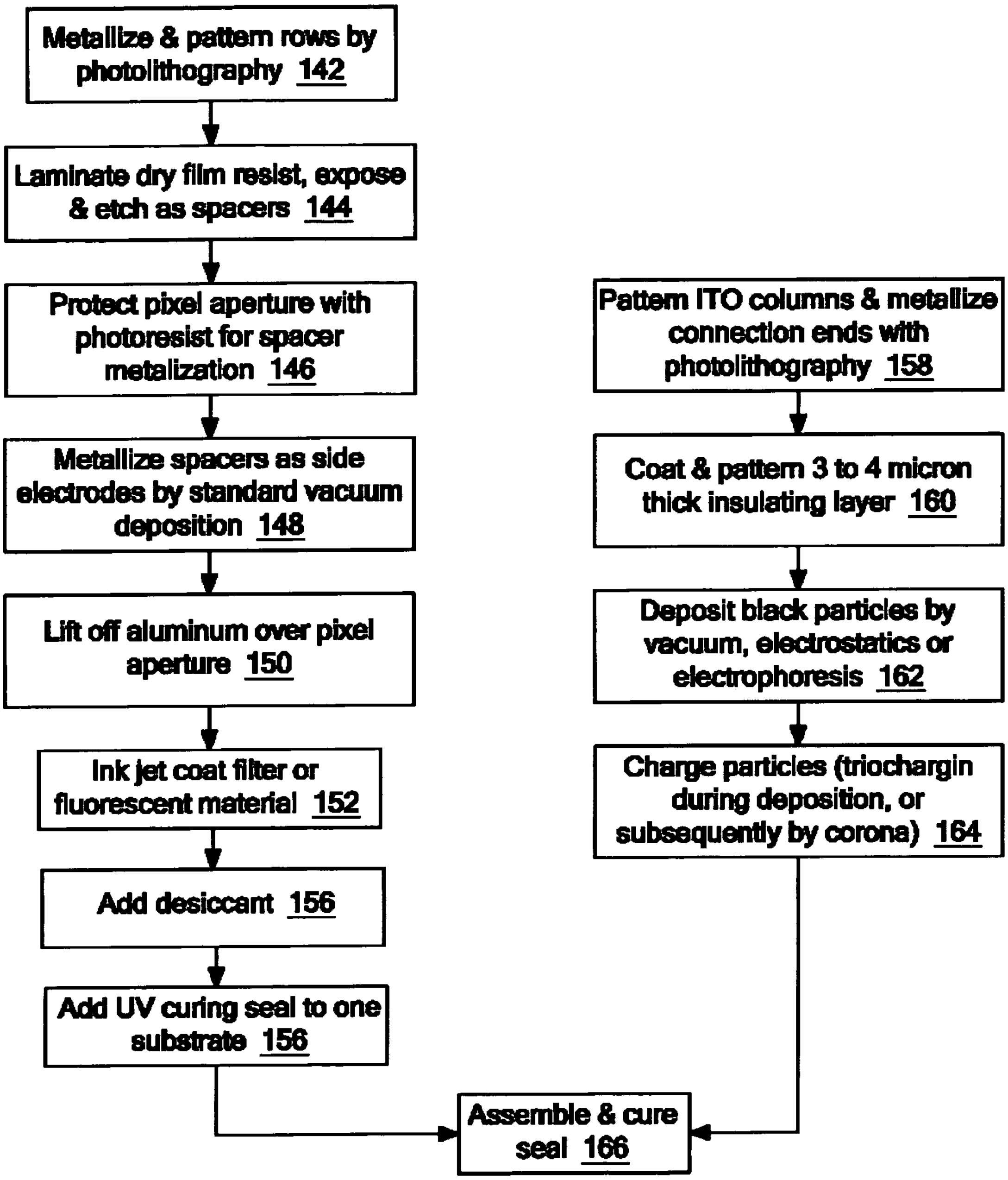

Metallize & pattern rows by photolithography 142
Laminate dry film resist, expose & etch as spacers 144
Protect pixel aperture with photoresist for spacer metalization 146
Metallize spacers as side electrodes by standard vacuum deposition 148
Lift off aluminum over pixel aperture 150
Ink jet coat filter or fluorescent material 152
Add desiccant 156
Add UV curing seal to one substrate 156
Pattern ITO columns & metallize connection ends with photolithography 158
Coat & pattern 3 to 4 micron thick insulating layer 160
Deposit black particles by vacuum, electrostatics or electrophoresis 162
Charge particles (triochargin during deposition, or subsequently by corona) 164
Assemble & cure seal 166

FIGURE 16

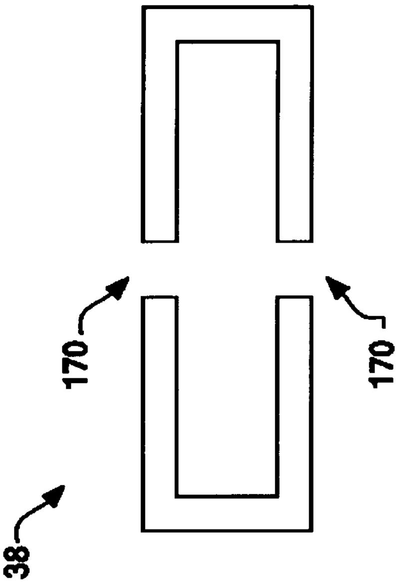


FIGURE 17