US009627463B2

(12) **United States Patent**
Kwon et al.

(10) **Patent No.: US 9,627,463 B2**
(45) **Date of Patent: Apr. 18, 2017**

(54) **FLEXIBLE DISPLAY DEVICE WITH SPACE REDUCING WIRE CONFIGURATION**

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(73) Assignee: **LG Display Co., Ltd.**, Seoul (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/556,087**

(22) Filed: **Nov. 28, 2014**

(65) **Prior Publication Data**

US 2016/0155788 A1 Jun. 2, 2016

(51) **Int. Cl.**
H01L 27/32 (2006.01)
H01L 51/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 27/3276*** (2013.01); ***H01L 27/3258*** (2013.01); ***H01L 51/0097*** (2013.01)

(58) **Field of Classification Search**
CPC H01L 27/3276; H01L 51/0097
See application file for complete search history.

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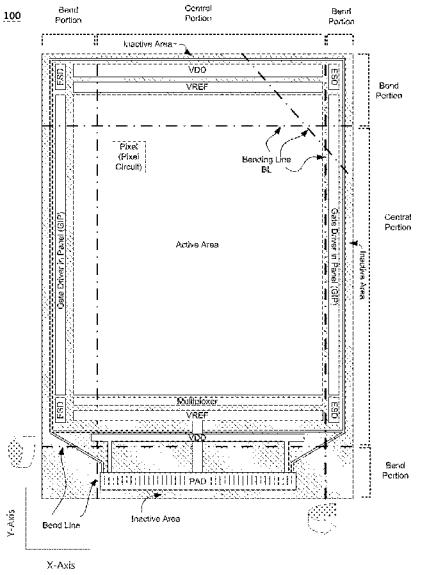
(74) *Attorney, Agent, or Firm* — Fenwick & West LLP

(57) **ABSTRACT**

There is provided a flexible display having a plurality of innovations configured to allow bending of a portion or portions to reduce apparent border size and/or utilize the side surface of an assembled flexible display.

13 Claims, 20 Drawing Sheets



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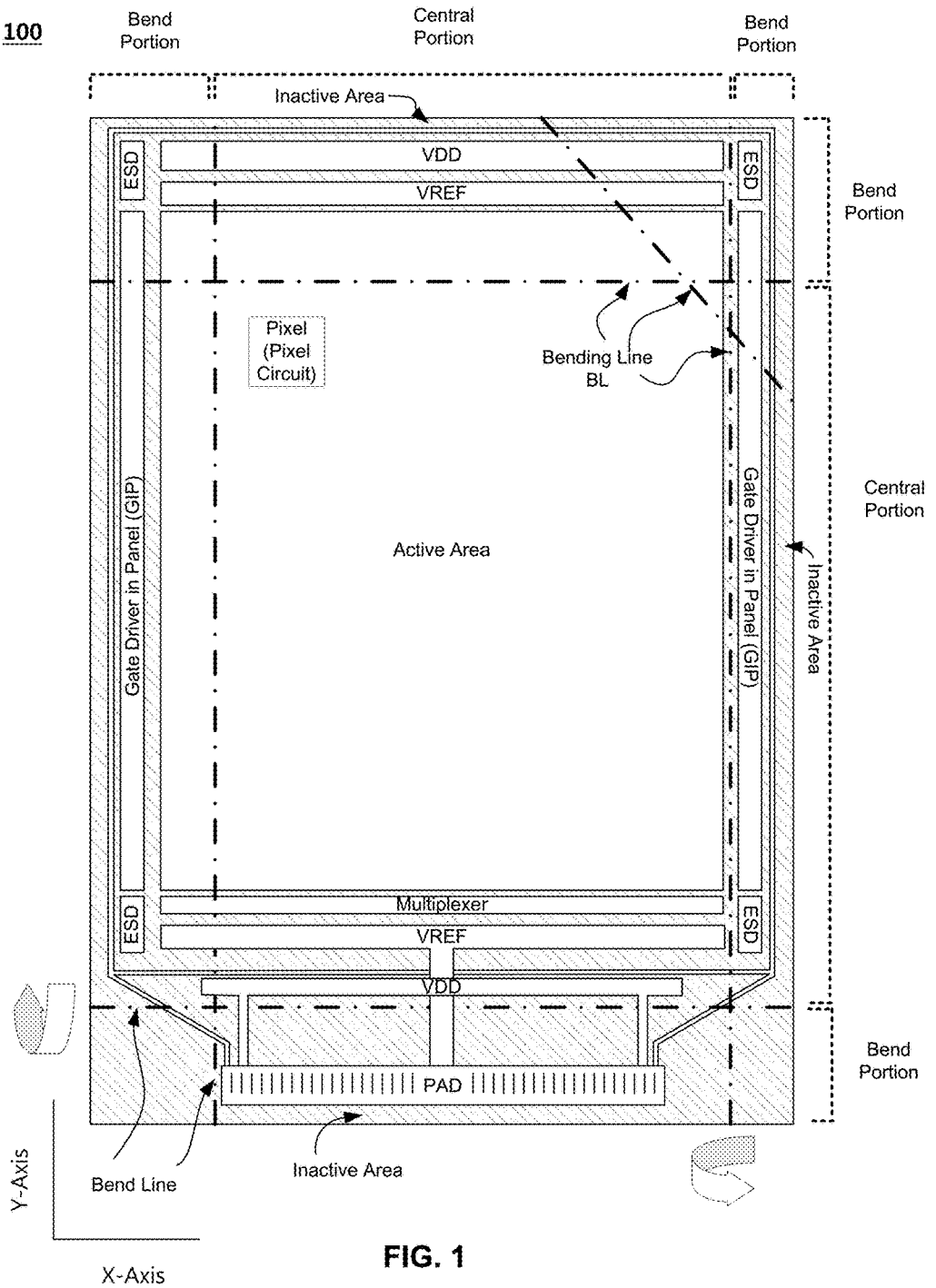
100
Bend Portion
Central Portion
Bend Portion
Inactive Area
ESD
VDD
VREF
ESD
Bend Portion
Pixel (Pixel Circuit)
Bending Line BL
Gate Driver in Panel (GIP)
Active Area
Gate Driver in Panel (GIP)
Central Portion
Inactive Area
ESD
Multiplexer
VREF
ESD
VDD
PAD
Bend Portion
Bend Line
Inactive Area
Y-Axis
X-Axis

FIG. 1

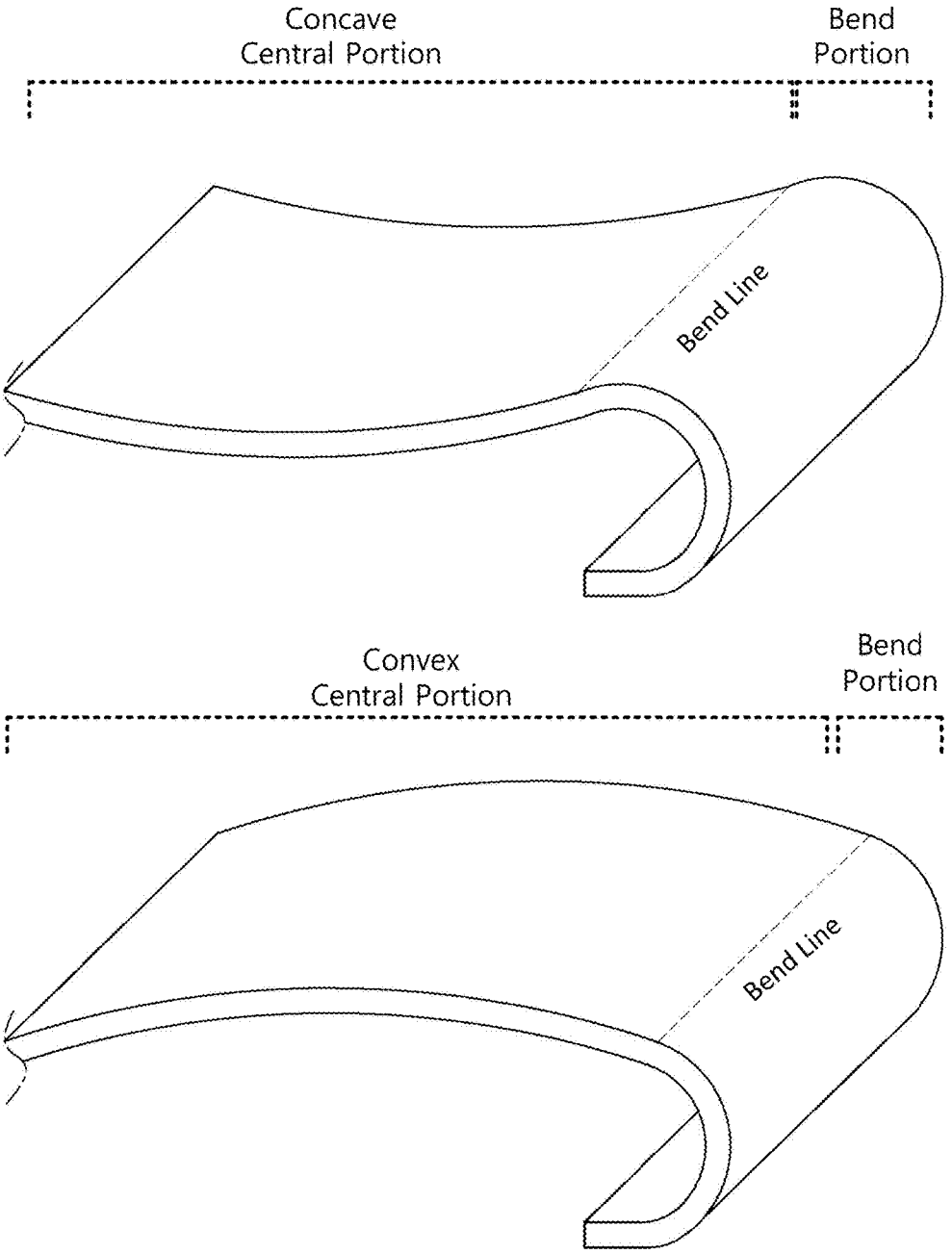
Concave
Central Portion
Bend
Portion
Bend Line
Convex
Central Portion
Bend
Portion
Bend Line

FIG. 2

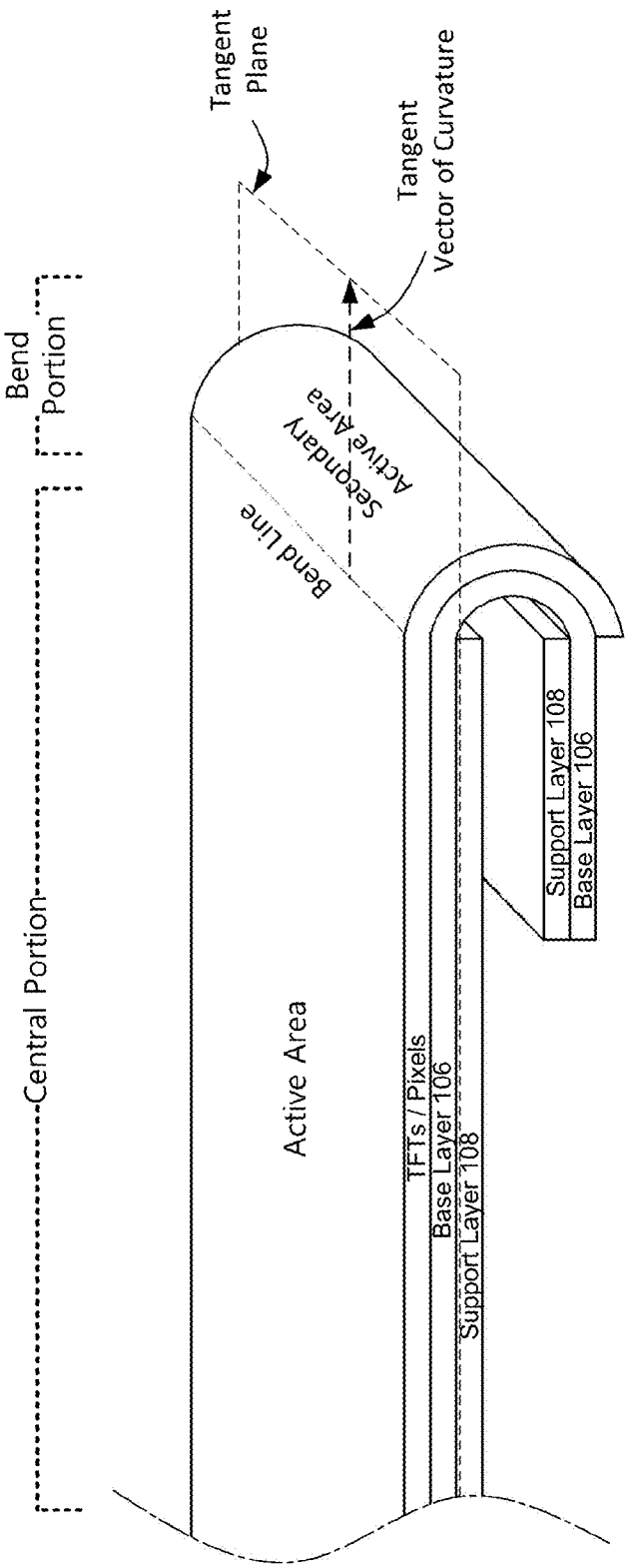
Tangent Plane
Tangent Vector of Curvature
Bend Portion
Central Portion
Bend Line
Secondary Active Area
Active Area
TFTs / Pixels
Base Layer 106
Support Layer 108
Support Layer 108
Base Layer 106

FIG. 3A

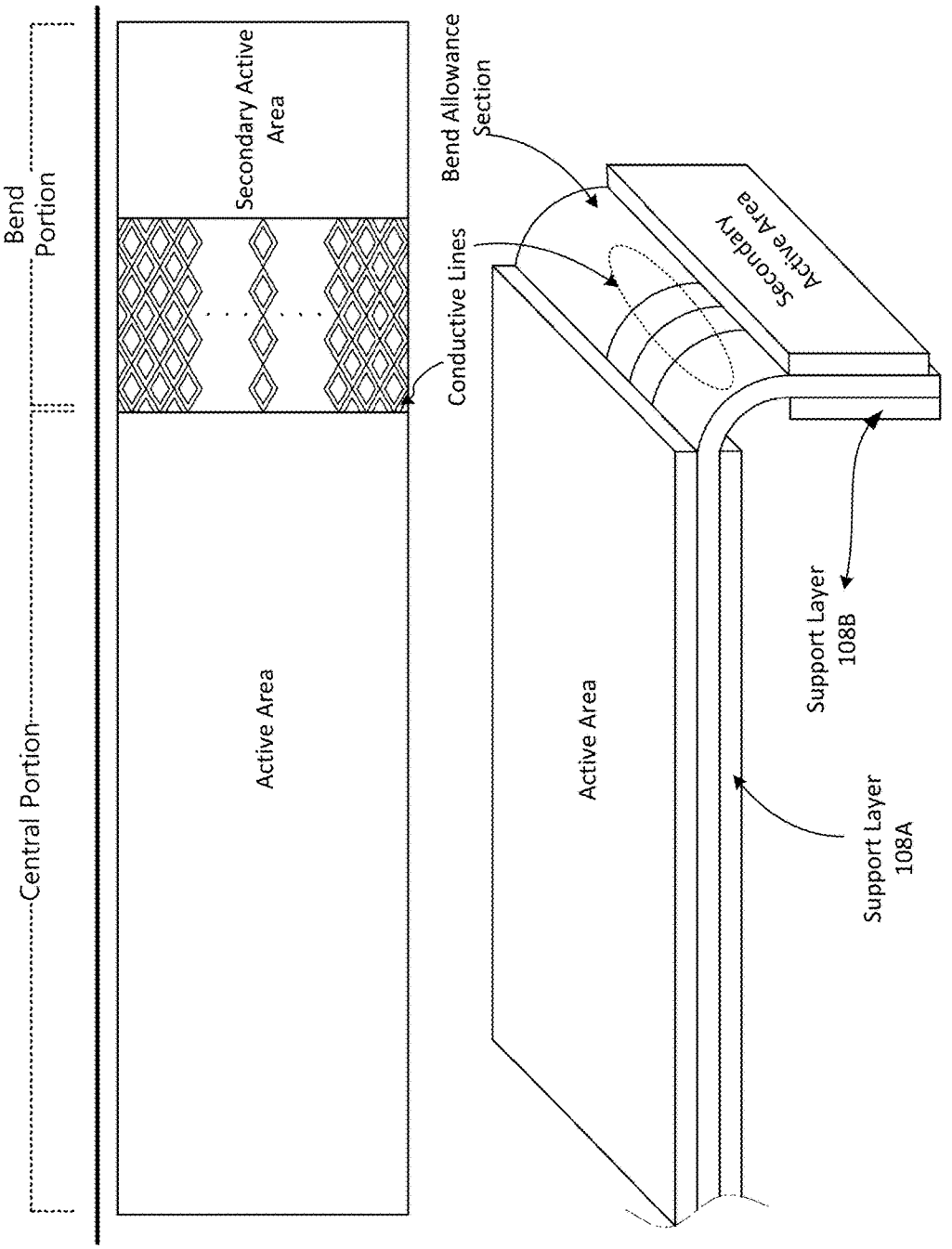
Bend Portion
Central Portion
Secondary Active Area
Active Area
Bend Allowance Section
Conductive Lines
Secondary Active Area
Active Area
Support Layer 108B
Support Layer 108A

FIG. 3B

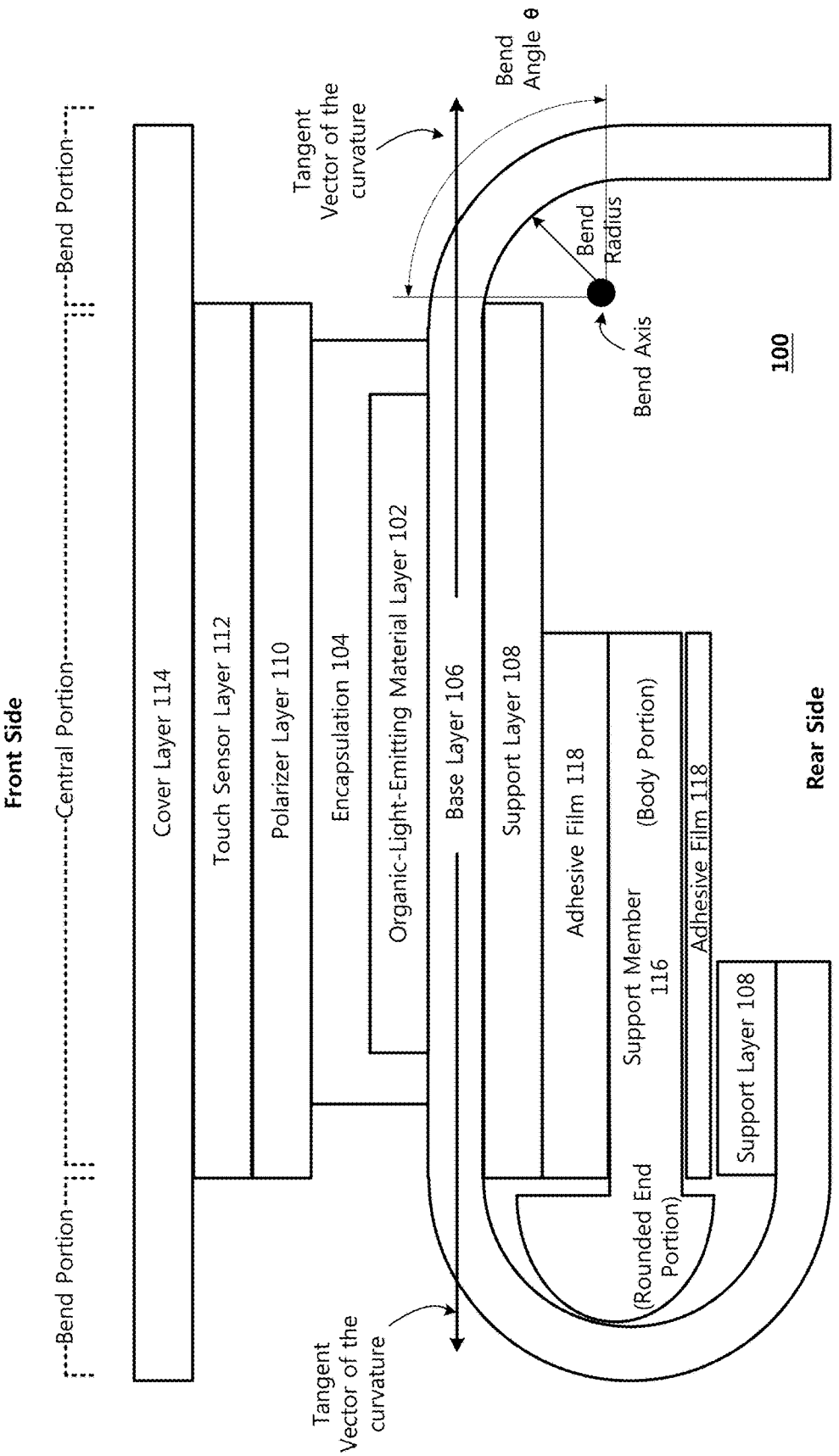
Front Side
Central Portion
Bend Portion
Bend Portion
Cover Layer 114
Touch Sensor Layer 112
Polarizer Layer 110
Encapsulation 104
Organic-Light-Emitting Material Layer 102
Base Layer 106
Support Layer 108
Adhesive Film 118
Support Member 116
(Body Portion)
(Rounded End Portion)
Adhesive Film 118
Support Layer 108
Rear Side
Tangent Vector of the curvature
Tangent Vector of the curvature
Bend Angle θ
Bend Radius
Bend Axis
100

FIG. 4

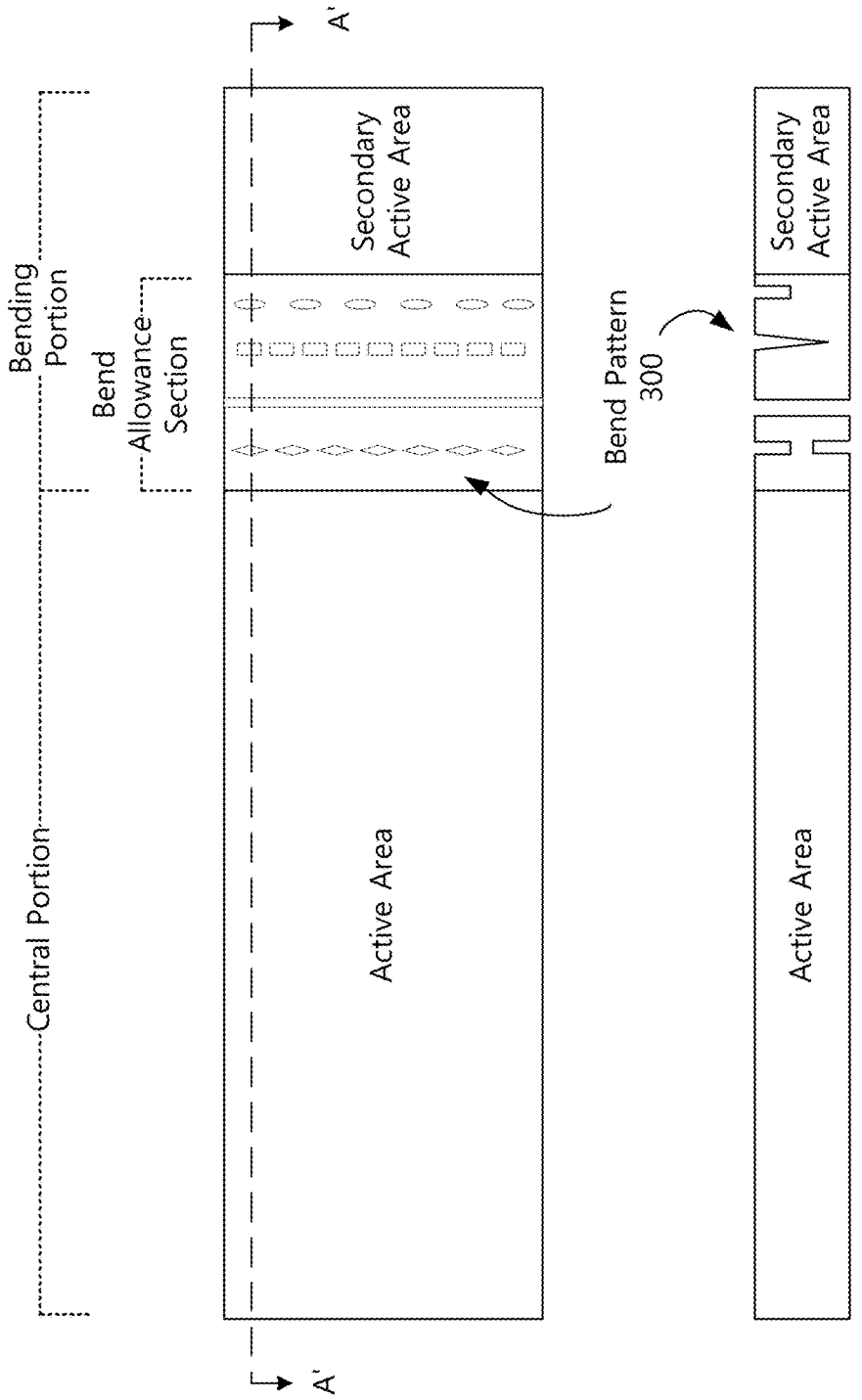
A'
Bending Portion
Bend Allowance Section
Central Portion
Secondary Active Area
Active Area
Bend Pattern 300
Secondary Active Area
Active Area
A'

FIG. 5

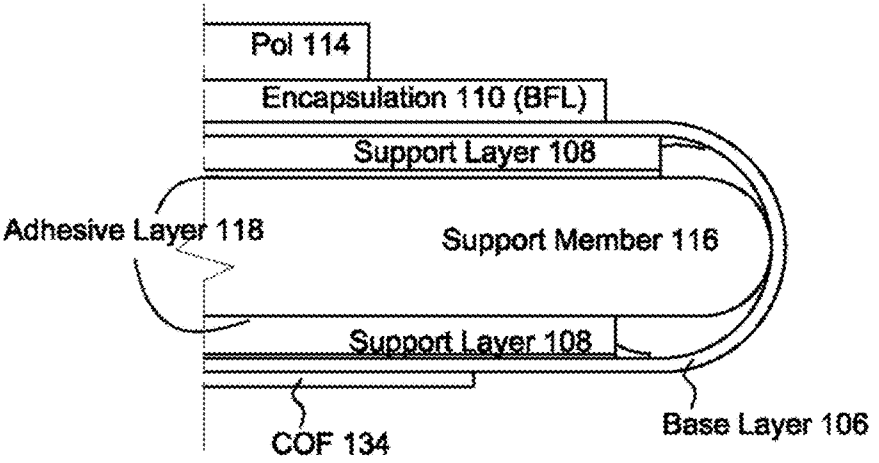

FIG. 6A

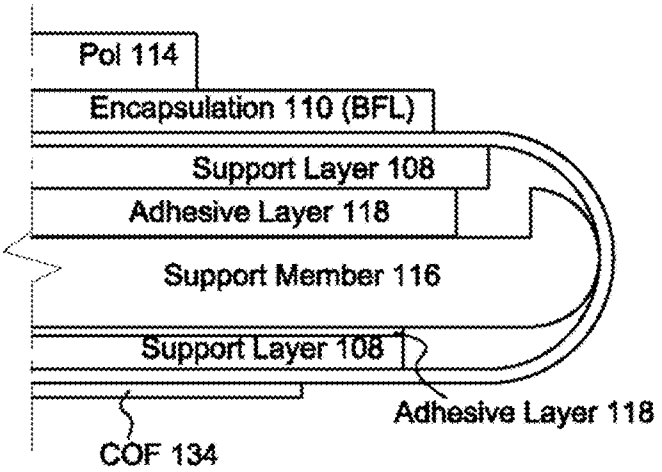

FIG. 6B

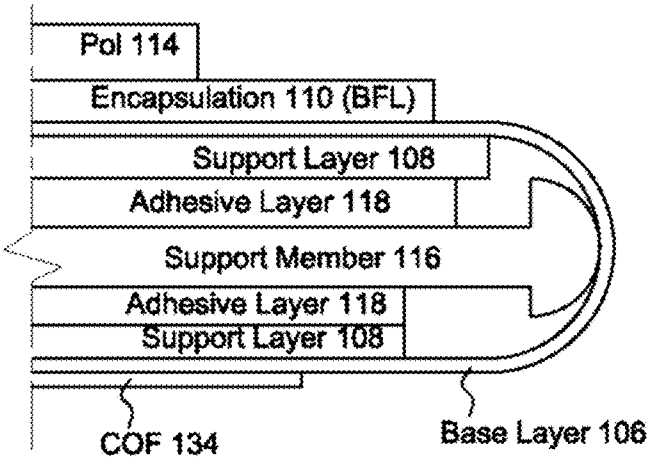

FIG. 6C

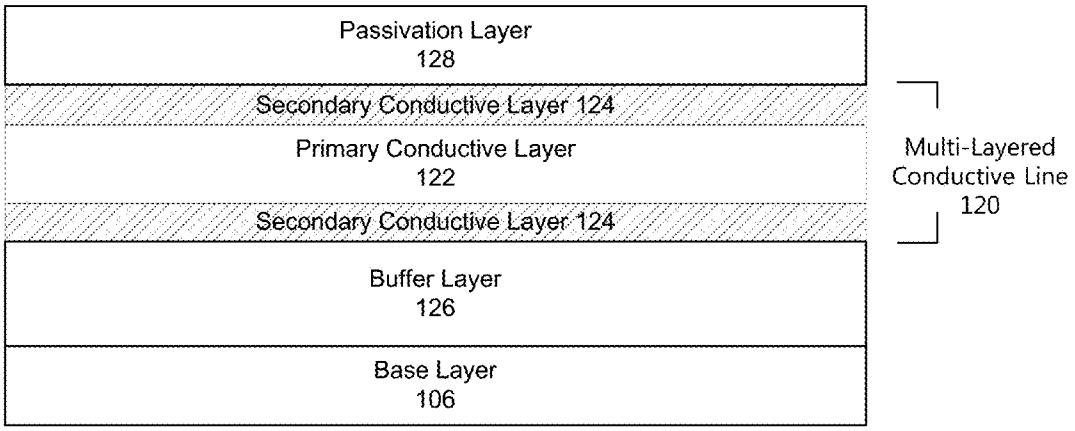
Passivation Layer
128
Secondary Conductive Layer 124
Primary Conductive Layer
122
Secondary Conductive Layer 124
Buffer Layer
126
Base Layer
106
Multi-Layered
Conductive Line
120

FIG. 7A

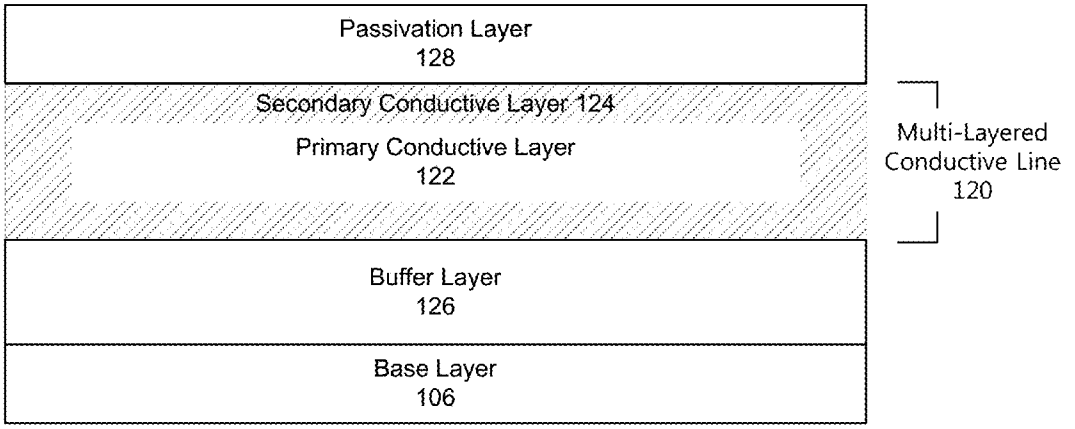
Passivation Layer
128
Secondary Conductive Layer 124
Primary Conductive Layer
122
Buffer Layer
126
Base Layer
106
Multi-Layered
Conductive Line
120

FIG. 7B

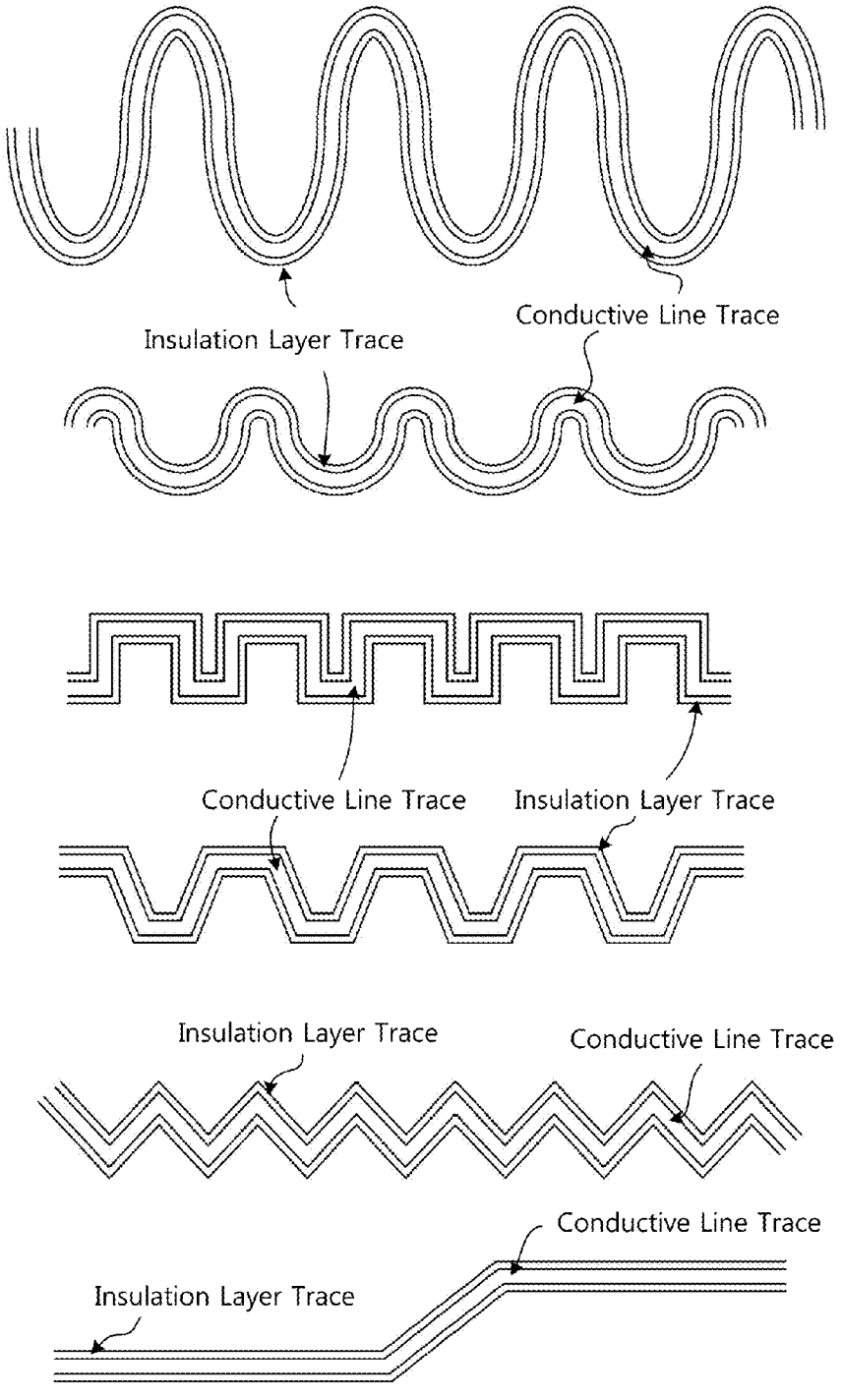
Insulation Layer Trace
Conductive Line Trace
Conductive Line Trace
Insulation Layer Trace
Insulation Layer Trace
Conductive Line Trace
Conductive Line Trace
Insulation Layer Trace

FIG.8

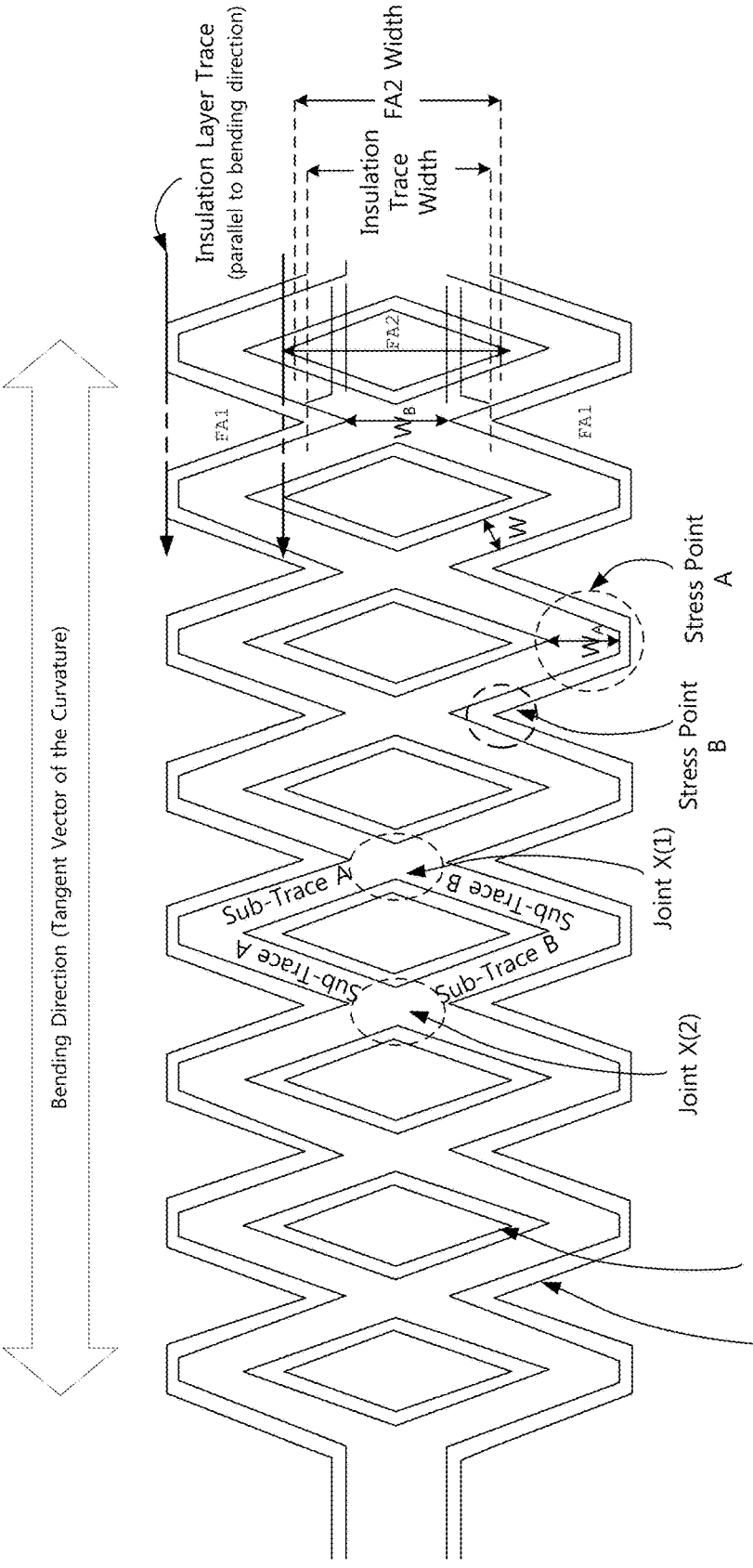

FIG. 9A
(Wire Trace)

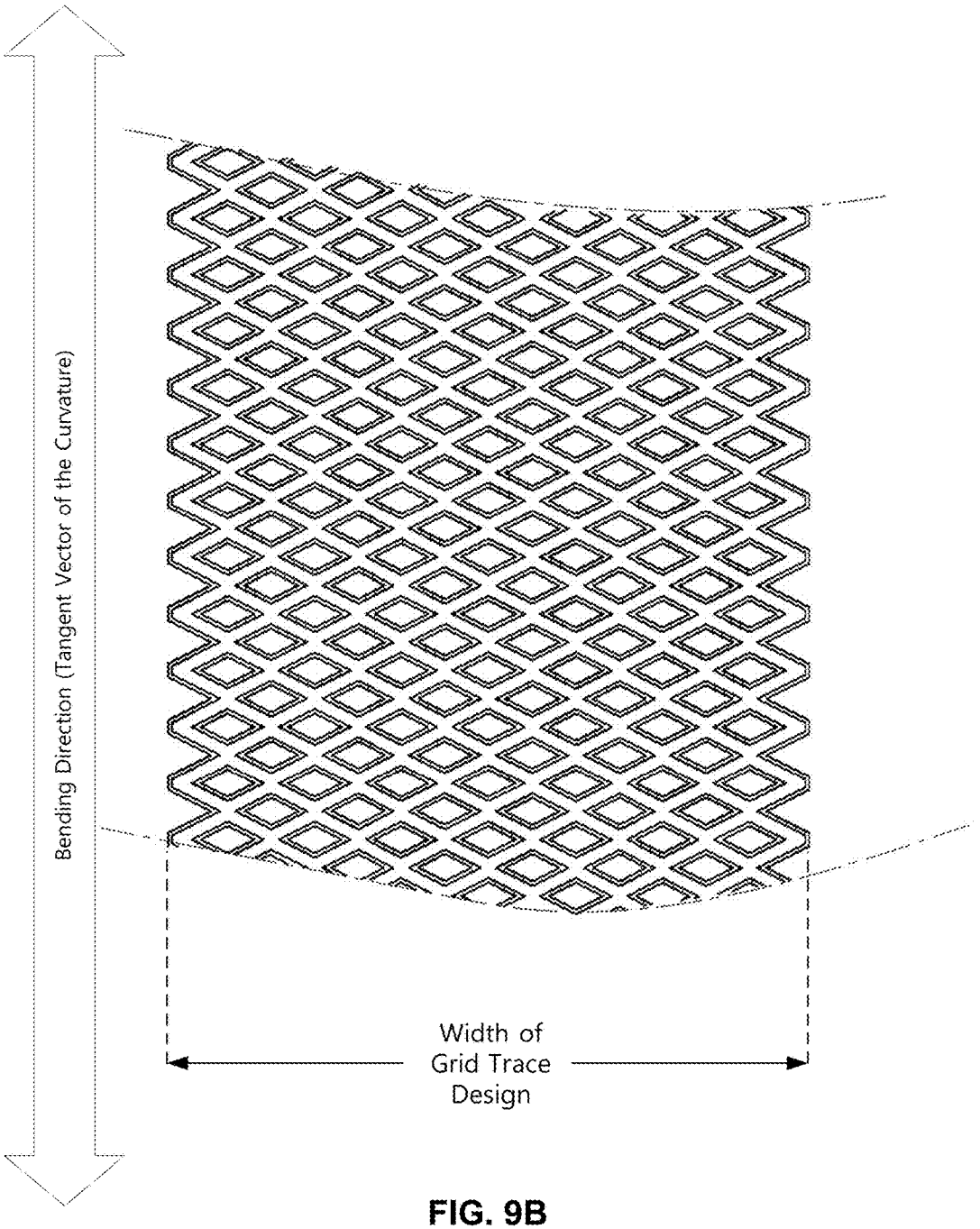
Bending Direction (Tangent Vector of the Curvature)
Width of
Grid Trace
Design

FIG. 9B

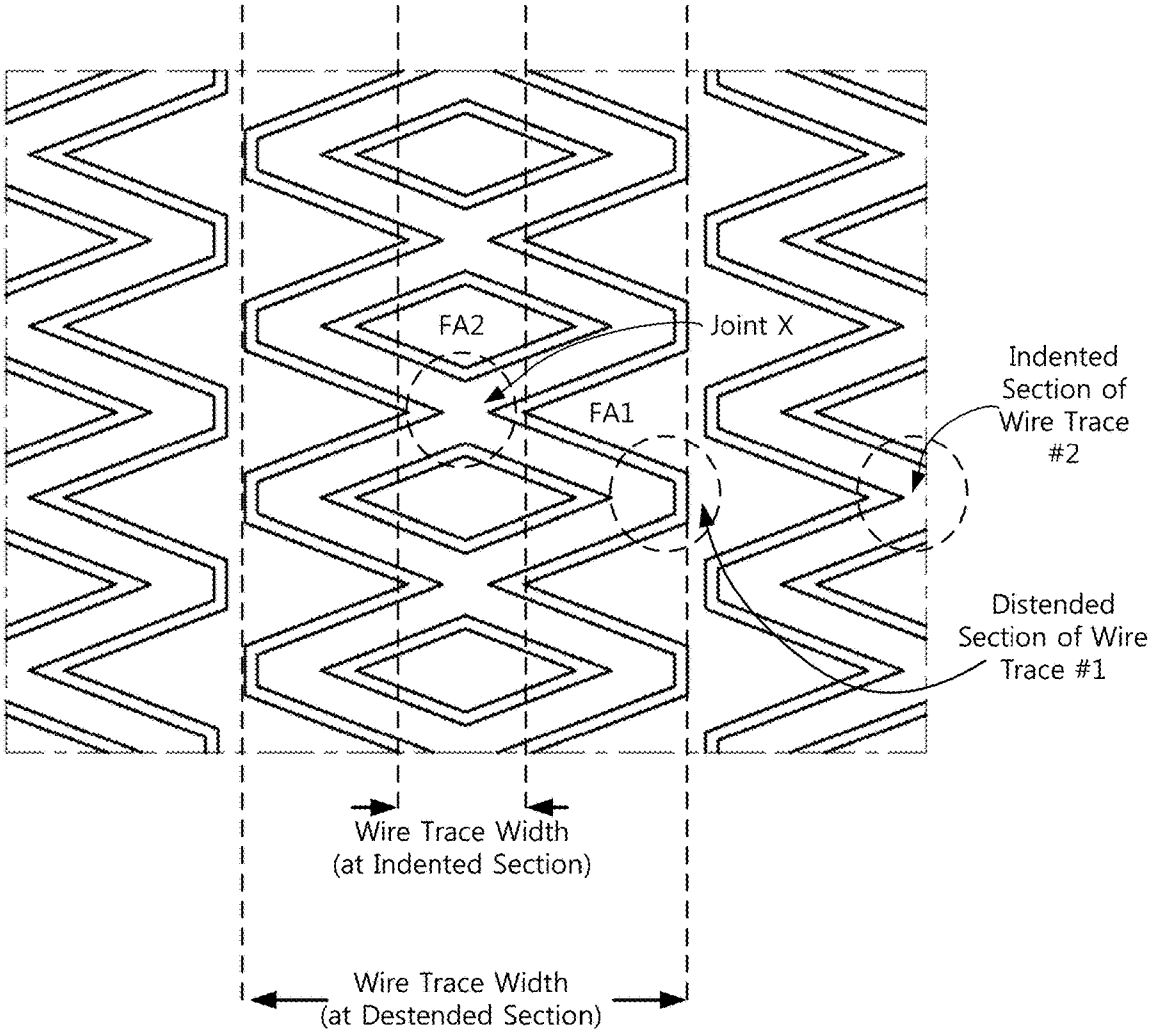
FA2
Joint X
FA1
Indented Section of Wire Trace #2
Distended Section of Wire Trace #1
Wire Trace Width (at Indented Section)
Wire Trace Width (at Destended Section)

FIG. 10

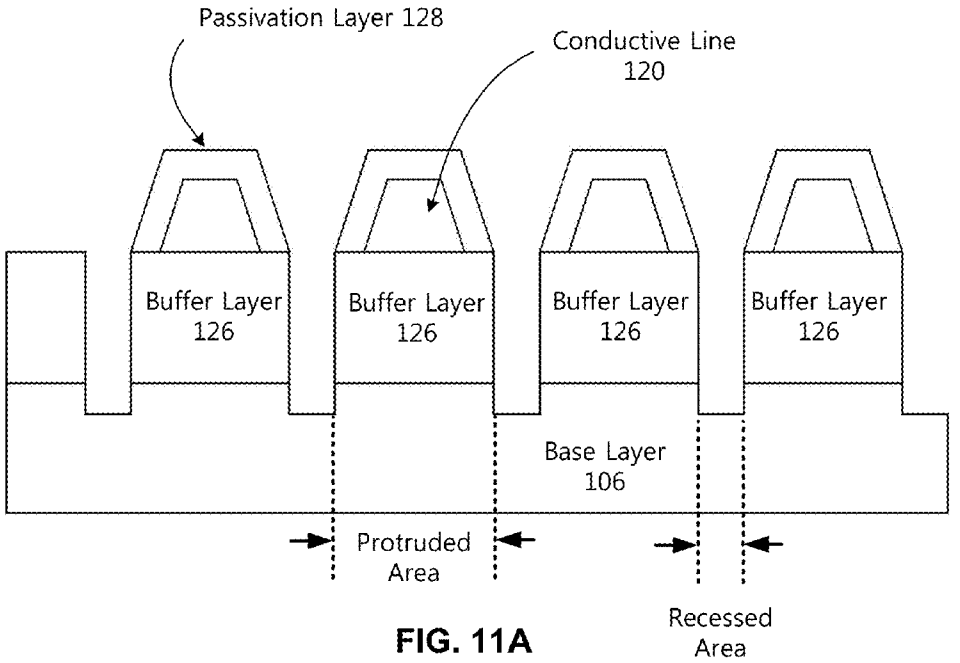

FIG. 11A

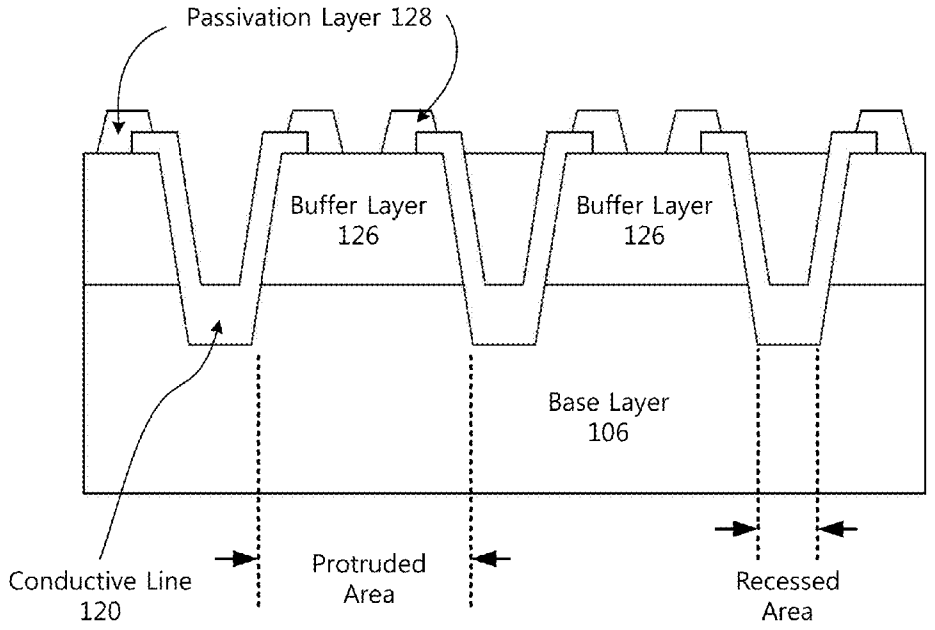

FIG. 11B

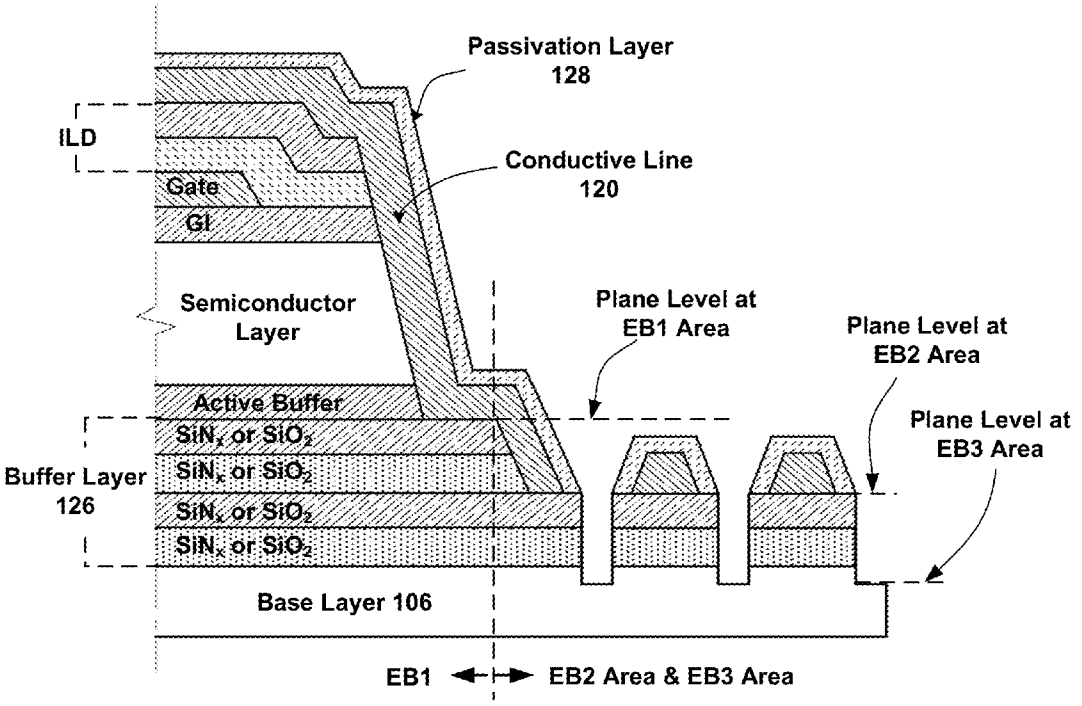

FIG. 12A

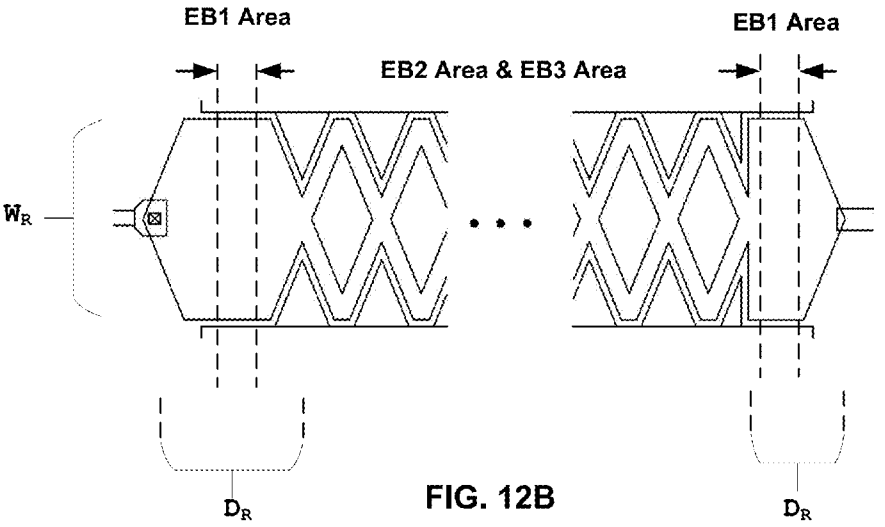

FIG. 12B

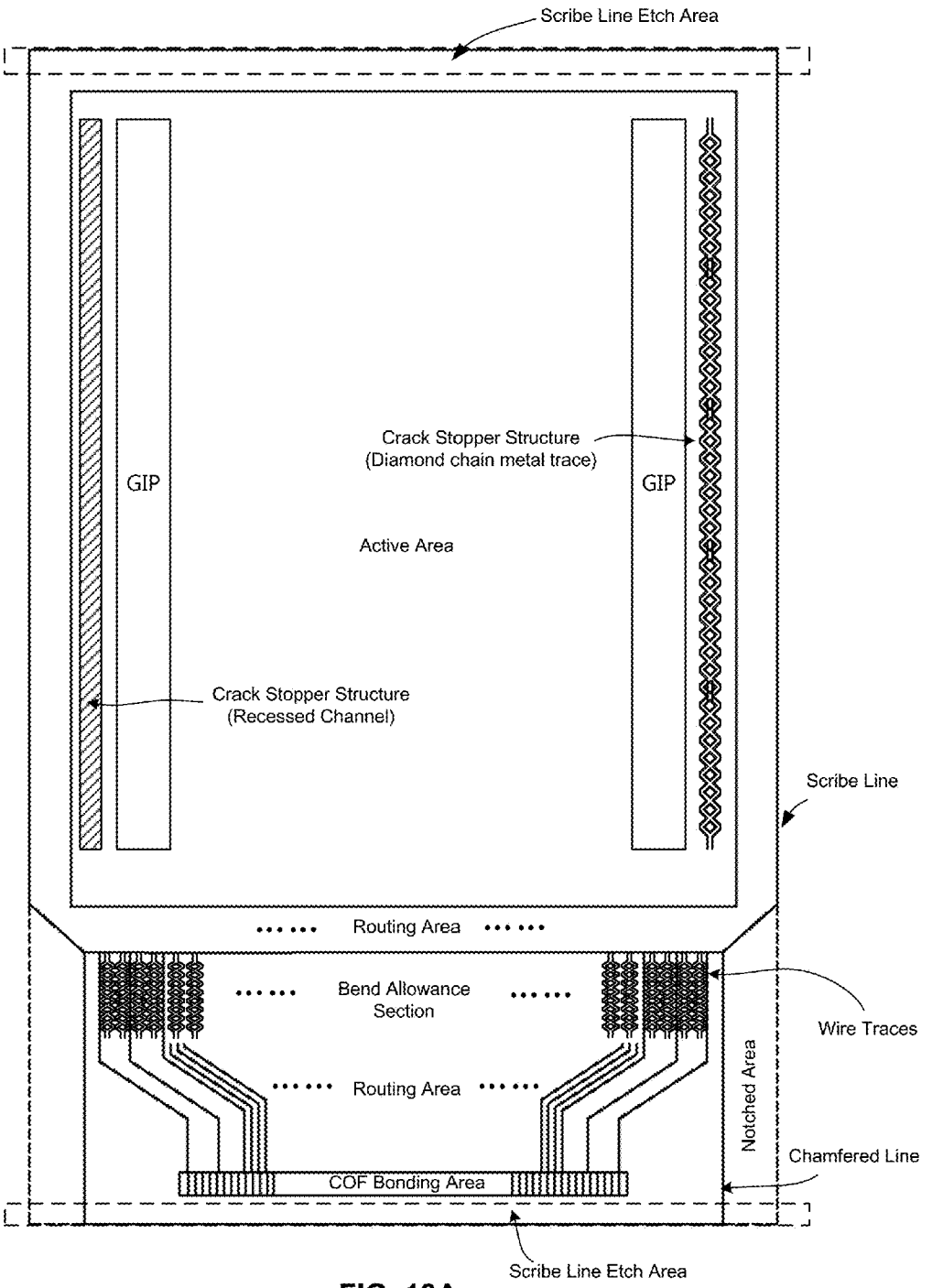
Scribe Line Etch Area
GIP
GIP
Crack Stopper Structure
(Diamond chain metal trace)
Active Area
Crack Stopper Structure
(Recessed Channel)
Scribe Line
Routing Area
Bend Allowance
Section
Wire Traces
Routing Area
Notched Area
Chamfered Line
COF Bonding Area
Scribe Line Etch Area

FIG. 13A

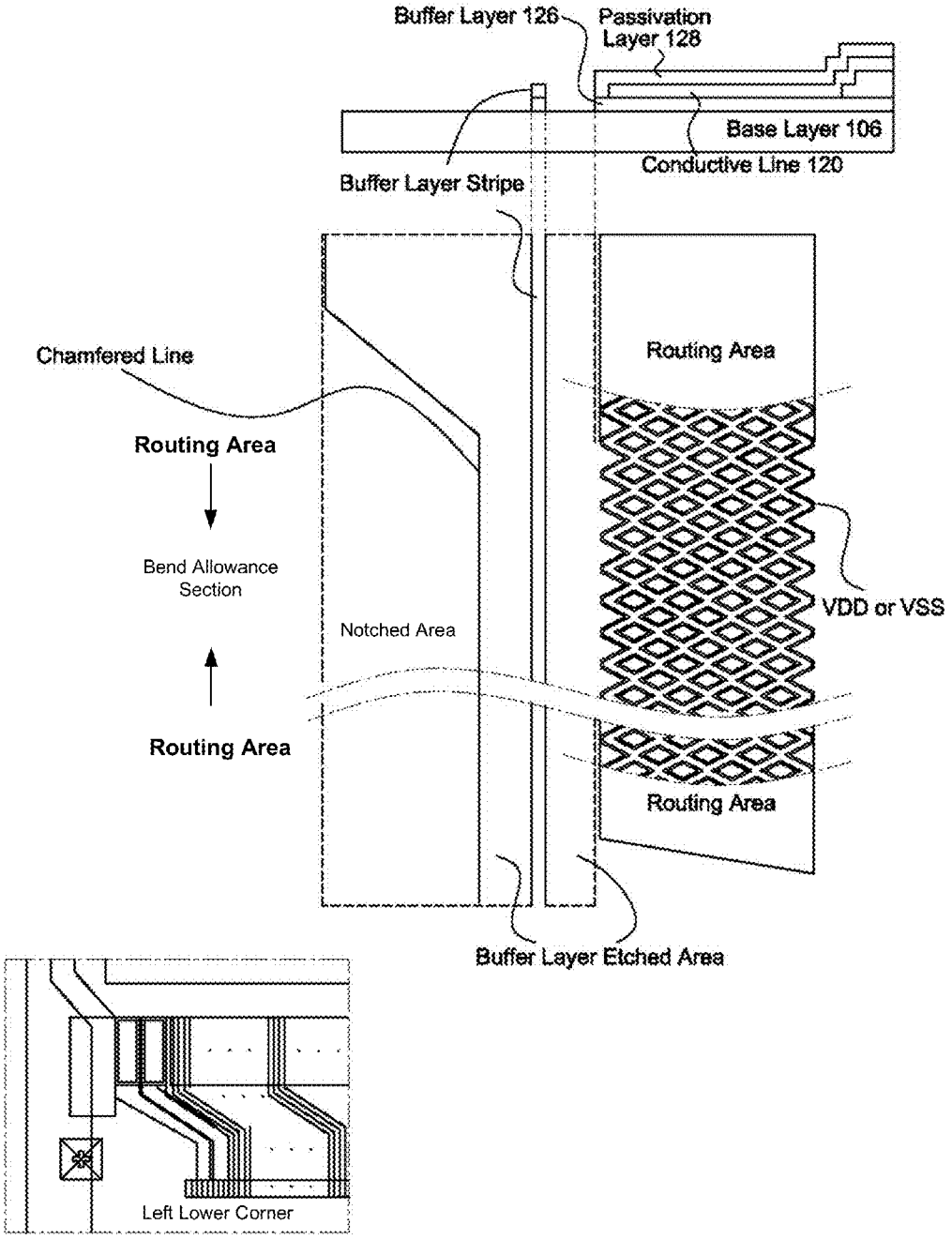
Buffer Layer 126
Passivation Layer 128
Base Layer 106
Conductive Line 120
Buffer Layer Stripe
Chamfered Line
Routing Area
Routing Area
Bend Allowance Section
Notched Area
VDD or VSS
Routing Area
Routing Area
Buffer Layer Etched Area
Left Lower Corner

FIG. 13B

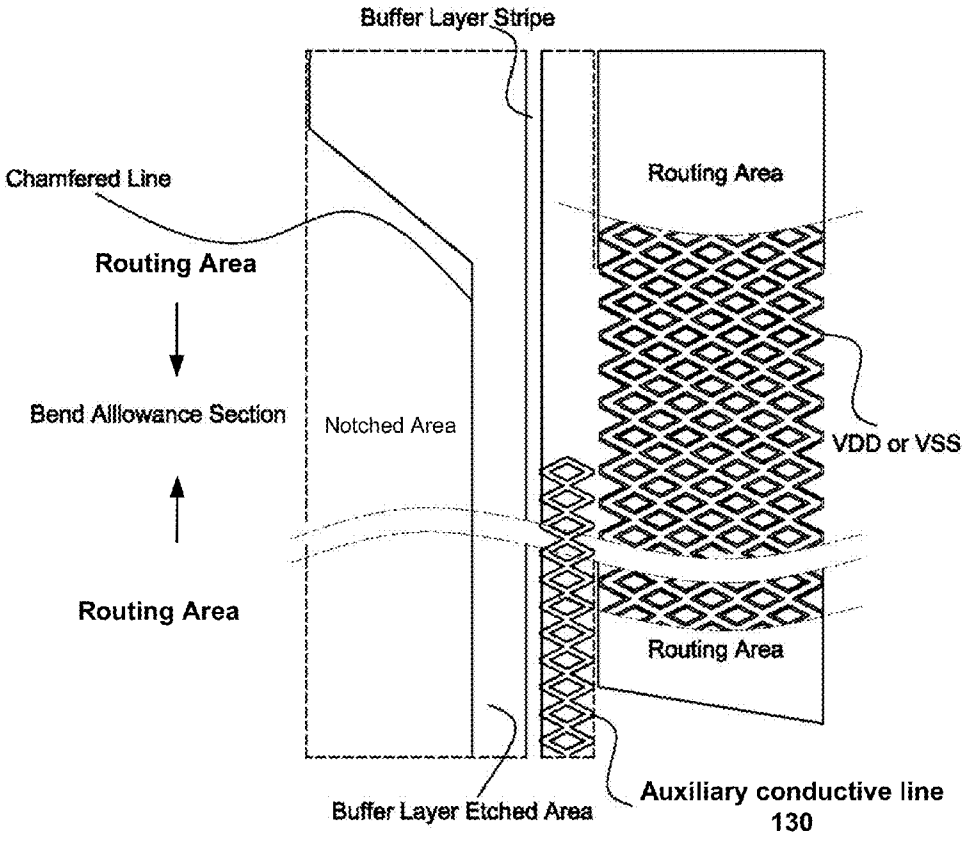
Buffer Layer Stripe
Chamfered Line
Routing Area
Bend Allowance Section
Routing Area
Notched Area
Routing Area
VDD or VSS
Routing Area
Buffer Layer Etched Area
Auxiliary conductive line
130

FIG. 13C

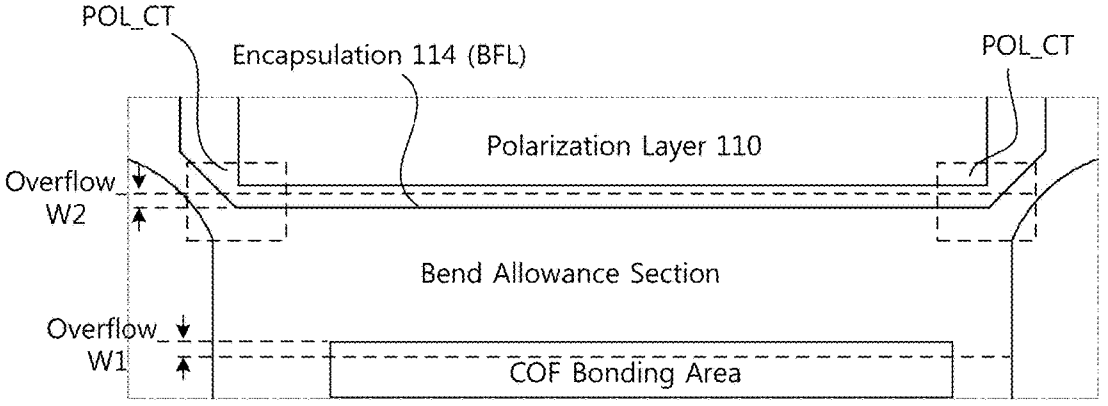

FIG. 14A

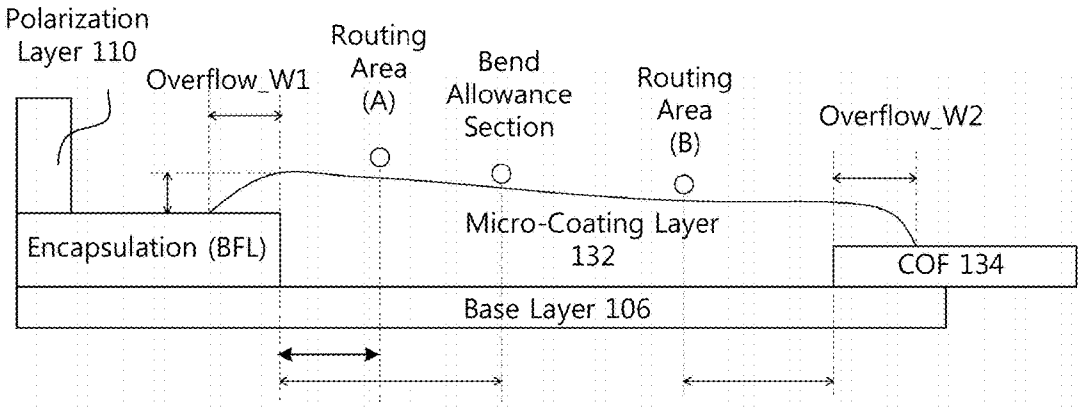

FIG. 14B

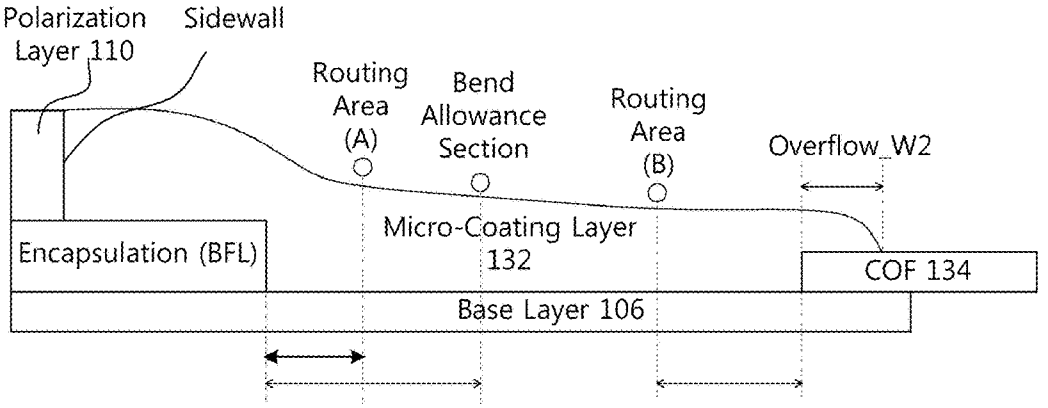

FIG. 14C

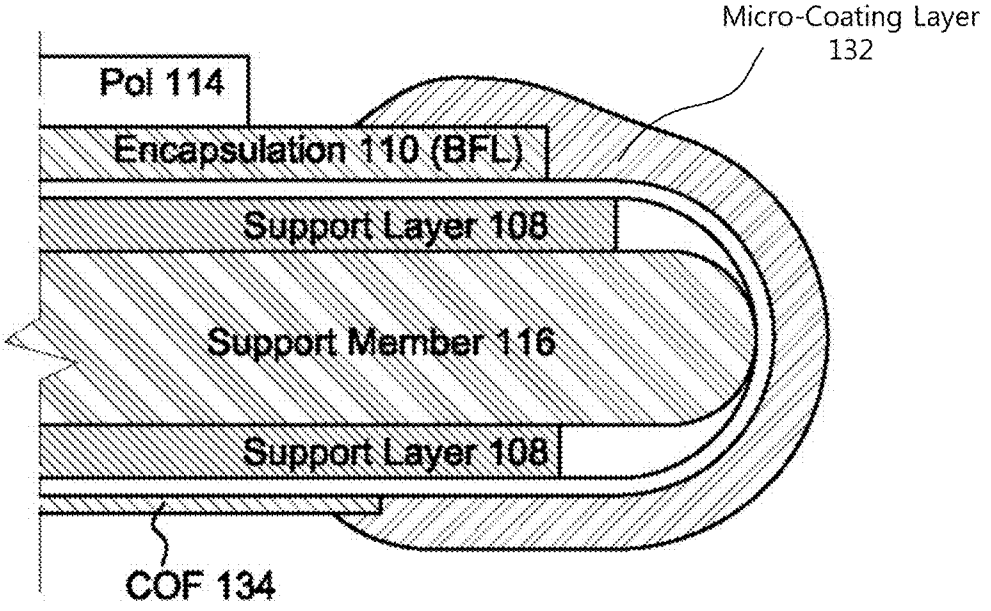

FIG. 15A

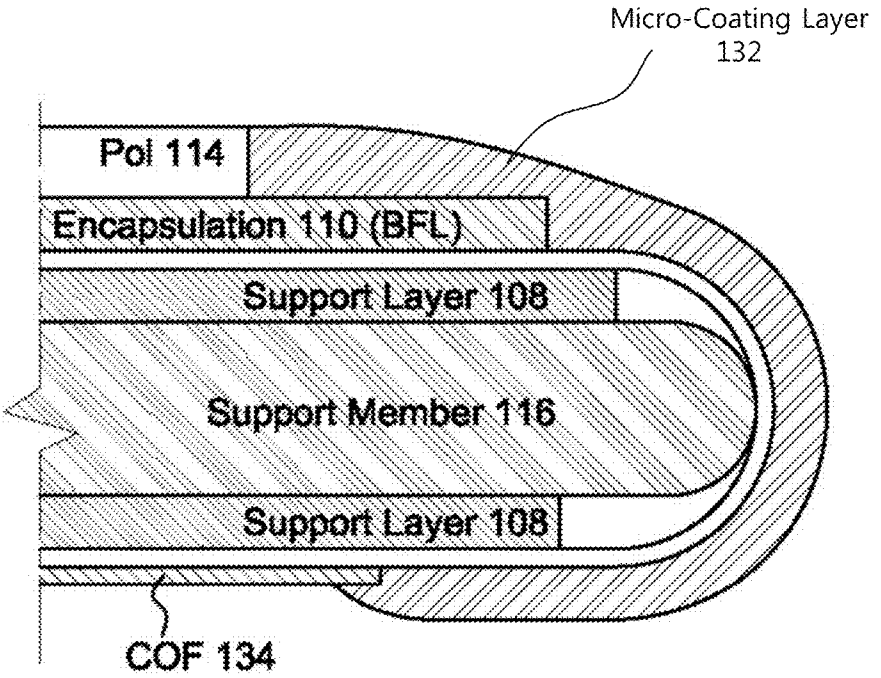

FIG. 15B

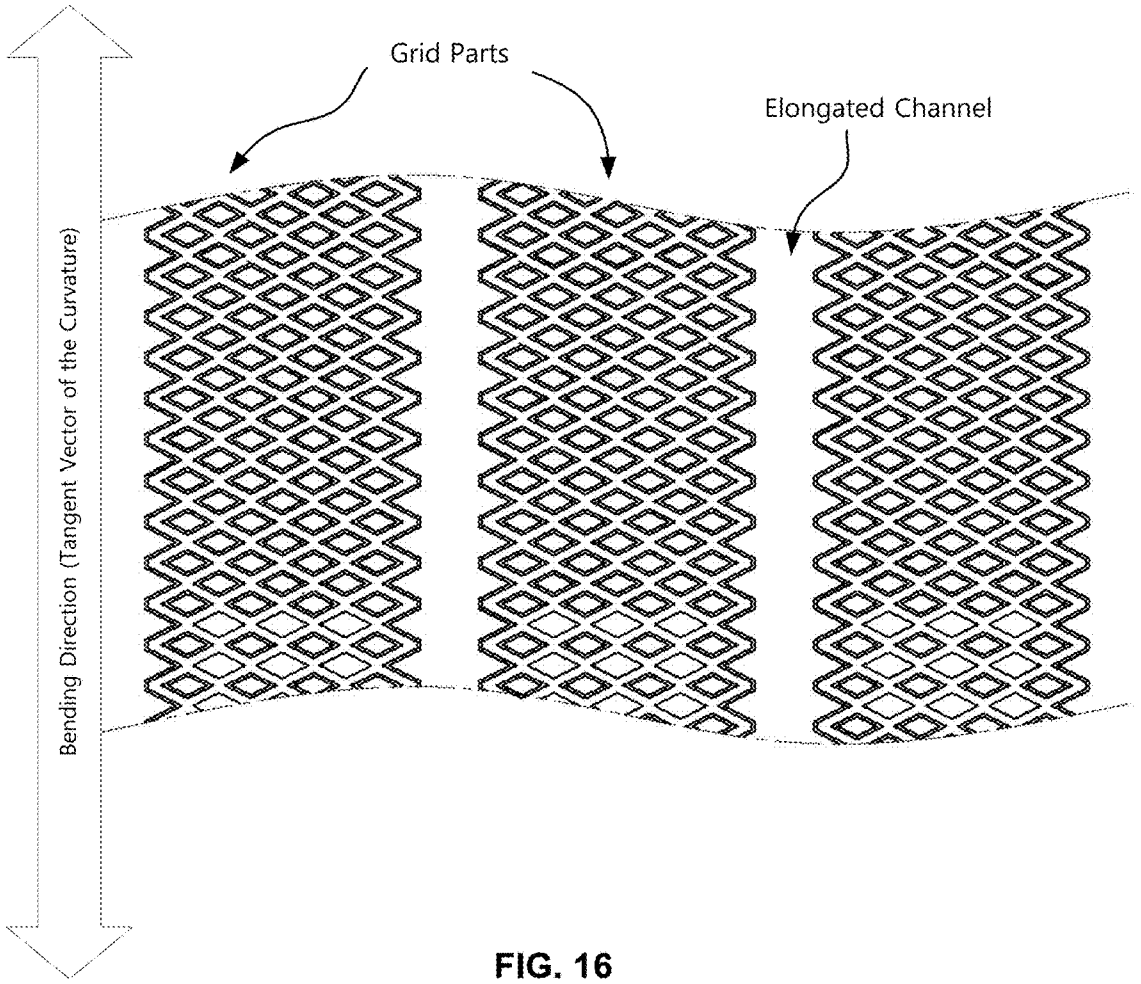
Grid Parts
Elongated Channel
Bending Direction (Tangent Vector of the Curvature)

FIG. 16

FLEXIBLE DISPLAY DEVICE WITH SPACE REDUCING WIRE CONFIGURATION

BACKGROUND

Technical Field

This relates generally to electronic devices, and more particularly, to electronic devices with a display.

Description of the Related Art

Electronic devices often include displays. For example, cellular telephones and portable computers include displays for presenting information to a user. Components for the electronic device, including but not limited to a display, may be mounted in a plastic or a metal housing.

An assembled display may include a display panel and a number of components for providing a variety of functionalities. For instance, one or more display driving circuits for controlling the display panel may be included in a display assembly. Examples of the driving circuits include gate drivers, emission (source) drivers, power (VDD) routing, electrostatic discharge (ESD) circuits, multiplex (mux) circuits, data signal lines, cathode contacts, and other functional elements. There may be a number of peripheral circuits included in the display assembly for providing various kinds of extra functions, such as touch sense or fingerprint identification functionalities. Some of the components may be disposed on the display panel itself, often in the periphery areas next to the display area, which is referred in the present disclosure as the non-display area and/or the inactive area.

Size and weight are of the critical importance in designing modern electronic devices. Also, a high ratio of the active area size compared to that of inactive area, which is sometimes referred to as the screen to bezel ratio, is one of the most desired feature. However, placing some of the aforementioned components in a display assembly may require large inactive area, which may add up to a significant portion of the display panel. Large inactive area tends to make the display panel bulky, making it difficult to incorporate it into the housing of electronic devices. Large inactive area may also necessitate a large masking (e.g., bezel, borders, covering material) to cover a significant portion of the display panel, leading to unappealing device aesthetics.

Some of the components can be placed on a separate flexible printed circuit (FPC) and positioned on the rear side of the display panel. Even with such a configuration, however, the interfaces for connecting the FPC and the wires between the active area and the connection interface still limit how much reduction in the size of the inactive area can be realized by placing components on a separate FPC.

BRIEF SUMMARY

Accordingly, it is desirable to bend the base substrate where the display area and the inactive area are formed thereon. This would allow even some of the inactive area to be positioned behind the active area of the display panel, thereby reducing or eliminating the inactive area that needs to be hidden under the masking or the device housing. Not only does the bending of the base substrate will minimize the inactive area size need to be hidden from view, but it will also open possibility to various new display device designs.

However, there are various new challenges that need to be solved in providing such flexible displays. The components formed directly on the base substrate along with the display pixels tend to have tremendously small dimensions with unforgiving margin of errors. Further, these components need to be formed on extremely thin sheet to provide flexibility, making those components extremely fragile to various mechanical and environmental stresses instigated during the manufacture and/or in the use of the displays. If care is not taken, the mechanical stresses from bending of the flexible display can negatively affect the reliability or even result in complete component failure. Even a micro-scale defect in the component thereof can have devastating effects on the performance and/or reliability of the display pixels amounting to scrap the entire display panel without an option to repair. On the other hand, simply increasing the bending radius to ease the bend stress may make it difficult to garner any significant benefits in bending the base substrate of the display panel.

As such, various factors and special parameters must be taken in consideration in designing a flexible display. An aspect of the present disclosure is related to a flexible display, which includes configurations for wire traces to withstand bend stress for reliable operation of the flexible display.

In an aspect, a flexible display having an array of pixels is provided. The flexible display includes a flexible base layer defined with a display area and a non-display area. The plurality of pixels, which may include one or more organic light-emitting diodes, is provided in the display area of the flexible base layer. The flexible display further includes a first wire trace and a second wire trace positioned adjacent to each other on the flexible base layer. The first wire trace includes a trace of a conductive line, which is covered with at least one insulation layer that is patterned according to the trace of the conductive line. The second wire trace also includes a trace of a conductive line and one or more of insulation layers patterned according to the trace of the conductive line. Space is provided between the first wire trace and the second wire trace. In this space, at least one of the insulation layers patterned according to the trace of the conductive lines of the first and second wire traces is absent.

In some embodiments, both the first wire trace and the second wire trace have a trace design in which one or more of a non-linear sections is provided in the wire trace. The non-linear section has a convex side and a concave side, and the convex side of the non-linear section in one of the first and second wire traces is positioned next to the concave side of the non-linear section in the other wire trace.

In some embodiments, the trace design of the first wire trace and the trace design of the second wire trace may differ from each other, and the non-linear section in one of the first and second wire traces may be larger than the non-linear section in the other wire trace.

In another aspect, a flexible display apparatus includes a flexible base layer that has a display area and a non-display area. An array of pixels, which includes one or more organic light-emitting diodes, is provided on the display area of the flexible base layer. The flexible display apparatus further includes a first wire trace and a second wire trace on the flexible base layer. Both the first wire trace and the second wire trace have a trace design, in which each wire trace is provided with an indented section between two distended sections of the respective wire trace. The first wire trace and the second wire trace are arranged in a staggered configuration such that one of the distended sections of the first wire trace is aligned next to the indented section of second wire trace.

In some embodiments, a channel of space is provided between the first wire trace and the second wire trace, and one or more insulation layers provided under and over the

first wire trace and the second wire trace are absent in the channel of space between the first and second wire traces.

Additional embodiments and features are set forth in part in the description that follows, and in part will become apparent to those skilled in the art upon examination of the specification or may be learned by the practice of the embodiments discussed herein. A further understanding of the nature and advantages of certain embodiments may be realized by reference to the remaining portions of the specification and the drawings, which forms a part of this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates schematic view of an exemplary flexible display apparatus according to embodiments of the present disclosure.

FIG. **2** illustrates exemplary arrangement of a substantially flat portion and bend portion of a flexible display apparatus according to embodiments of the present disclosure.

FIGS. **3**A-**3**B illustrate exemplary arrangement of active areas of a flexible display apparatus according to embodiments of the present disclosure.

FIG. **4** illustrates simplified stack up structure of components in an exemplary flexible display apparatus according to embodiment of the present disclosure.

FIG. **5** illustrates various examples of bend patterns applicable to facilitate bending of a display apparatus.

FIGS. **6**A-**6**C are cross-sectional views of illustrative arrangement of components in a flexible display apparatus according to various embodiments of the present disclosure.

FIGS. **7**A-**7**B illustrate schematic view of an exemplary multi-layered conductive lines and insulation layers according to embodiments of the present disclosure.

FIG. **8** illustrates schematic view of exemplary non-split strain-reducing trace designs usable for wire traces in a flexible display apparatus according to embodiments of the present disclosure.

FIGS. **9**A-**9**B illustrate a schematic view of exemplary strain-reducing wire trace designs having a plurality of sub-traces that split and merge at a certain interval according to embodiments of the present disclosure.

FIG. **10** illustrates an exemplary arrangement of the wire traces including indented sections and distended sections.

FIGS. **11**A-**11**B illustrate schematic cross-sectional views of exemplary trace designs usable for wire traces in a flexible display apparatus according to embodiments of the present disclosure.

FIGS. **12**A-**12**B illustrate schematic views of an exemplary strain-reducing wire trace design with modified portions adopted for the wire trace to extend across the areas with different plane levels within the flexible display according to embodiments of the present disclosure.

FIG. **13**A illustrates a schematic view of an exemplary configuration for the crack stopper structures according to an embodiment of the present disclosure.

FIGS. **13**B-**13**C illustrate schematic views of exemplary configurations near the notched area of the flexible display apparatus.

FIGS. **14**A-**14**C illustrate schematic views of the flexible display provided with a micro-coating layer according to embodiments of the present disclosure.

FIGS. **15**A-**15**B illustrate schematic views of embodiments of the flexible display in a bent state, which are provided with a micro-coating layer according to embodiments of the present disclosure.

FIG. **16** illustrates a schematic view of an exemplary strain-reducing wire trace design provided with elongated channel(s) for improving spread dynamics of a micro-coating layer.

DETAILED DESCRIPTION

Flexible Display

FIG. **1** illustrate exemplary flexible display **100** which may be incorporated in electronic devices. Referring to FIG. **1**, the flexible display **100** includes at least one active area (i.e., display area), in which an array of display pixels are formed therein. One or more inactive areas may be provided at the periphery of the active area. That is, the inactive area may be adjacent to one or more sides of the active area. In FIG. **1**, the inactive area surrounds a rectangular shape active area. However, it should be appreciated that the shapes of the active area and the arrangement of the inactive area adjacent to the active area are not particularly limited as the exemplary flexible display **100** illustrated in FIG. **1**. The active area and the inactive area may be in any shape suitable to the design of the electronic device employing the flexible display **100**. Non-limiting examples of the active area shapes in the flexible display **100** include a pentagonal shape, a hexagonal shape, a circular shape, an oval shape, and more.

Each pixel in the active area may be associated with a pixel circuit, which includes at least one switching thin-film transistor (TFT) and at least one driving TFT on the backplane of the flexible display **100**. Each pixel circuit may be electrically connected to a gate line and a data line to communicate with one or more driving circuits, such as a gate driver and a data driver positioned in the inactive area of the flexible display **100**.

For example, one or more driving circuits may be implemented with TFTs fabricated in the inactive area as depicted in FIG. **1**. Such a driving circuit may be referred to as a gate-in-panel (GIP). Also, some of the components, such as data drive-IC, may be mounted on a separate printed circuit and coupled to a connection interface (Pads/Bumps) disposed in the inactive area using a printed circuit film such as flexible printed circuit board (FPCB), chip-on-film (COF), tape-carrier-package (TCP) or any other suitable technologies. As will be described in further detail below, the inactive area with the connection interface can be bent away from the plane of the adjacent portion of the flexible display so that the printed circuit film (e.g., COF, FPCB and the like) is positioned at the rear side of the flexible display **100**.

The flexible display **100** may include various additional components for generating a variety of signals or otherwise operating the pixels in the active area. Non limiting examples of the components for operating the pixels include an inverter circuit, a multiplexer, an electro static discharge (ESD) circuit and the like. The flexible display **100** may also include components associated with functionalities other than for operating the pixels of the flexible display **100**. For instance, the flexible display **100** may include components for providing a touch sensing functionality, a user authentication functionality (e.g., finger print scan), a multi-level pressure sensing functionality, a tactile feedback functionality and/or various other functionalities for the electronic device employing the flexible display **100**. Some of the aforementioned components can be placed in the inactive area of the flexible display **100** and/or on a separate printed circuit that is connected to the connection interface of the flexible display **100**.

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Flat/Bend Portions

Multiple parts of the flexible display **100** can be bent along the bend line BL. The bend line BL in the flexible display **100** may extend horizontally (e.g., X-axis shown in FIG. **1**), vertically (e.g., Y-axis shown in FIG. **1**) or even diagonally. Accordingly, the flexible display **100** can be bent in any combination of horizontal, vertical and/or diagonal directions based on the desired design of the flexible display **100**.

As mentioned, one or more edges of the flexible display **100** can be bent away from the plane of the central portion along the bend line BL. Although the bend line BL is depicted as being located near the edges of the flexible display **100**, it should be noted that the bend lines BL can extend across the central portion or extend diagonally at one or more corners of the flexible display **100**. Such configurations would allow the flexible display **100** to provide a foldable display or a double-sided display having display pixels on both outer sides of a folded display.

With the ability to bend one or more portions of the flexible display **100**, part of the flexible display **100** may be defined as a substantially flat portion and a bend portion. A part of the flexible display **100** may remain substantially flat and referred to as a substantially flat portion of the flexible display **100**. A part of the flexible display **100** may be bent in a certain bend angle from the plane of an adjacent portion, and such portion is referred to as a bend portion of the flexible display **100**. The bend portion includes a bend allowance section, which can be actively curved in a certain bend radius.

It should be understood that the term "substantially flat" includes a portion that may not be perfectly flat. For example, the concave central portion and the convex central portion depicted in FIG. **2** may be described as a substantially flat portion in some embodiments discussed in the present disclosure. In FIG. **2**, one or more bend portions exist next to the convex or concave central portion, and bent inwardly or outwardly along the bend line in a bend angle about a bend axis. The bend radius of the bend portion is smaller than the bend radius of the central portion. In other words, the term "substantially flat portion" refers to a portion with a lesser curvature than that of an adjacent bend allowance section of the flexible display **100**.

Depending on the location of the bend line BL in the flexible display **100**, a portion on one side of the bend line may be positioned toward the center of the flexible display **100**, whereas the portion on the opposite side of the bend line BL is positioned toward an edge portion of the flexible display **100**. The portion toward the center may be referred to as the central portion and the portion toward the edge may be referred to as the edge portion of the flexible display **100**. Although this may not always be the case, a central portion of the flexible display **100** can be the substantially flat portion and the edge portion can be the bend portion of the flexible display **100**. It should be noted that a substantially flat portion can also be provided in the edge portion of the flexible display **100**. Further, in some configuration of the flexible display **100**, a bend allowance section may be positioned between two substantially flat portions.

As mentioned above, bending the inactive area allows to minimize or to eliminate the inactive area to be seen from the front side of the assembled flexible display **100**. Part of the inactive area that remains visible from the front side can be covered with a bezel. The bezel may be formed, for example, from a stand-alone bezel structure that is mounted to the cover layer **114**, a housing or other suitable components of the flexible display **100**. The inactive area remaining visible from the front side may also be hidden under an opaque masking layer, such as black ink (e.g., a polymer filled with carbon black) or a layer of opaque metal. Such an opaque masking layer may be provided on a portion of various layers included in the flexible display **100**, such as a touch sensor layer, a polarization layer, a cover layer, and other suitable layers.

Active Areas

In some embodiments, the bend portion of the flexible display **100** may include an active area capable of displaying image from the bend portion, which is referred herein after as the secondary active area. That is, the bend line BL can be positioned in the active area so that at least some display pixels of the active area is included in the bend portion of the flexible display **100**.

FIGS. **3**A and **3**B each illustrates an exemplary configuration of active areas in an embodiment of flexible display **100** of the present disclosure. In the configuration depicted in FIG. **3**A, the matrix of pixels in the secondary active area of the bend portion may be continuously extended from the matrix of the pixels in the active area of the central portion. Alternatively, in the configuration depicted in FIG. **3**B, the secondary active area within the bend portion and the active area within the central portion of the flexible display **100** may be separated apart from each other by the bend allowance section of the flexible display **100**. Some components in the central portion and the bend portion can be electrically connected via one or more conductive line **120** laid across the bend allowance section of the flexible display **100**.

The pixels in the secondary active area and the pixels in the central active area may be addressed by the driving circuits (e.g., gate driver, data driver, etc.) as if they are in a single matrix. In this case, the pixels of the central active area and the pixels of the secondary active area may be operated by the same set of driving circuits. By way of example, the Nth row pixels of the central active area and the Nth row pixels of the secondary active area may be configured to receive the gate signal from the same gate driver. As shown in FIG. **3**B, the part of the gate line crossing over the bend allowance section (i.e., bend allowance region) or a bridge for connecting the gate lines of the two active areas may have a strain-reducing trace design, which will be described in further detail below.

Depending on the functionality of the secondary active area, the pixels of the secondary active area can be driven discretely from the pixels in the central active area. That is, the pixels of the secondary active area may be recognized by the display driving circuits as being an independent matrix of pixels separate from the matrix of pixels of the central active area. In such cases, the pixels of the secondary active area may receive signals from at least one discrete driving circuit other than a driving circuit for providing signals to the pixels of the central active area.

Regardless of the configuration, the secondary active area in the bend portion may serve as a secondary display area in the flexible display **100**. Also, the size of the secondary active area is not particularly limited. The size of the secondary active area may depend on its functionality within the electronic device. For instance, the secondary active area may be used to provide images and/or texts such a graphical user interface, buttons, text messages, and the like. In some cases, the secondary active area may be used to provide light of various colors for various purposes (e.g., status indication light), and thus, the size of the secondary active area need not be as large as the active area in the central portion of the flexible display **100**.

Stack-Up Structure

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FIG. **4** is a simplified cross-sectional view showing an exemplary stack up structure of a flexible display **100** in an embodiment of the present disclosure. For convenience of explanation, the central portion of the flexible display **100** is illustrated as being substantially flat, and the bend portions are provided at the edges of the flexible display **100** in FIG. **4**.

As shown, one or more bend portions may be bent away from the plane of the substantially flat portion in a certain bend angle θ and with a bend radius R about the bending axis. The size of each bend portion that is bent away from the central portion needs not be the same. That is, the length of the base layer **106** from the bend line BL to the outer edge of the base layer **106** at each bend portion can be different from other bend portions. Also, the bend angle θ around the bend axis and the bend radius R from the bend axis can vary between the bend portions.

In the example shown in FIG. **4**, the right side bend portion has the bend angle θ of 90°, and the bend portion includes a substantially flat section. A bend portion can be bent at a larger bend angle θ, such that at least some part of the bend portion comes underneath the plane of the central portion of the flexible display **100** as the bend portion on the left side of the flexible display **100**. Also, a bend portion can be bent at a bend angle θ that is less than 90°.

In some embodiments, the radius of curvatures (i.e., bend radius) for the bend portions in the flexible display **100** may be between about 0.1 mm to about 10 mm, more preferably between about 0.1 mm to about 5 mm, more preferably between about 0.1 mm to about 1 mm, more preferably between about 0.1 mm to about 0.5 mm. In some embodiments, the bend radius at a bend portion of the flexible display **100** may be less than 0.5 mm.

One or more support layers **108** may be provided at the underside of the base layer **106** to increase rigidity and/or ruggedness at the selective portion of the flexible display **100**. For instance, the support layer **108** can be provided on the inner surface of the base layer **106** at the substantially flat portions of the flexible display **100**. The support layer **106** may not be provided in the bend allowance section where more flexibility is needed. The support layer **106** may also be provided on the base layer **106** of the bend portion that is positioned under the central portion of the flexible display **100**. Increased rigidity at selective parts of the flexible display **100** may help in ensuring accurate configuration and placement of various components during manufacturing and using the flexible display **100**. The support layer **108** can also serve to suppress generation of cracks in the base layer **106**, if the base layer **106** has a higher modulus than the support layer **108**.

The base layer **106** and the support layer **108** may each be made of a thin plastic film formed from polyimide, polyethylene naphthalate (PEN), polyethylene terephthalate (PET), other suitable polymers, a combination of these polymers, etc. Other suitable materials that may be used to form the base layer **106** and the support layer **108** include, a thin glass, a metal foil covered with a dielectric material, a multi-layered polymer stack and a polymer composite film comprising a polymer material combined with nanoparticles or micro-particles dispersed therein, etc. Support layers **108** provided in various parts of the flexible display **100** need not be made of the same material. For example, a thin-glass layer may be used as a support layer **108** for the central portion of the flexible display **100** while a thin plastic film layer is used as a support layer **108** for edge portions.

In addition to the constituent material, the thickness of the base layer **106** and the support layer **108** is another factor to consider in designing the flexible display **100**. On the one hand, bending of the base layer **106** at a small bend radius can be difficult if the base layer **106** has excessively high thickness. Also, excessive thickness of the base layer **106** can increase mechanical stress to the components disposed thereon during bending the base layer **106**. On the other hand, however, the base layer **106** can be too fragile to serve as a substrate for various components of the flexible display if it is too thin.

To meet such requirements, the base layer **106** may have a thickness in a range of about from 5 μm to about 50 μm, more preferably in a range of about 5 μm to about 30 μm, and more preferably in a range of about 5 μm to about 16 μm. The support layer **108** may have a thickness from about 100 μm to about 125 μm, from about 50 μm to about 150 μm, from about 75 μm to 200 μm, less than 150 μm, or more than 100 μm.

In one suitable exemplary configuration, a layer of polyimide with a thickness of about 10 μm to about 16 μm serves as the base layer **106** while a polyethylene terephthalate (PET) layer with a thickness of about 50 μm to about 125 μm serves as the support layer **108**. In another suitable exemplary configuration, a layer of polyimide with a thickness of about 10 μm to about 16 μm serves as the base layer **106** while a thin-glass layer with a thickness of about 50 μm to about 200 μm is used as the support layer **108**. In yet another suitable exemplary configuration, a thin glass layer is used as the base layer **106** with a layer of polyimide serving as the support layer **108** to suppress breaking of the base layer **106**.

During manufacturing, some part of the flexible display **100** may be exposed to external light. Some materials used in fabricating the components on the base layer **106** or the components themselves may undergo undesirable state changes (e.g., threshold voltage shift in the TFTs) due to the light exposure during the manufacturing of the flexible display **100**. Some parts of the flexible display **100** may be more heavily exposed to the external light than others, and this can lead to a display non-uniformity (e.g., mura, shadow defects, etc.). To minimize such problems, the base layer **106** and/or the support layer **108** may include one or more materials capable of reducing the amount of external light passing through in some embodiments of the flexible display **100**.

The light blocking material, for instance chloride modified carbon black, may be mixed in the constituent material of the base layer **106** (e.g., polyimide or other polymers). In this way, the base layer **106** may formed of polyimide with a shade to provide a light blocking functionality. Such a shaded base layer **106** can also improve the visibility of the image content displayed on the flexible display **100** by reducing the reflection of the external light coming in from the front side of the flexible display **100**.

Instead of the base layer **106**, the support layer **108** may include a light blocking material to reduce the amount of light coming in from the rear side (i.e., the support layer **108** attached side) of the flexible display **100**. The constituent material of the support layer **108** may be mixed with one or more light blocking materials in the similar fashion as described above with the base layer **106**. Further, both the base layer **106** and the support layer **108** can include one or more light blocking materials. Here, the light blocking materials used in the base layer **106** and the support layer **108** need not be the same.

While making the base layer **106** and the support layer **108** to block the unwanted external light may improve display uniformity and reduce reflection as described above, recognizing alignment marks for accurate positioning of the

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components or for carrying out manufacturing process may become difficult. For example, accurate positioning of the components on the base layer **106** or the alignment during bending of the flexible display **100** can be difficult as the positioning of the layers may need to be determined by comparing the outer edges of the overlapping portions of the layer(s). Further, checking for unwanted debris or other foreign materials in the flexible display **100** can be problematic if the base layer **106** and/or the support layer **108** blocks the excessive range(s) of light spectrum (i.e., wavelengths in the visible, the ultraviolet and the infrared spectrum).

Accordingly, in some embodiments, the light blocking material, which may be included in the base layer **106** and/or the support layer **108** is configured to pass the light of certain polarization and/or the light within specific wavelength ranges usable in one or more manufacturing and/or testing processes of the flexible display **100**. By way of example, the support layer **108** may pass the light to be used in quality check and/or alignment processes (e.g., UV, IR spectrum light) during the manufacturing the flexible display **100**, but filter the light in the visible light wavelength range. The limited range of wavelengths can help reduce the display non-uniformity problem, which may be caused by the shadows generated by the printed circuit film attached to base layer **106**, especially if the base layer **106** includes the light blocking material as described above.

It should be noted that the base layer **106** and the support layer **108** can work together in blocking and passing specific types of light. For instance, the support layer **108** can change the polarization of light, such that the light will not be passable through the base layer **106**. This way, certain type of light can be passed through the support layer **108** for various purposes during manufacturing of the flexible display **100**, but unable to penetrate through the base layer **106** to cause undesired effects to the components disposed on the opposite side of the base layer **106**.

Backplane of the flexible display **100** is implemented on the base layer **106**. In some embodiments, the backplane of the flexible display **100** can be implemented with TFTs using low-temperature poly-silicon (LTPS) semiconductor layer as its active layer. In one suitable configuration, the pixel circuit and the driving circuits (e.g., GIP) on the base layer **106** are implemented with NMOS LTPS TFTs. In other suitable configuration, the backplane of the flexible display **100** can be implemented with a combination of NMOS LTPS TFTs and PMOS LTPS TFTs. For instance, the driving circuit (e.g., GIP) on the base layer **106** may include one or more CMOS circuits to reduce the number of lines for controlling the scan signals on the gate line.

Further, in some embodiments, the flexible display **100** may employ multiple kinds of TFTs to implement the driving circuits in the inactive area and/or the pixel circuits in the active area. That is, a combination of an oxide semiconductor TFT and an LTPS TFT may be used to implement the backplane of the flexible display **100**. In the backplane, the type of TFTs may be selected according to the operating conditions and/or requirements of the TFTs within the corresponding circuit.

Low-temperature-poly-silicon (LTPS) TFTs generally exhibit excellent carrier mobility even at a small profile, making them suitable for implementing condensed driving circuits. The excellent carrier mobility of the LTPS TFT makes it an ideal for components requiring a fast speed operation. Despite the aforementioned advantages, initial threshold voltages may vary among the LTPS TFTs due to the grain boundary of the poly-crystallized silicon semiconductor layer.

A TFT employing an oxide material based semiconductor layer, such as an indium-gallium-zinc-oxide (IGZO) semiconductor layer (referred hereinafter as "the oxide TFT"), is different from the LTPS TFT in many respects. Despite a lower mobility than the LTPS TFT, the oxide TFT is generally more advantageous than the LTPS TFT in terms of power efficiency. Low leakage current of the oxide TFT during its off state allows to remain in active state longer. This can be of a great advantage for driving the pixels at a reduced frame rate when a high frame rate driving of the pixels is not needed.

By way of example, the flexible display **100** may be provided with a feature in which the pixels of the entire active area or selective portion of the active area are driven at a reduced frame rate under a specific condition. In this setting, the pixels can be refreshed at a reduced refresh rate depending on the content displayed from the flexible display **100**. Also, part of the active area displaying a still image data (e.g., user interface, text) may be refreshed at a lower rate than other part of the active area displaying rapidly changing image data (e.g., movie). The pixels driven at a reduced refresh rate may have an increased blank period, in which the data signal is not provided to the pixels. This would minimize the power wasted from providing the pixels with the same image data. In such embodiments, some of the TFTs implementing the pixel circuits and/or the driving circuits of the flexible display **100** can be formed of the oxide TFT to minimize the leakage current during the blank period. By reducing the current leakage from the pixel circuits and/or the driving circuits, the pixels can achieve more stable level of luminance even when the display is refreshed at a reduced rate.

Another feature of the oxide TFT is that it does not suffer from the transistor-to-transistor initial threshold voltage variation issue as much as the LTPS TFTs. Such a property can be of a great advantage when increasing the size of the flexible display **100**. Threshold shifts under bias stress is also different between LTPS TFT and oxide TFT.

Considering the aforementioned characteristics of LTPS TFT and oxide TFT, some embodiments of the flexible display **100** disclosed herein can employ a combination of the LTPS TFT and the oxide TFT in a single backplane. In particular, some embodiments of the flexible display **100** can employ LTPS TFTs to implement the driving circuits (e.g., GIP) in the inactive area and employ oxide TFTs to implement the pixel circuits in the active area. Due to the excellent carrier mobility of the LIPS TFTs, driving circuits implemented with LIPS TFTs may operate at a faster speed than the driving circuits implemented with the oxide TFTs. In addition, more condensed driving circuits can be provided with the LIPS TFT, which reduces the size of the inactive area in the flexible display **100**. With the excellent voltage holding ratio of the oxide TFTs used in the pixel circuits, leakage from the pixels can be reduced. This also enables to refresh pixels in a selective portion of the active area or to drive pixels at a reduced frame rate under a predetermined condition (e.g., when displaying still images) while minimizing display defects caused by the leakage current.

In some embodiments, the driving circuits in the inactive area of the flexible display **100** may be implemented with a combination of N-Type LIPS TFTs and P-Type LIPS TFTs while the pixel circuits are implemented with oxide TFTs. For instance, N-Type LIPS TFTs and P-Type LIPS TFTs can be used to implement a CMOS gate driver (e.g., CMOS GIP,

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Data Driver) whereas oxide TFTs are employed in at least some part of the pixel circuits. Unlike the GIP formed entirely of either the P-type or N-type LIPS TFTs, the gate out signal from the CMOS gate driver can be controlled by DC signals or logic high/low signals. This allows for more stable control of the gate line during the blank period such that the suppression of current leakage from the pixel circuit or unintended activation of the pixels connected the gate line can be achieved.

It should be noted that a CMOS gate driver or an inverter circuit on the backplane can be implemented by using a combination of LIPS TFTs and oxide TFTs. For instance, a P-type LIPS TFT and an N-Type oxide TFT can be used to implement a CMOS circuit. Also, the pixel circuits in the active area can also be implemented by using both the LIPS TFTs and the oxide TFTs. When employing both kinds of TFTs in the pixel circuit and/or the driving circuit, the LIPS TFT can be strategically placed within the circuit to remove bias remaining in a node between oxide TFTs during their off state and minimize the bias stress (e.g., PBTS, NBTS). In addition, the TFTs in a circuit, which are connected to a storage capacitor, can be formed of the oxide TFT to minimize leakage therefrom.

The organic light-emitting diode (OLED) element layer **102** is disposed on the base layer **106**. The OLED element layer **102** includes a plurality of OLED elements, which is controlled by the pixel circuits and the driving circuits implemented on the base layer **106** as well as any other driving circuits connected to the connection interfaces on the base layer **106**. The OLED element layer includes an organic-light emitting material layer, which may emit light of certain spectral color (e.g., red, green, blue). In some embodiments, the organic-light emitting material layer may have a stack configuration to emit white light, which is essentially a combination of multiple colored lights.

The encapsulation **104** is provided to protect the OLED element layer **102** from air and moisture. The encapsulation **104** may include multiple layers of materials for reducing permeation of air and moisture to protect OLED elements thereunder. In some embodiments, the encapsulation **104** may be provided in a form of a thin film.

The flexible display **100** may also include a polarization layer **110** for controlling the display characteristics (e.g., external light reflection, color accuracy, luminance, etc.) of the flexible display **100**. Also, the cover layer **114** may be used to protect the flexible display **100**.

Electrodes for sensing touch input from a user may be formed on an interior surface of a cover layer **114** and/or at least one surface of the polarization layer **110**. If desired, an independent layer with the touch sensor electrodes and/or other components associated with sensing of touch input (referred hereinafter as touch-sensor layer **112**) may be provided in the flexible display **100**. The touch sensor electrodes (e.g., touch driving/sensing electrodes) may be formed from transparent conductive material such as indium tin oxide, carbon based materials like graphene or carbon nanotube, a conductive polymer, a hybrid material made of mixture of various conductive and non-conductive materials. Also, metal mesh (e.g., aluminum mesh, silver mesh, etc.) can also be used as the touch sensor electrodes.

The touch sensor layer **112** may include a layer formed of one or more deformable dielectric materials. One or more electrodes may be interfaced with or positioned near the touch sensor layer **112**, and loaded with one or more signals to facilitate measuring electrical changes on one or more of the electrodes upon deformation of the touch sensor layer **112**. The measurement may be analyzed to assess the amount of pressure at a plurality of discrete levels and/or ranges of levels on the flexible display **100**.

In some embodiments, the touch sensor electrodes can be utilized in identifying the location of the user inputs as well as assessing the pressure of the user input. Identifying the location of touch input and measuring of the pressure of the touch input on the flexible display **100** may be achieved by measuring changes in capacitance from the touch sensor electrodes on one side of the touch sensor layer **112**. The touch sensor electrodes and/or other electrode may be used to measure a signal indicative of the pressure on the flexible display **100** by the touch input. Such a signal may be obtained simultaneously with the touch signal from the touch sensor electrodes or obtained at a different timing.

The deformable material included in the touch sensor layer **112** may be an electro-active material, which the amplitude and/or the frequency of the deformation is controlled by an electrical signal and/or electrical field. The examples of such deformable materials include piezo ceramic, electro-active-polymer (EAP) and the like. Accordingly, the touch sensor electrodes and/or separately provided electrode can activate the deformable material to bend the flexible display **100** to desired directions. In addition, such electro-active materials can be activated to vibrate at desired frequencies, thereby providing tactile and/or texture feedback on the flexible display **100**. It should be appreciated that the flexible display **100** may employ a plurality of electro-active material layers so that bending and vibration of the flexible display **100** can be provided simultaneously or at a different timing. Such a combination can be used in creating sound waves from the flexible display **100**.

Components of the flexible display **100** may make it difficult to bend the flexible display **100** along the bend line BL. Some of the elements, such as the support layer **108**, the touch sensor layer **112**, the polarization layer **110** and the like, may add too much rigidity to the flexible display **100**. Also, the thickness of such elements shifts the neutral plane of the flexible display **100** and thus some of the components may be subject to greater bend stresses than other components.

To facilitate easier bending and to enhance the reliability of the flexible display **100**, the configuration of components in the bend portion of the flexible display **100** differs from the substantially flat portion of the flexible display **100**. Some of the components existing in the substantially flat portion may not be disposed in the bend portions of the flexible display **100**, or may be provided in a different thickness. The bend portion may be free of the support layer **108**, the polarization layer **110**, the touch sensor layer **114**, a color filter layer and/or other components that may hinder bending of the flexible display **100**. Such components may not be needed in the bend portion if the bend portion is to be hidden from the view or otherwise inaccessible to the users of the flexible display **100**.

Even if the secondary active area is in the bend portion for providing information to users, the secondary active area may not require some of these components depending on the usage and/or the type of information provided by the secondary active area. For example, the polarization layer **110** and/or color filter layer may not be needed in the bend portion when the secondary active area is used for simply emitting colored light, displaying texts or simple graphical user interfaces in a contrast color combination (e.g., black colored texts or icons in white background). Also, the bend portion of the flexible display **100** may be free of the touch sensor layer **114** if such functionality is not needed in the bend portion. If desired, the bend portion may be provided

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with a touch sensor layer **112** and/or the layer of electro-active material even though the secondary active area for displaying information is not provided in the bend portion.

Since the bend allowance section is most heavily affected by the bend stress, various bend stress-reducing features are applied to the components on the base layer **106** of the bend allowance section. To this end, some of the elements in the central portion may be absent in at least some part of the bend portion. The separation between the components in the central portion and the bend portion may be created by selectively removing the elements at the bend allowance section of the flexible display **100** such that the bend allowance section is free of the respective elements.

As depicted in FIG. **4**, the support layer **108** in the central portion and the support layer **108** in the bend portion can be separated from each other by the absence of the support layer **108** at the bend allowance section. Instead of using the support layer **108** attached to the base layer **106**, a support member **116** with a rounded end portion can be positioned underside of the base layer **106** at the bend allowance section. Various other components, for example the polarization layer **110** and the touch sensor layer **114** and more, may also be absent from the bend allowance section of the flexible display **100**. The removal of the elements may be done by cutting, wet etching, dry etching, scribing and breaking, or other suitable material removal methods. Rather than cutting or otherwise removing an element, separate pieces of the element may be formed at the selective portions (e.g., substantially flat portion and the bend portion) to keep the bend allowance section free of such element.

Rather than being entirely removed from the bend portion, some elements may be provided with a bend pattern along the bend lines and/or the parts within the bend allowance section to reduce the bend stress. FIG. **5** illustrates a plane view and a cross-sectional view of exemplary bend patterns **300**, which may be applied to some of the components. The bend patterns **300** described above may be used in the support layer **108**, the polarization layer **110**, the touch sensor layer **114** and various other elements of the flexible display **100**.

The flexible display **100** may utilize more than one type of bend patterns. It should be appreciated that a number of bend patterns and the types of the bend patterns **300** utilized by the components is not limited. If desired, the depth of the patterns may not be deep enough to penetrate through the component entirely but penetrate only partially through the respective layer. As will be described in further detail below, a buffer layer positioned between the base layer **106** and the TFT as well as a passivation layer covering a conductive line may be also be provided with the bend pattern for reducing bend stress.

Support Member

As mentioned, the support layer **108** may not be present at the bend allowance section to facilitate easier bending of the base layer **106**. Absent the support layer **108**, however, the curvature at the bend allowance section may be easily altered by external force. To support the base layer **106** and maintain the curvature at the bend allowance section, the flexible display **100** may also include a support member **116**, which may also be referred to as a "mandrel." The exemplary support member **116** depicted in FIG. **4** has an elongated body portion and a rounded end portion. The base layer **106** and the support member **116** are arranged so that that the rounded end portion of the support member **116** is positioned at the underside of the base layer **106** corresponding to the bend allowance section of the flexible display **100**.

In embodiments where a bend portion is provided at an edge of the flexible display **100**, the support member **116** can be provided at the edge of the flexible display **100**. In this setting, a part of the base layer **106** may come around the rounded end portion of the support member **116** and be positioned at the underside the support member **116** as depicted in FIG. **4**. Various circuits and components in the inactive area of the flexible display **100**, such as drive ICs and interfaces for connecting chip-on-flex (COF) and flexible printed circuit board (FPCB), may be provided on the base layer **106** that is positioned at the rear side of the flexible display **100**. In this way, even the components that are not flexible enough to be bent in a bend radius desired by the flexible display **100** can be placed under the active area of the flexible display **100**.

The support member **116** can be formed of plastic material such as polycarbonate (PC), polyimide (PI), polyethylene naphthalate (PEN), polyethylene terephthalate (PET), other suitable polymers, a combination of these polymers, etc. The rigidity of the support member **116** formed of such plastic materials may be controlled by the thickness of the support member **116** and/or by providing additives for increasing the rigidity. The support member **116** can be formed in a desired color (e.g., black, white, etc.). Further, the support member **116** may also be formed of glass, ceramic, metal or other rigid materials or combinations of aforementioned materials.

Size and shape of the rounded end portion of the support member **116** can vary depending on the minimum curvature desired at the bend allowance section of the flexible display **100**. In some embodiments, the thickness of the rounded end portion and the thickness of the elongated body portion may be substantially the same. In other embodiments, the elongated body portion, which has a planar shape, may be thinner than the rounded end portion of the support member **116**. With a thinner profile at the elongated body portion, the support member **116** can support the bend allowance section while avoiding unnecessary increase in the thickness in the flexible display **100**.

Since the support at the bend allowance section is provided by the rounded end portion of the support member **116**, the elongated planar portion extending toward the substantially flat portion of the flexible display **100** needs not be extended into the active area. While the elongated body portion can be extended under the active area for various reasons, the length of the elongated body portion from the rounded end portion towards the opposite end is sufficient so long as it provides enough surface area for securing the support member **116** in a desired location of the flexible display **100**.

To secure the support member **116** in the flexible display **100**, an adhesive layer **118** may be provided on the surface of the support member **116**. The adhesive layer **118** may include a pressure-sensitive adhesive, a foam-type adhesive, a liquid adhesive, a light-cured adhesive or any other suitable adhesive material. In some embodiments, the adhesive layer **118** can be formed of, or otherwise includes, a compressible material and serve as a cushion for the parts bonded by the adhesive layer **118**. As an example, the constituent material of the adhesive layer **118** may be compressible. The adhesive layer **118** may be formed of multiple layers, which includes a cushion layer (e.g., polyolefin foam) interposed between an upper and a lower layers of an adhesive material.

The adhesive layer **118** can be placed on at least one of the upper surface and the lower surface of the elongated body portion of the support member **116**. When the bend portion

of the flexible display **100** wraps around the rounded end portion of the support layer **116**, an adhesive layer **118** can be provided on both the lower surface (i.e., the surface facing the rear side) and the upper surface (i.e., the surface facing the front side) of the elongated body portion. If desired, an adhesive layer **118** may be provided between the surface of the rounded end portion of the support member **116** and the inner surface of the base layer **106**.

During bending, a part of the flexible display **100** on one side of the support member **116** may be pulled toward the support member **116**, and the base layer **106** may be damaged by the highest and the lowest edges of the rounded end portion. As such, the height of the adhesive layer **118** and the support layer **108** between the support member **116** and the base layer **106** may be at least equal to or greater than the vertical distance between the highest edge of the rounded end portion and the surface of the elongate body portion where the adhesive layer **118** is placed. In other words, the height of the space created by the thickness difference between the rounded end portion and the elongated body portion of the support member **116** may be equal to or less than the collective thickness of the support layer **108** and the adhesive layer **118**.

Depending on the shape of the support member **116**, a thickness of the adhesive layer **118** on the upper and the lower surfaces of the elongated body portion may be different. For instance, the elongated body portion, which is thinner than the rounded end portion, may not be at the center of the rounded end portion of the support member **116**. In such cases, the space on one side of the support member **116** may be greater than the space on the opposite side.

In another example, the lowest edge of the rounded end portion may be in-line with the bottom surface of the elongated body portion such that the space is provided only on one side of the elongated body portion. In such cases, the adhesive layer **118** on one side of the elongated body portion of the support member **116** can be thicker than the one on the opposite side. It should be appreciated that the dimensions of the support member **116** in FIG. **4** may be exaggerated for the purposes of simpler explanation.

Exemplary Arrangement

FIGS. **6**A, **6**B and **6**C are simplified cross-sectional view showing an exemplary arrangement of elements in various embodiments of the flexible display **100**. In one suitable configuration, the thickness of the rounded end portion and the elongated body portion of the support member **116**A may be substantially the same as illustrated in FIG. **6**A. Such a support member **116**A can be formed of the plastic materials mentioned above. The support member **116**A may also be formed of a folded thin sheet metal (e.g., SUS). In this case, the folded edge of the sheet metal can serve as the rounded end portion of the support member **116**A. Even when a sheet metal is used to form the support member, the rounded end portion can have greater thickness than the elongated body portion. For instance, pressure can be applied on the part of the folded metal sheet for the elongated body portion to make that portion thinner than the folded edge.

In FIG. **6**A, the adhesive layer **118**A is illustrated as being applied on the upper, the lower surface and the surface of the rounded end portion of the support member **116**A. As the thickness of the support member **116**A at the rounded end portion and the elongated body portion is about the same, the thickness of the adhesive layer **118**A may have a substantially uniform thickness on the surface of the support member **116**A. However, it should be noted that the adhesive layer **118**A can be thinner and/or thicker at selective parts of the support member **116**A.

In another suitable configuration, the elongated body portion of the support member **116** is thinner than its rounded end portion. In this regard, the bottom surface of the elongated body portion is in-line with the lowest edge of the rounded end portion, providing a support member **116**B with a flat bottom as depicted in FIG. **6**B. In this exemplary configuration, the support members **116**B may be formed of one or a combination of aforementioned plastic materials (e.g., polycarbonate). Also, the adhesive layer **118**B provided on the upper surface of the elongated body portion is thicker than the adhesive layer **118**B provided on the bottom surface of the elongated body portion of the support member **116**B. The adhesive layer **118**B on the upper surface of the elongated body portion may include a cushion layer described above while the adhesive layer **118**B on the lower surface does not.

In yet another suitable configuration shown in FIG. **6**C, neither the top nor the bottom surfaces of the elongated body portion of the support member **116**C is in-line with the highest/lowest edges of the rounded portion. The support members **116**C may be formed of one or a combination of aforementioned plastic materials (e.g., polycarbonate). In this example, the elongated body portion is off-centered (i.e., closer to the lowest edge of the rounded portion), and the adhesive layer **118**C on the upper surface of the elongated body portion is thicker than the adhesive layer **118**C on the lower surface. The adhesive layer **118**C on the upper surface of the elongated body portion may include a cushion layer described above while the adhesive layer **118**C on the lower surface does not.

In the exemplary configurations depicted in FIGS. **6**A-**6**C, the support layer **108** on the upper side of the support member **116** is extended further out toward the bend allowance section than the encapsulation **114** there above. In other words, a part of the base layer **106** toward the bend allowance section is not covered by the encapsulation **114**, but provided with the support layer **108** thereunder. The extra length of the support layer **108** can help in keeping a steady rate of curvature in the bend allowance section. The edge of the support layer **108** under the support member **116** may be shifted away from the bend allowance section. In some embodiments, the edge of the support layer **108** toward the bend allowance section can be provided with a flange, which extends even further out toward the bend allowance section as shown in FIG. **6**A. In one example, the flange may be made by cutting, or otherwise patterning, the support layer **108** to have a tapered edge. In another example, the flange can be provided by stacking at least two support layers with their edges shifted from each other. While omitted in FIGS. **6**B and **6**C, the flange can be provided in those embodiments as well.

It should be appreciated that the configurations described above in reference to FIGS. **6**A-**6**C are merely illustrative. Adhesive layers having the same thickness can be provided on the upper and the lower surfaces of the support member regardless of the position of the elongated body portion. Further, adhesive layers on both the upper surface and the lower surface of the support member can include a cushion layer.

Wire Trace

Several conductive lines are included in the flexible display **100** for electrical interconnections between various components therein. The circuits fabricated in the active area and inactive area may transmit various signals via one or

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more conductive lines to provide a number of functionalities in the flexible display **100**. As briefly discussed, some conductive lines may be used to provide interconnections between the circuits and/or other components in the central portion and the bend portion of the flexible display **100**.

As used herein, the term conductive lines broadly refers to a trace of conductive path for transmitting any type of electrical signals, power and/or voltages from one point to another point in the flexible display **100**. As such, conductive lines may include source/drain electrodes of the TFTs as well as the gate lines/data lines used in transmitting signals from some of the display driving circuits (e.g., gate driver, data driver) in the inactive area to the pixel circuits in the active area. Likewise, some conductive lines, such as the touch sensor electrodes, pressure sensor electrodes and/or fingerprint sensor electrodes may provide signals for sensing touch input or recognizing fingerprints on the flexible display **100**. Furthermore, conductive lines can provide interconnections between elements of the active area in the central portion and elements of the secondary active area in the bend portion of the flexible display **100**. It should be appreciated that the functionalities of conductive lines described above are merely illustrative.

Conductive lines in a flexible display **100** should be carefully designed to meet various electrical and non-electrical requirements. For instance, a conductive line may have a specific minimum electrical resistance level, which may vary depending on the type of signals to be transmitted via the conductive line. Some conductive lines may be routed from the substantially flat portion to the bend portion of the flexible display **100**. Such conductive lines should exhibit sufficient flexibility to maintain its mechanical and electrical robustness. To this end, some conductive lines of the flexible display **100** may have a multi-layered structure.

FIGS. **7**A and **7**B each illustrates exemplary stack structure of the multi-layered conductive line. Referring to FIG. **7**A, the conductive line **120** has a multi-layered structure in which the primary conductive layer **122** is sandwiched between the secondary conductive layers **124**. The primary conductive layer **122** may be formed of material with a lower electrical resistance than that of the secondary conductive layer **144**. Non-limiting examples of the materials for the primary conductive layer **122** includes copper, aluminum, transparent conductive oxide, or other flexible conductors.

The secondary conductive layer **124** should be formed of conductive material that exhibits sufficiently low ohmic contact resistance when formed in a stack over the primary conductive layer **122**. Low ohmic contact resistance between the conductive layers is not the only factor in the selection of materials for the conductive layers in the multi-layered conductive line **120**. While meeting the stringent electrical and thermal requirements (e.g., resistance, heat generation, etc., the materials of the conductive line **120** should also satisfy the minimum mechanical stress requirement (e.g., Young's modulus). That is, both the primary conductive layer **122** and the secondary conductive layer **124** should be formed of materials exhibiting sufficient flexibility.

Accordingly, in some embodiments, at least some of the conductive lines **120** of the flexible display **100** may be formed with two or more of layers selected from aluminum (Al), titanium (Ti), molybdenum (Mo), Copper (Cu) layers. Examples of such combination include an aluminum layer sandwiched between titanium layers (Ti/Al/Ti), an aluminum layer sandwiched between upper and lower molybdenum layers (Mo/Al/Mo), a copper layer sandwiched between titanium layers (Ti/Cu/Ti) and a copper layer sandwiched between upper and lower molybdenum layers (Mo/Cu/Mo). Of course, other conductive materials can be used for the primary/secondary conductive layers.

Electronic device employing the flexible display **100**, for instance a wearable electronic device or a water submergible electronic device, may expose the flexible display **100** in a humid environment. In some cases, moist can reach the conductive line **120**. Dissimilar metals and alloys have different electrode potentials, and when two or more come into contact in an electrolyte, one metal acts as anode and the other as cathode. The electro-potential difference between the dissimilar metals accelerates corrosion on the anode member of the galvanic couple, which would be the primary conductive layer **122** in the multi-layered conductive line **120** (e.g., Al layer in the Ti/Al/Ti stack). The anode metal dissolves into the electrolyte, and deposit collects on the cathodic metal.

When using a multi-layered conductive line **120** described above, any surface that exposes both the primary conductive layer **122** and the secondary conductive layer **124** may become a galvanic corrosion initiation point. Accordingly, in some embodiments of the flexible display **100**, at least some conductive lines **120** is provided with a structure in which the outer surface of the primary conductive layer **122** is surrounded by the secondary conductive layer **124** as shown in FIG. **7**B. Such a configuration hinders the electrolyte from being in contact with both the primary conductive layer **122** and the secondary conductive layer **124**, thereby minimizing loss of the primary conductive layer **122** by galvanic corrosion.

Such a multi-layered conductive lines **120** can be created by first depositing the material for the primary conductive layer **122** (e.g., Al) over the secondary conductive layer **124** (e.g., Ti). Here, the secondary conductive layer **124** underneath the primary conductive layer **122** may have greater width. Etch resist material is formed over the stack of these two layers and etched (e.g., dry etch, wet etch, etc.) to form the conductive line in a desired trace. After striping the etch resistance material, another layer of secondary conductive layer **124** (i.e., Ti) is deposited over the patterned structure (i.e., Ti/Al). The width of the secondary conductive layer **124** deposited over the primary conductive layer **122** may be greater than the width of the primary conductive layer **122** to cover the outer surface of the primary conductive layer **122**. Another round of etching and striping of the etch resistance material is performed to form the stack of a multi-layered conductive line in a desired conductive line trace design. It should be understood that the multi-layered conductive line formation processes described above are merely an example. Accordingly, some processes may be added and/or skipped in making a multi-layered conductive line.

A trace design of a conductive line is an important factor, which can affect the conductive line's electrical and mechanical properties. To meet the electrical and mechanical requirements, some portion of a conductive line may be configured differently from another portion of the conductive line. As such, a portion of a conductive line at or near the bend allowance section of the flexible display **100** may be provided with several features for bend stress management.

Bend stress management of the insulation layers near the conductive line is just as important as the managing the strain of the conductive line itself. Various insulation layers, such as the buffer layer **126**, the passivation layer **128**, a gate insulation layer (GI layer) and an interlayer dielectric layer

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(ILD layer) positioned below and/or above the conductive line **120** may include a layer of inorganic materials. Layers that are formed of inorganic material, for instance a silicon oxide layer and a silicon nitride layer, are generally more prone to cracks than the metal layers of the conductive line. Even when the conductive lines have a sufficient flexibility to cope with the bend stress without a crack, some of the cracks initiated from the insulation layer can propagate into the conductive lines and create spots of poor electrical contacts in the flexible display **100**.

In addition to applying a trace design for reducing bend stress on a conductive line, some of the insulation layers above and/or below the layer of conductive line may be patterned according to the trace design of the conductive line to minimize the chance of cracks. Various insulation layer patterning methods, such as wet etching and/or dry etching processes, can be used to form a trace of insulation layer that corresponds to the trace of a conductive line. Lack of insulation layer, especially the inorganic material based insulation layer around the trace of a conductive line not only lowers the chance of crack generation, but it also cuts off the path for a crack propagation. For convenience of explanation, a trace of conductive line **120** and a trace of insulation layers covering at least some part of the conductive line **120** are collectively referred to as the "wire trace" in the following description.

Trace Design

As mentioned, a trace design for the conductive line and the insulation layer covering the conductive line plays an important role in increasing the robustness of the wire trace. Numerous parameters, ranging from a thickness and a width of a wire trace to a length and a fan-out angle of a wire trace segment with respect to the bending direction of the flexible display **100**, are associated with the wire trace design. In addition to the aforementioned parameters, various other parameters regarding the conductive line **120** and the insulation layer trace are specifically tailored based on the placement and the orientation of the wire trace within embodiments of the flexible display **100**.

Strain on a wire trace from the bend stress will be greater as the direction in which the wire trace extends is more aligned with the tangent vector of the curvature. In other words, a wire trace will withstand better against the bend stress if the length of a wire trace segment being parallel to the tangent vector of the curvature is reduced. No matter which direction the wire trace is extended to, there will always be a portion in the wire trace that is measurable in the bending direction. However, a length for each continuous measurable portion (i.e., a segment) being aligned parallel to the bending direction can be reduced by employing a strain-reducing trace design in the wire trace.

FIG. **8** illustrates some of the exemplary strain-reducing trace designs. Any one or more of a sign-wave, a square-wave, a serpentine, a saw-toothed and a slanted line trace designs illustrated in FIG. **8** can be used for wire traces of the flexible display **100**. Employing such a strain-reducing trace design increases the portion of the wire trace arranged in a slanted orientation with respect to the tangent vector of the curvature. This, in turn, limits the length of the wire trace segment extending in a straight line parallel to the bending direction.

Since the cracks in the wire trace by bending of the flexible display generally initiate from an inorganic insulation layer, it is imperative that the length of the insulation layer trace being aligned with the tangent vector of the curvature is also minimized. In the single line strain-reducing designs, the width and the shape of the conductive line trace as well as the width of the patterned inorganic insulation layers interfacing with the surface of the conductive line trace should be kept minimal.

The strain-reducing trace designs illustrated in FIG. **8** are merely exemplary, and other trace designs for reducing the length of a wire trace segment parallel to the bending direction may be used in various embodiments of the flexible display **100**. Further, it should be noted that some wire traces may adopt different strain-reducing trace design from other wire traces in a flexible display **100** depending on their electrical and/or mechanical requirements. For instance, a strain-reducing trace design used for a data signal line may be different from a strain-reducing trace design used for a power line.

To further improve robustness, a wire trace may employ a trace design in which the wire trace repeatedly splits and converges back in a certain interval. In other words, a wire trace includes at least two sub-traces arranged to form a trace design resembling a chain with a series of connected links. The angles of split and merge define the shape of each link, which allows to limit the length of the wire trace segment measurable in straight line parallel to the bending direction.

Referring to FIG. **9**A, the conductive line **120** includes sub-trace A and sub-trace B, which are split away from each other and merge back at each joint X. Between the first joint X(**1**) and the second joint X(**2**), a part of the sub-trace A is extended for a predetermined distance in a first direction angled away from the tangent vector of the curvature, and another part of the sub-trace A is extended in a second direction. The sub-trace B is arranged in a similar manner as the sub-trace A, but in a mirrored orientation in reference to the tangent vector of the curvature. The distances and directions in which the sub-traces are arranged between the two adjacent joints X define the shape and the size of the link in the chain as well as the open area surrounded by the sub-traces. In this example, the shape of the conductive line **120** between the joint X(**1**) and X(**2**) (i.e., link) has a diamond shape with an open area surrounded by the sub-trace A and the sub-trace B. With additional joints X, the conductive line **120** forms a chain of diamond shaped links, and thus the trace design may be referred to as the diamond trace design.

Compare to the non-split strain-reducing trace designs shown in FIG. **8**, the strain-reducing trace design shown in FIG. **9**A can provide significant advantages in terms of electrical property. For instance, the wire trace provided with the split/merge trace design can provide much lower electrical resistance than the wire traces employing the mountain trace design, the sign-wave trace designs or other single line strain-reducing trace designs of FIG. **8**. In addition, sub-traces can serve as a backup electrical pathway in case one of the sub-traces is damaged or severed by cracks.

The insulation layers covering the surfaces of the conductive line **120** is also patterned in a trace design corresponding to the trace design of the conductive line **120**. As such, the open area surrounded by the sub-trace A and the sub-trace B is free of the inorganic insulation layer(s), or has thinner inorganic insulation layer(s) than the areas under and/or above the trace of conductive line **120**. As such, the length of the insulation layer trace measurable in straight line parallel to the bending direction can be limited to reduce the chance of crack initiation and propagation.

Various additional factors must be considered for the strain-reducing trace designs based on a plurality of sub-traces. The split/merge angles and the length of each sub-traces between two adjacent joints X should provide an offset for the inorganic insulation layer at the joints X and at

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the outer corners where the sub-trace changes its direction between two adjacent joints X. To put it in another way, the open area, which is surrounded by the split sub-traces between two joints X of the wire trace, should have a size and a shape to minimize the length in which an inorganic insulation layer trace of the wire trace extending parallel to the bending direction.

In the diamond trace design depicted in FIG. **9**A, the buffer layer **126** and the passivation layer **128** covering the trace of the conductive line **120** are patterned with a predetermined margin from the outer trace (i.e., outer edge) of the conductive line **120**. Other than the insulation layers with the predetermined margin remaining to cover the conductive line **120**, the open area surrounded by the sub-traces A and B, which is denoted as FA**2**, is free of the insulation layers. As such, a trace of insulation layers are formed in accordance with the trace design of the conductive line **120**. The length of the open area without the insulation layers measured in orthogonal direction from the bending direction is greater than the width of the inorganic insulation layer trace at the joint X measured in the same direction. In this setting, the open area FA**2** surrounded by the sub-traces A and B as well as the area next to the joint X can be free of the inorganic insulation layers, or otherwise provided with a reduced number of inorganic insulation layers.

Referring to FIG. **9**A, the insulation layer free area FA**1** prohibits the insulation layer of the sub-trace A and the sub-trace B between the two joints X(**1**) and X(**2**) to be extended in a continuous straight line. Similarly, the insulation layer free area FA**2** prohibits the insulation layer between the two joints X(**1**) and X(**2**) to be extended in a continuous straight line. Accordingly, the length of each segment of the insulation layer trace being aligned to the tangent vector of the curvature is minimized.

Further reduction in the length of the insulation layer trace aligned to the tangent vector of the curvature can be obtained by reducing the width of the conductive line **120** and the margin of the insulation layer beyond the edge of conductive line **120**. It should be noted that the amount of reduction in the width of conductive line **120** is limited with the single line strain-reducing trace designs depicted in FIG. **8** because the reduction of conductive line width can make its electrical resistance too high for its particular use within the flexible display **100**. With the split/merge trace design of FIG. **9**A, however, the width of the conductive line **120** and the insulation layer trace can be reduced while providing sufficient electrical property.

Greater split/merge angle of the sub-traces with respect to the bending direction may allow to reduce the lengths of the conductive line **120** and the insulation layer trace extending along the tangent vector of the curvature to a greater extent. Accordingly, a lower chance of crack initiation may be afforded in the wire trace by selectively increasing the split/merge angle of sub-traces at high bend stress regions.

It should be noted that the split angle of the sub-traces can affect the distance between the two adjacent joints X in the diamond trace design. The distance between the joints X need not be uniform throughout the entire wire trace. The intervals at which the trace splits and merges can vary within a single trace of wire based on the level of bend stress exerted on the parts of the wire trace. The distance between the joints X may be progressively shortened down for the parts of the wire trace towards the area of the flexible display **100** subjected to higher bend stress (e.g., area having smaller bend radius, area having larger bend angle). Conversely, the distances between the joints X can progressively widen out towards the area subjected to lower bend stress.

Even with the strain-reducing trace design, the inevitable bend stress remains at certain points of the trace (i.e., stress point). The location of stress point is largely dependent on the shape of the trace as well as the bending direction. It follows that, for a given bending direction, the wire trace can be designed such that the remaining bend stress would concentrate at the desired parts of the wire trace. Knowing the location of the stress point in the wire trace, a crack resistance area can be provided to the stress point to make the wire trace last longer against the bend stress.

Referring back to FIG. **9**A, when a wire trace having the diamond trace design is bent in the bending direction, the bend stress tends to focus at the angled corners (i.e., the vertexes of each diamond shaped link), which are denoted as the stress point A and stress point B. As such, cracks tends to initiate and grow between the inner and outer edges of the wire trace. For instance, at the stress points A, a crack may initiate from the inner trace line **120**(IN) and grow toward the outer trace line **120**(OUT). Similarly, a crack may initiate from the outer wire trace line **120**(OUT) and grow toward the inner trace line **120**(IN) at the stress points B.

Accordingly, the width of the conductive line **120** at the stress points A can be selectively increased to serve as the crack resistance area. As depicted in FIG. **9**A, the widths (WA, WB) of the conductive line **120** at the stress points A and B, which are measured in the direction perpendicular to the bending direction, may be longer than the width (W) of the conductive line **120** at the parts between the stress points A and B. The extra width at the stress points can make the conductive line **120** hold out longer before a complete severance in the conductive line **120** occurs by the growth of a crack at the stress points.

It should be reminded that the length for the continuous portion of the insulation layer trace being aligned to the bending direction should be kept minimal. Increasing the width of the conductive line **120** at the stress points A and B may necessitate increase in the width of the insulation layer trace at the respective area, which results in lengthening the insulation layer trace being aligned parallel to the bending direction.

Accordingly, in some embodiments, the width of the conductive line **120** measured in the direction perpendicular to the tangent vector of the curvature at the stress points A ranges from about 2.5 μm to about 8 μm, more preferably, from about 3.5 μm to about 6 μm, more preferably from about 4.5 μm to about 8.5 μm, and more preferably at about 4.0 μm. The width of the conductive line **120** at the stress points B should also be maintained in the similar manner as the width of the conductive line **120** at the stress points A. As such, the width of the conductive line **120** at the stress points B may range from about 2.5 μm to about 8 μm, more preferably, from about 3.5 μm to about 6 μm, more preferably from about 4.5 μm to about 8.5 μm, and more preferably at about 4.0 μm. Since the sub-trace A and the sub-trace B merges at the stress point B, the width of the conductive line **120** at the stress points B may be longer than width at the stress points A.

In some embodiments, one of the inner trace line **120**(IN) and the outer trace line **120**(OUT) may not be as sharply angled as the other trace line at the stress points A to minimize the chance of crack initiating from both sides. In the embodiment depicted in FIG. **9**A, the inner trace line **120**(IN) is more sharply angled than the outer trace line **120**(OUT) at the stress points A. However, in some other embodiments, the outer trace line **120**(OUT) may be more sharply angled than the inner trace line **120**(IN) at the stress points A. In both cases, the less sharply angled trace line can

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simply be more rounded rather than being a straight line as the outer trace line **120**(OUT) depicted in FIG. **9**A. Further, both the inner trace line **120**(IN) and the outer trace line **120**(OUT) at the stress points A can be rounded.

The wire trace may split into additional number of sub-traces, resulting series of links arranged in a grid-like configuration. As an example, a wire trace can be configured as a web of diamond trace shapes as illustrated in FIG. **9**B. Such a trace design is particularly useful for a wire trace that transmit a common signal to multiple points or for a wire trace that require a very low electrical resistance. For example, a VSS line and a VDD line in the flexible display **100** may have the grid-like trace design, especially if such lines are arranged to cross over a bend allowance section. Neither the number of sub-traces nor the shapes of the sub-traces of the grid-like trace design are particularly limited as the exemplary design depicted in FIG. **9**B.

In some embodiments, the grid width can be reduced or increased in between two ends within the flexible display **100**. Also, the grid-like wire trace shown in FIG. **9**B can converge back to form the diamond trace shown in FIG. **9**A or to form a non-split strain-reducing trace design. In some cases, the size of each diamond-shaped trace of a grid-like wire trace may be larger than the size of each diamond-shaped trace of a diamond-chain trace to reduce the resistance.

Wire Trace Arrangement

Due to the portions angled away from the bending direction, a wire trace with a strain-reducing trace design may necessitate a larger routing area within the flexible display **100**. In embodiments where a non-display area at the edge of the flexible display **100** is bent, the increase in the routing area for accommodating the wire traces can actually increase the size of the inactive area to be hidden under a masking.

Accordingly, wire traces applied with a strain-reducing trace design may be arranged to facilitate tight spacing between adjacent wire traces. For instance, two adjacent wire traces with a strain-reducing trace design may each include a non-linear section, which would have a convex side and a concave side. The two adjacent wire traces can be arranged in the flexible display such that the convex side of the non-linear section in the first wire trace is positioned next to the concave side the non-linear section in the second wire trace. Since the spacing between the two adjacent wire traces is limited by the shape and the size of the wire traces, the non-linear section in the strain-reducing trace design of the first wire trace may be larger than the non-linear section in the strain-reducing trace design of the second wire trace. Of course, one of the first wire trace and the second wire trace may have a different strain-reducing trace design to better accommodate the non-linear section of the other wire trace.

In some instances, two or more wire traces arranged next to each other may each be applied with a strain-reducing trace design, and each of the wire traces may have a plurality of indented sections and distended. In such cases, the wire traces can be arranged such that the distended section of one of the wire traces to be positioned next to the indented sections of the adjacent wire trace.

FIG. **10** illustrates an exemplary arrangement of multiple wire traces, each having the diamond trace design described above. The split of the sub-traces widens the layout of the wire trace to create the distended section, whereas merging of the sub-traces narrows the layout of the wire trace to create the indented section. Accordingly, in terms of its layout, the indented section of the wire trace is at the joint X, whereas the distended section of the wire trace is at the point where the split/merge angles of the sub-traces change between two adjacent joints X.

As shown in FIG. **10**, position of the joints X in a first wire trace and the joints X in a second wire trace are arranged in a staggered configuration. In this arrangement, the vertexes of the diamond shaped link at the distended section in the first wire trace are positioned next to the joints X at the indented sections of the adjacent wire traces. Such a staggered arrangement of the wire traces may help in lowering the electrical noises on the wire traces due to close proximity between the wire traces, and thus the distance between the wire traces can be reduced. Even a tight spacing between the wire traces may be possible by arranging the distended section of a wire trace to be positioned closer toward the indented section of the adjacent wire trace. For instance, the vertexes at the wide parts of one wire race can be placed in the open area FA**1**, which is created by the split/merge angle and the length of the sub-trace in the adjacent wire trace. As such, the staggered arrangement allows to maintain certain minimal distance between the wire traces while reducing the amount of space taken up by the wire traces.

Patterned Insulation Layer

As mentioned, it should be noted that cracks primarily initiate from the inorganic insulation layers. Accordingly, propagation of cracks can be suppressed by selectively removing inorganic insulation layers from the areas prone to cracks. To achieve this, one or more inorganic insulation layers and/or stack of insulation layers including a layer of inorganic material can be selectively etched away at various parts of the flexible display **100**.

For example, the insulation layer under the conductive line **120** can be etched away. The insulation layer under the conductive line **120** may be the buffer layer **126**, which may include one or more layers of inorganic material layers. The buffer layer **126** may be formed of one or more layers of a SiNx layer and a SiO2 layer. In one suitable configuration, the buffer layer **126** may be formed of alternating stacks of a SiNx layer and a SiO2 layer. The buffer layer **126** is disposed on the base layer **126**, but under the TFT.

To facilitate easier bending of the flexible display **100**, a part of the buffer layer **126** may etched away in the bend portion of the flexible display **100**. Accordingly, the buffer layer **126** formed on the substantially flat portion of the base layer **106** may be thicker than the buffer layer **126** over the bend portion of the base layer **106**. When the buffer layer **126** is formed in a stack of multiple sub-layers, the buffer layer **126** in the substantially flat portion of the flexible display **100** may include one or more additional sub-layers than the buffer layer in the bend portion of the flexible display **100**.

For example, the buffer layer **126** in the substantially flat portion may include multiple stacks of a SiNx layer and a SiO2 layer, and the buffer layer **126** in the bend portion includes a single stack of a SiNx layer and a SiO2 layer. It is also possible to have only a single layer of either a SiNx layer or a SiO2 layer in some part of the bend portion. In one suitable configuration, each SiNx layer and SiO2 layer in the buffer layer **126** may have a thickness of about 1000 Å. As such, the thickness of the buffer layer **126** in the bend portion of the flexible display may range from about 100 Å to about 2000 Å.

In the substantially flat portion of the flexible display **100**, additional layer of inorganic layer may be provided immediately below the semiconductor layer of the TFT, which may be referred to as the active buffer. In some embodiments, an inorganic layer, which is most closely positioned

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under the active layer of the TFT, may be much thicker than the individual inorganic layers of the buffer layer **126**.

The buffer layer **126** in the bend allowance section may be etched even further to expose the base layer **106** while leaving the buffer layer **126** intact under the conductive line **120**. In other words, a recessed area and a protruded area are provided in the bend portion of the flexible display **100**. The protruded area includes the buffer layer **126** provided on the base layer **106**, whereas the recessed area has the base layer **106** exposed without the buffer layer **126** disposed thereon.

In one exemplary configuration shown in FIG. **11**A, the conductive line **120** is positioned on the protruded area, and the passivation layer **128** is positioned over the conductive line **120** on the protruded area. Although the passivation layer **128** may be temporarily deposited over the recessed area, the passivation layer **128** can be removed from the recessed area by a dry etch or a wet etch process. As such, the recessed area can be substantially free of the passivation layer **128**. When etching the passivation layer **128** from the recessed area, part of the base layer **106** can be etched as well. Accordingly, the thickness of the base layer **106** at the recessed area can be lower than that of the base layer **106** elsewhere in the flexible display **100**. When the buffer layer **126** is etched away as shown in FIG. **11**A, propagation of crack from one part of the buffer **126** to another part of the buffer layer **126** can be hindered by the space in the recessed area. Similarly, propagation of cracks by the passivation layer **128** is also hindered by the space of the recessed area. Accordingly, damage to the conductive line **120** by propagation of cracks can be reduced.

In another suitable configuration shown in FIG. **11**B, the recessed area includes the base layer **106** that is etched to a certain depth, and the conductive line **120** is deposited on the base layer **106** of the recessed area. In this setting, the portion of the conductive line **120** is disposed within the base layer **106**. Some part of the conductive line **120** is also deposited on a part of the buffer layer **126** that provides the protruded area. A passivation layer **128** can be deposited over the conductive line **120**, and then etched away from the recessed area to expose the conductive line **120** in the recessed area.

Accordingly, the passivation layer **128** remains on the conductive line **120** positioned on the protruded area. In this configuration, the passivation layer **128** remaining on the buffer layer **126** can inhibit galvanic corrosion as it covers the cross-sectional side surface of the multi-layered conductive line **120**. While cracks generated from the buffer layer **126** may penetrate to the conductive line **120** on the wall of hollow space in the buffer layer **126**, but reaching the part of the conductive line **120** positioned within the base layer **106** will be difficult.

When the conductive line **120** has the multi-layered structure discussed above, the part of the conductive line **120** in the recessed area needs not be covered by the passivation layer **128**. With the passivation layer **128** removed from the surface of the conductive line **120** in the recessed area, crack propagation from the passivation layer **128** can also be prevented. Further, galvanic corrosion generally starts from the edge of the conductive line **120** on the buffer layer, and thus the passivation layer **128** covering the edge of the conductive line **120** on the buffer **126** may not be needed if the distance between the conductive line **120** on the buffer layer **126** and the conductive line **120** in the base layer **106** is sufficiently spaced apart from each other. The configurations shown in FIGS. **11**A and **11**B may be used for the wire traces in the bend allowance section with the strain-reducing trace patterns of FIGS. **8**, **9**A and **9**B. In addition to the bend allowance section, in some embodiments, the patterned insulation layer may also be provided in the routing area between the active area and the bend allowance section as well as the routing area between the COF bonding area and the bend allowance section.

Further, the patterned insulation layer described above can be provided in the active area. However, removal of inorganic insulation layers near the TFTs of the flexible display **100** may affect the electrical characteristic of components in the flexible display **100**. For instance, undesired threshold voltage shift of TFTs may result when some part of the buffer layer **126** is removed. In order to maintain the stability of the TFTs, an additional shield metal layer can be formed under the semiconductor layer of the TFTs. The shield metal layer may be under the buffer layer **126** or interposed between the inorganic layers of the buffer layer **126**. In some embodiments, the shield metal layer may be electrically connected to the source electrode or gate electrode of the TFTs.

In addition to the patterning of insulation layers in various parts of the flexible display **100**, other structural elements can be removed or simplified in some areas of the flexible display **100** to facilitate bending. For example, the touch sensor layer **112**, the polarization layer **110** and the likes may be absent in the bend area of the flexible display **100**. Absence or simplification of these components and the layers would create a number of uneven surfaces where the wire trace may need to cross.

When a wire trace is laid over such an uneven surface, some parts of the wire trace may be placed on a different plane level from another parts of the wire trace. As the parts are on different plane levels, the amount and direction of bend stress and the strain resulting from the bend stress can differ even among the parts of the wire trace. To accommodate the difference, a strain-reducing trace design for the wire traces can include a modified trace design for the portion of the wire trace on the uneven surfaces.

FIG. **12**A is an enlarged cross-sectional view showing an exemplary backplane configuration for a flexible display **100**, in which several insulation layers are removed from the bend portion to facilitate more reliable bending.

Several organic and inorganic layers may be formed in between the base layer **106** and the OLED element layer **102**. In this particular example, alternating stacks of SiNx and SiO2 layers can be disposed on the base layer **106** to serve as the buffer layer **126**. The semiconductor layer of a TFT may be sandwiched by an active-buffer layer and a gate insulation layer that are formed of SiO2 layer. The gate of the TFT is disposed on an interlayer dielectric layer (ILD), and the source/drain of the TFT having the multi-layered structure as discussed above is sandwiched between the ILD and a passivation layer. Here, the ILD may be formed of a stack of SiNx and SiO2, and the passivation layer is formed of SiNx. Then, a planarization layer is disposed over the passivation layer so that the anode for the OLED can be disposed thereon.

As mentioned above, use of the strain-reducing trace design is not just limited to the part of the wire traces within the bend portion. Also, the strain-reducing trace design can be applied to the part of the wire traces in the routing areas outside the bend allowance section. Using the strain-reducing trace design for the wire trace in such routing area can afford increased protection to the wire trace against the bend stress.

In the routing area, however, several layers of organic and/or inorganic material layers between the base layer **106** and the OLED element layer **102** may be absent to facilitate

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bending of the flexible display **100**. Such organic and/or inorganic layers, including but not limited to the ILD, the gate insulation layer, buffer layer, passivation layer, planarization layer, etc. may not be present in the bend portion of the flexible display **100**. Some of these layers may have been removed from the area by several etching processes.

By way of example, several insulation layers on the buffer layer **126** may be etched by a first etch process EB**1**, which is followed by the second etch process EB**2** that etches away the active buffer and a part of the buffer layer **126** (e.g., a stack of a SiNx layer and a SiO2 layer). These etching processes create multiple stepped regions as shown in FIG. **12**A, with one or more of vertically sloped surfaces and horizontally leveled surfaces, where the wire trace is disposed thereon. The wire trace laid over the vertically sloped surfaces and horizontally leveled surfaces would have several bent spots, such as EB**1** area and EB**2** area.

When bending the flexible display **100** in the bending direction, the wire trace may experience more strain at or near the stepped region. Numerous tests and experiments indicate that the chance of a crack is especially high in the wire trace crossing over the stepped region between the EB**1** area and the EB**2** area. Accordingly, in some embodiments, the strain-reducing trace design for the wire trace has a reinforced portion at or near the stepped region between a high-leveled surface and a low-leveled surface provided by insulation layers of the flexible display.

In the example shown in FIG. **12**B, the wire trace has a simple straight line trace at its both ends. However, the part of the conductive line **120** that crosses over the bent areas EB**1** and EB**2** is reinforced with a modified trace design. At the modified portion, the conductive line **120** is provided with a wider width extra width WR to ensure the preservation of the conductive line **120** even if cracks initiate from the insulation layer near EB**1** and EB**2** areas. The distance DR in which the conductive line **120** is provided with the modified trace design depends on the thickness of the insulation layers etched by the etch processes as well as the distance between the first leveled surface (e.g., plane level at EB**1**) and a second leveled surface (e.g., plane level at EB**2**).

Past the modified portion (i.e., reinforced portion), the wire trace is illustrated as having the strain-reducing trace design (i.e., diamond trace design), which is previously described with FIG. **9**A. It should be appreciated that the strain-reducing trace design of the wire trace applied with the modified portion is not limited to the strain-reducing trace design depicted in FIG. **12**B. Various embodiments of the strain-reducing trace design can include a modified trace design for the portion of the wire trace corresponding to the stepped areas of two differently leveled surfaces.

While this may not always be the case, the routing areas adjacent to the bend allowance section may be the substantially flat portions of the flexible display **100**. In such cases, the EB**1** and EB**2** areas would be positioned at or just outside start of the bend allowance section in the bend portion, and the wire trace may be provided with the reinforced portion in its trace design.

The increased width WR of the reinforced conductive line **120** portion may serve its purpose well at or near the beginning and the end of the bend allowance section where the curvature is relatively small. The wider width WR of the wire trace and the length in which the modified trace portion is applied in the wire trace can increase the length of the wire trace that is aligned parallel to the bending direction. This would be make the wire trace harder to hold out against the bend stress at the region with greater bend radius.

For this reason, the distance DR in which the reinforced portion is should be limited such that the reinforced conductive line portion does not extend too much toward the bend allowance section. Accordingly, the distance DR of the reinforced conductive line portion may be limited such that the trace design of the reinforced conductive line portion does not extend beyond the bend allowance section where it is bent more than a predetermined threshold bend angle. By way of an example, the reinforced conductive line portion may not extend beyond the point where it is 30° curved away from the tangent plane of the curvature. The threshold bend angle may be less than 20°, for example 10°, and more preferably less than 7°.

The wire trace, which is provided with the reinforced portion at the stepped areas, may extend across the bend allowance section and routed to pads for COF or other components of the flexible display **100**. In such instances, additional stepped region (similar to EB**1** and EB**2**) may exist at or near the opposite end of the bend allowance section. The conductive line at or near such bent spots may be reinforced in the similar manner as the modified portion of the wire trace at the opposite end as shown in FIG. **12**B. If desired, the reinforced conductive line portion at or near the stepped regions at the opposite ends of the bend allowance section may have a different shape as depicted in FIG. **12**B.

Areas near the scribing line and/or chamfering line of the flexible display **100** may be another spots vulnerable to cracks. For instance, cracks can initiate from the insulation layers during scribing the base layer **106** or chamfering a portion of the base layer **106**. The cracks generated at the far end of the flexible display **100** can propagate towards central portion. The cracks from the chamfering line of the flexible display **100** may propagate into the bending area and the routing areas adjacent to the bending area. In some cases, cracks from the scribing lines at the inactive areas provided in a flat central portion of the flexible display **100** can propagate toward the active area and damage various circuits in the inactive areas, such as the GIP.

Accordingly, selective areas along one or more scribing lines of the flexible display **100** may be substantially free of inorganic material layers. For example, area at one or more edges of the base layer **106** in the flexible display **100**, denoted as "the scribe line etch area" in FIG. **13**A, may be substantially free of insulation layers of inorganic materials such the buffer layer **126**. In the scribe line etch areas, the base layer **106** may be exposed or only a predetermined minimal thickness of the buffer layer **126** may remain. Although the scribe line etch areas are marked at the top edge and the bottom edge of the flexible display **100** in FIG. **13**A, the location, the size and the shape of the scribe line etch area are not particularly limited as shown in FIG. **13**A. The scribe line etch area can be provided at the side edges of the flexible display **100**. In an embodiment in which the flexible display **100** is provided with a rounded base layer **106**, the scribe line etch area may be provided at the periphery of the active area.

Several side crack stopper structures may also be provided in the area between the edge (i.e., scribed line/chamfered line) and the active area in a central portion of the flexible display **100**. For instance, a recessed channel can be formed in the inactive area by etching the insulation layers. Also, a dummy wire trace pattern may be disposed in the inactive area to change the direction of crack propagating from the outer edge of the flexible display **100** toward the circuits in the inactive area. Such crack stopper structures can be provided between a circuit (or other fragile elements)

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positioned in the inactive area and the outer edge of the flexible display **100**. For example, a metal trace having a strain reduction pattern and insulation layer covering the metal trace can be formed between the GIP and the edge of the flexible display **100** as depicted in FIG. **9**A (right side). While the recessed channel and the dummy wire trace pattern are provided on the left and right sides, respectively, such crack stopper structures can be provided in the top and bottom sides as well.

It should be noted that the recessed channel on the left side of the active area can also be provided on the right side of the active area. Likewise, the dummy wire trace with the strain-reducing pattern provided on the right side of the inactive area can also be provided on the left side of the inactive area. In some embodiments, both the recessed channel and the metal trace having the strain-reducing pattern can be provided on one or more sides of the active area. In this configuration, the cracks propagating from the outer edge of the inactive area in the direction towards the GIP may change its course due to the angle of the diamond metal/insulation trace formed before the GIP.

Patterning of insulation layers, especially the inorganic insulation layers, can also be performed in the routing area between the active area and the bend allowance section as well as the routing area between the COF bonding area and the bend allowance section. Further, the inorganic material layers may be removed from at least some part of areas adjacent to the chamfered lines so that cracks do not propagate from the chamfered line toward the conductive lines **120**.

FIG. **13**B is an enlarged view of lower left corner of the flexible display near the notched area. In order to reduce crack initiation and propagation from the inorganic layers near the chamfered line, the insulation layer is etched in the area between the wire trace (e.g., VSS line) to the chamfered line. In particular, the buffer layer **126** disposed on the base layer **106** in the area between the chamfered line and the conductive line **120** in the bend allowance section, which is closest to the chamfering line (e.g., VSS line) can be removed. In this area, the base layer **106** may be exposed or buffer layer **126** with a limited thickness (i.e., thinner than the buffer layer **126** under the conductive line **120**) may remain. Accordingly, crack initiation and propagation from the chamfered line can be hindered by the buffer layer etched area.

When etching the buffer layer **126** near the chamfering line, a stripe of buffer layer **126** can be configured to remain between the chamfered line and the wire trace closest to the chamfered line as depicted in FIG. **13**B. This stripe of buffer layer can serve as a dam for inhibiting moistures of other foreign material from reaching the wire trace from the chamfered side of the flexible display **100**.

The aforementioned buffer layer etched area can also be applied in the routing area between the chamfering line and the closest wire trace. The stripe of buffer layer **126** may also be provided in the routing area. Further, the buffer layer **126** under the conductive lines **120** and the passivation layer **128** on the conductive lines **120** can be patterned to correspond to the trace of the conductive lines **120** throughout the routing area to further reduce the chance of crack propagation by the inorganic insulation layers in the routing areas next to the bend allowance section. For instance, the configuration of wire trace structures depicted in FIGS. **11**A and **11**B may also be applied to the wire traces in the routing areas.

FIG. **13**C is an enlarged view near the notched area of the flexible display **100**, provided with another type of crack stopper structure. In this embodiment, an auxiliary conductive line **130** having the diamond trace pattern is provided between the chamfered line and the wire trace (e.g., VSS). The buffer layer **126** under the auxiliary conductive line **130** and the passivation **128** on the auxiliary conductive line **130** can be etched in the similar manner as depicted in FIGS. **11**A and **11**B. Accordingly, the auxiliary conductive line **130** may inhibit propagation of cracks from the chamfered line to the wire trace. The auxiliary conductive line **130** may be a floating line. If desired, the auxiliary conductive line **130** may extend outside the routing area towards the bottom edge of the flexible display **100**. In some embodiments, the auxiliary conductive line **130** may be in contact with adjacent conductive line **120**. In addition to the auxiliary conductive line **130**, the stripe of buffer layer **126** may also be provided to stop moisture or other foreign materials traveling towards the auxiliary conductive line **130**.

Micro-Coating Layer (MCL)

With the inorganic insulation layers etched away from the bend portion of the flexible display **100**, the wire traces in the bend portion can be vulnerable to moistures and other foreign materials. In particular, various pads and conductive lines for testing the components during manufacturing of the flexible display **100** may be chamfered, and this can leave conductive lines extended to the notched edge of the flexible display **100**. Such conductive lines can easily corrode by the moistures, and cause other nearby conductive line to corrode as well.

Accordingly, a protective coating layer, which may be referred to as a "micro-coating layer" can be provided over the wire traces in the bend portion to provide added protection against moistures and other foreign materials. In addition to having a good moisture resistance, the micro-coating layer should have sufficient flexibility so that it can be used in the bend portion of the flexible display **100**. Further, the material of the micro-coating layer may be a curable material with low energy within a limited time so that the components under the micro-coating layer are not damaged during the curing process.

FIG. **14**A is a schematic illustration of one suitable exemplary configuration of the micro-coating layer **132** in an embodiment of flexible display **100**. The micro-coating layer **132** may be provided as photo-curable (e.g., UV light, Visible light, UV LED) resin and coated over the desired areas of the flexible display **100**. In this regard, the micro-coating layer **132** is coated over the area between the encapsulation **114** and the COF **134** attached in the inactive area. Depending on the adhesive property of the micro-coating layer **132**, however, the micro-coating layer **132** can be detached from the encapsulation **114** and/or the COF **134**. Any open space between the micro-coating layer **132** and the encapsulation **114** or the COF **132** may become a defect site where moisture can permeate through.

Accordingly, the micro-coating layer **132** may be coated to overflow into a part of the top surface of the encapsulation **114** for enhanced sealing between the encapsulation **114** and the micro-coating layer **132**. The additional contact area between the micro-coating layer **132** and the surface of the encapsulation **114** can provide stronger bonding, and reduce the cracks and corrosion of the wire traces at the bend portion of the flexible display **100**. Likewise, the micro-coating layer **132** can be coated on as least some part of the COF **134** for stronger bonding between the micro-coating layer **132** and the COF **134**.

Referring to FIGS. **14**B and **14**C, the width of the encapsulation **114** coated with the micro-coating layer **134** (denoted as Overflow_W**1**) and the width of the COF **134**

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coated with the micro-coating layer **134** (denoted as Overflow_W2) are not particularly limited and may vary depending on the adhesiveness of the micro-coating layer **132**. As shown in FIG. **14**B, the flexible display **100** may include a portion where the micro-coating layer **132** on the encapsulation **114** is spaced apart from the sidewall of the polarization layer **110**. In some embodiments, the flexible display **100** may include a portion where the micro-coating layer **132** on the encapsulation **114** is in contact with the polarization layer **110** disposed on the encapsulation **114** as depicted in FIG. **14**C.

In one suitable configuration, the micro-coating layer **132** may be in contact with the polarization layer **110** at the two opposite corners (denoted "POL_CT") while the micro-coating layer **132** only covers up to some part of the encapsulation **114** in the areas between the two opposite corners. After the bending process, the part of the flexible display **100** where the micro-coating layer **132** is spaced apart from the polarization layer **110** may be configured as shown in FIG. **15**A. In the region where micro-coating layer **132** is configured to be in contact with the polarization layer **110**, the flexible display **100** may be configured as shown in FIG. **15**B.

It should be noted that the micro-coating layer **132** is dispensed in a resinous form, and may spread on the dispensed surface. The spreading dynamic depends on the viscosity of the micro-coating layer **132** as well as the surface energy of which the micro-coating layer **132** is dispensed. As such, the micro-coating layer **132** overflowed into the encapsulation **114** may reach the polarization layer **110**. When the micro-coating layer **132** reaches the sidewall of the polarization layer **114**, the micro-coating layer **132** may climb over the sidewall of the polarization layer **110**. Such sidewall wetting of the micro-coating layer **132** can make uneven edges over the surface of the polarization layer **132**, which may cause various issues when placing another layer thereon. Accordingly, the amount of the micro-coating layer **134** dispensed on the targeted surface can be adjusted to control the width of the micro-coating layer **134** on the encapsulation layer **114**.

The micro-coating layer **132** may be coated in a predetermined thickness to adjust the neutral plane of the flexible display **100** at the bend portion. More specifically, added thickness at the bend portion of the flexible display **100** by the micro-coating layer **132** can change the neutral plane so that the plane of the wire traces is shifted closer to the neutral plane.

In some embodiments, the thickness of the micro-coating layer **132** in the area between the encapsulation **114** and the COF **134**, which is measured from the surface of the base layer **106**, may be substantially the same as the distance between the surface of the base layer **106** to the top surface of the encapsulation **104**. In such embodiments, the vertical distance between the top surface of the micro-coating layer **132** in the bend allowance section and the top surface of the encapsulation **114** may be less than 25 μm.

Various resin dispensing methods, such as slit coating, jetting and the like, may be used to dispense the micro-coating layer **132** at the targeted surface. In way of an example, the micro-coating layer **132** can be dispensed by using a jetting valve. The dispensing speed from the jetting valve(s) may be adjusted during the coating process for accurate control of the thickness and the spread size of the micro-coating layer **132** at the targeted surface. Further, additional number of jetting values may be used to reduce the dispense time and limit the amount of spread before the micro-coating layer **132** is cured through UV irradiation.

Divided VSS-VDD Wire Trace

Spreading dynamic of the micro-coating layer **132** over the wire traces can be affected by the trace design of the wire traces. More specifically, patterning of the insulation layers along the wire trace in the bend portion of the flexible display **100** creates recessed areas and protruded areas, which essentially become a micro-grooved surface to be covered by the micro-coating layer **132**.

When applying the strain-reducing trace design in the wire traces, patterning of the insulation layers around the split sub-traces creates the recessed open area, which is surrounded by the protruded stack of wire traces. During coating of the micro-coating layer **132**, some portion of the micro-coating layer droplet can permeate into the recessed open area. It can hinder the spreading and reduce the maximum spreading diameter of the micro-coating layer **132** on such a micro-grooved surface, and result in some part of the bend portion being exposed without the micro-coating layer **132**.

Decrease in the wettability of micro-coating layer **132** by the distribution of the recessed areas and the protruded areas may be magnified even more in the area over the wire trace applied with the grid-like trace design shown in FIG. **9**B. To counteract the viscid drag, in some embodiments, a wire trace, which includes multiple diamond-chain traces adjoined side-by-side, can be provided with a rail between two parts of the wire trace.

Referring to FIG. **16**, a wire trace with a grid-like trace strain-reducing trace design is provided with an elongated channel between divided grid-parts of the wire trace. Within the elongated channel, the conductive line **120** is not formed. Also, at least some of the inorganic insulation layers on the base layer **106** are removed in the elongated channel. The elongated channel between the grid-parts of the wire trace extends from the signal supplying side to the signal receiving side of the wire trace. That is, the elongated channel may be extended in the direction parallel to the bending direction. It should be noted that the separated parts of the wire trace on one side of the elongated channel is connected to the part of the wire trace on the opposite side of the elongated channel, and thus both parts of the wire trace transmit the identical signal. The connection between the divided parts of the wire trace may be achieved at one or both ends of the wire trace by a conductive path, which may be a part of the wire trace. The connection of the divided parts of the wire trace may be achieved within the bend allowance section or outside the bend allowance section.

Even though the parts of the wire trace on each side of the elongated channel has the grid-like trace design, the reduced number of diamond-chain traces adjoined in each grid-part and the channel between the grid-parts can reduce the viscid drag of the micro-coating layer **132**. More importantly, the elongated recessed channel between the parts of the wire trace serves as a path that improves the wettability of the micro-coating layer **132** over the wire trace. In sum, increase in the maximum spread diameter of the micro-coating layer **132** can be achieved by positioning one or more elongated channel within the wire having the grid-like strain-reducing trace design.

It should be noted that the resistance of the wire trace can increase with the elongated channel dividing the wire trace into multiple grid-parts. Increase in the resistance of the wire can raise the temperature of the wire trace when it is supplied with a signal. Accordingly, the number of elongated channels provided in a single wire trace can depend on the signal transmitted via the wire trace. In some cases, the size of each diamond shaped link in a grid-like wire trace may be

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larger than the size of diamond-shaped links in other wire traces of the flexible display **100**.

In one suitable configuration, one or more of power signal wires of the flexible display **100**, such as the VDD and/or the VSS, has the grid-like wire trace formed of multiple diamond-chain traces adjoined side-by-side as depicted in FIG. **16**. The power signal wire trace includes one or more elongated channels in its grid-like wire trace. Each of the elongated channels is provided between two divided grid parts, which are on the opposite sides of the elongated channel. The divided grid parts are connected at one or both ends of the power signal wire. The size of the divided grid parts may be substantially the same. That is, the number of diamond-chain traces forming a gird part on one side of the elongated channel may be the same as the number of diamond-chain traces forming a gird part on the opposite side. If desired, however, the number of diamond-chain traces adjoined to each other to form one grid part may differ from the number of diamond-chain forming another grid part.

Although the concepts and teachings in the present disclosure are described above with reference to OLED display technology, it should be understood that several features may be extensible to any form of flexible display technology, such as electrophoretic, liquid crystal, electrochromic, displays comprising discreet inorganic LED emitters on flexible substrates, electrofluidic, and electrokinetic displays, as well as any other suitable form of display technology.

As described above, a flexible display **100** may include a plurality of innovations configured to allow bending of a portion or portions to reduce apparent border size and/or utilize the side surface of an assembled flexible display **100**. In some embodiments, bending may be performed only in the bend portion and/or the bend allowance section having only the conductive line **120** rather than active display components or peripheral circuits. In some embodiments, the base layer **106** and/or other layers and substrates to be bent may be heated to promote bending without breakage, then cooled after the bending. In some embodiments, metals such as stainless steel with a passive dielectric layer may be used as the base layer **106** rather than the polymer materials discussed above. Optical markers may be used in several identification and aligning process steps to ensure appropriate bends absent breakage of sensitive components. Components of the flexible display **100** may be actively monitored during device assembly and bending operations to monitor damage to components and interconnections.

Constituent materials of conductive line **120** and/or insulation layers may be optimized to promote stretching and/or compressing rather than breaking within a bending area. Thickness of a conductive line **120** may be varied across a bending area and/or the bend allowance section to minimize stresses about the bend portion or the bend allowance section of the flexible display **100**. Trace design of conductive line **120** and insulation layers may be angled away from the bending direction (i.e., tangent vector of the curvature), meandering, waving, or otherwise arranged to reduce possibility of severance during bending. The thickness of the conductive line **120**, insulation layers and other components may be altered or optimized in the bend portion of the flexible display **100** to reduce breakage during bending. Bend stresses may be reduced by adding protective microcoating layer(s) over components in addition to disclosed encapsulation layers. Conductive films may be applied to the conductive line **120** before, during, or after bending in a repair process. Furthermore, the constituent material and/or the structure for conductive line **120** in a substantially flat area of a flexible display **100** may differ from the conductive line **120** in a bend portion and/or the bend allowance section.

These various aspects, embodiments, implementations or features of the described embodiments can be used separately or in any combination. The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope of the invention.

What is claimed is:

1. A flexible display apparatus, comprising:

a flexible base layer having an active area and an inactive area, the active area including a plurality of pixels with one or more organic light-emitting diodes;

a first wire trace and a second wire trace on the flexible base layer, each having a trace design that includes an indented section between two distended sections of the respective wire trace, wherein the first wire trace and the second wire trace are arranged in a staggered configuration such that one of the distended sections of the first wire trace is aligned next to the indented section of the second wire trace; and

a micro-coating layer over a portion of the first wire trace and a portion of the second wire trace positioned in a bend allowance section of the flexible display apparatus,

wherein each of the first wire trace and the second wire trace includes a series of links connected in a chain,

wherein at least one or more insulation layers provided under and over the first and second wire traces are absent in an open area at a middle of a link,

wherein at least some portion of the first wire trace and at least some portion of the second wire trace are positioned in the bend allowance section of the flexible display apparatus,

wherein the active area is provided in a central portion of the flexible display apparatus, and the bend allowance section is provided in the bend portion located at one of edges of the flexible display apparatus.

2. The flexible display apparatus of claim **1**, wherein at least one of the first wire trace and the second wire trace has a grid trace design.

3. The flexible display apparatus of claim **1**, wherein the first wire trace is configured to transfer data signals to a first group of pixels, and the second wire trace is configured to transfer data signals to a second group of pixels among the plurality of pixels in the active area.

4. The flexible display apparatus of claim **1**, wherein each of the first wire trace and the second wire trace includes a trace of a conductive line covered with at least one of the insulation layers patterned according to the trace of the respective conductive line.

5. The flexible display apparatus of claim **4**, wherein the trace design of the first wire trace and the second wire trace comprises at least one of serpentine trace design, sine wave trace design and square wave trace design.

6. The flexible display apparatus of claim **4**, wherein at least one of the insulation layers patterned according to the trace of the conductive line includes a buffer layer under the conductive line.

7. The flexible display apparatus of claim **6**, wherein at least one of the insulation layers patterned according to the trace of the conductive line includes a passivation layer on the conductive line.

8. The flexible display apparatus of claim **7**, wherein the buffer layer under the first wire trace and the second wire

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trace is thinner in the bend allowance section than the active area of the flexible display apparatus.

9. The flexible display apparatus of claim **7**, wherein the buffer layer and the passivation layer include one or more sub-layers of silicon oxide or silicon nitride, and

the one or more sub-layers of silicon oxide or silicon nitride are absent in the space between the first wire trace and the second wire trace.

10. The flexible display apparatus of claim **9**, wherein the buffer layer has a lesser number of sub-layers under the first and second wire traces in the bend allowance section than the active area of the flexible display apparatus.

11. A flexible display apparatus, comprising:

a flexible base layer having an active area and an inactive area, the active area including a plurality of pixels with one or more organic light-emitting diodes;

a first wire trace and a second wire trace on the flexible base layer, each having a trace design that includes an indented section between two distended sections of the respective wire trace, wherein the first wire trace and the second wire trace are arranged in a staggered configuration such that one of the distended sections of the first wire trace is aligned next to the indented section of the second wire trace; and

a micro-coating layer over a portion of the first wire trace and a portion of the second wire trace positioned in a bend allowance section of the flexible display apparatus,

wherein a channel of space provided between the first wire trace and the second wire trace is absent of one or more insulation layers provided under and over the first wire trace and the second wire trace,

wherein at least one or more insulation layers provided under and over the first and second wire traces are absent in an open area,

wherein at least some portion of the first wire trace and at least some portion of the second wire trace are positioned in the bend allowance section of the flexible display apparatus,

wherein the active area is provided in a central portion of the flexible display apparatus, and the bend allowance section is provided in the bend portion located at one of edges of the flexible display apparatus.

12. The flexible display apparatus of claim **11**, wherein each of the first wire trace and the second wire trace includes a trace of conductive line covered with at least one of the insulation layers patterned according to the trace of the respective conductive.

13. The flexible display apparatus of claim **11**, wherein the first wire trace is configured to transfer data signals to a first group of pixels, and the second wire trace is configured to transfer data signals to a second group of pixels among the plurality of pixels in the active area.

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