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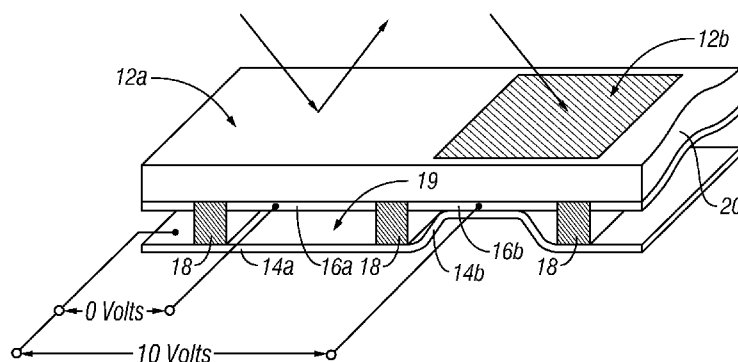


FIG. 1

(57) Abstract: An environmental sensing device includes an interferometric modulator which permanently actuates, in a visually-detectable manner, in response to being exposed to a predetermined environmental threshold or condition. The device can include a reactive layer, coating, or proof mass disposed on a movable member of the interferometric modulator. The reactive layer, coating, or proof mass can expand, contract, bend, or otherwise move when exposed to a predefined chemical, level of humidity, temperature threshold, type of radiation, and/or level of mechanical shock, causing the interferometric modulator to collapse and permanently indicate such exposure.



HUMAN-READABLE, BI-STATE ENVIRONMENTAL SENSORS BASED ON MECHANICAL MEMBRANES

BACKGROUND

Field of the Invention

[0001] The present invention relates to microelectromechanical systems (MEMS).

Description of the Related Art

[0002] Microelectromechanical systems (MEMS) include micro mechanical elements, actuators, and electronics. Micromechanical elements may be created using deposition, etching, and/or other micromachining processes that etch away parts of substrates and/or deposited material layers or that add layers to form electrical and electromechanical devices. One type of MEMS device is called an interferometric modulator. As used herein, the term interferometric modulator or interferometric light modulator refers to a device that selectively absorbs and/or reflects light using the principles of optical interference. In certain embodiments, an interferometric modulator may comprise a pair of conductive plates, one or both of which may be transparent and/or reflective in whole or part and capable of relative motion upon application of an appropriate electrical signal. In a particular embodiment, one plate may comprise a stationary layer deposited on a substrate and the other plate may comprise a metallic membrane separated from the stationary layer by an air gap. As described herein in more detail, the position of one plate in relation to another can change the optical interference of light incident on the interferometric modulator. Such devices have a wide range of applications, and it would be beneficial in the art to utilize and/or modify the characteristics of these types of devices so that their features can be exploited in improving existing products and creating new products that have not yet been developed.

SUMMARY

[0003] In one aspect, a sensor comprises an interferometric modulator which is configured to permanently actuate in response to a presence of at least one selected chemical, wherein the actuation of the interferometric modulator is visually detectable.

[0004] In another aspect, a sensor comprises means for interferometrically modulating light and means for inducing permanent actuation of the light modulating means in response to a presence of at least one selected chemical.

[0005] In another aspect, a display comprising an array of sensors, where each sensor comprises an interferometric modulator which is configured to permanently actuate in response to a presence of at least one selected chemical, wherein the actuation of the interferometric modulator is visually detectable.

[0006] In another aspect, a method of manufacturing an interferometric modulator is provided. The method comprises providing a reactive layer on a movable member of the interferometric modulator, the reactive layer being configured to deform sufficiently to cause the interferometric modulator to collapse when exposed to a predetermined chemical. The method also comprises treating the movable member or an optical stack of the interferometric modulator so as to ensure that adhesion will be permanent upon collapse.

[0007] In another aspect, a method of indicating exposure to an environmental stimulus is provided. The method comprises providing an interferometric modulator having a reactive layer disposed on a movable member of the interferometric modulator, the reactive layer being configured to deform in response to being exposed to a predetermined chemical by an amount sufficient to cause the interferometric modulator to collapse, the interferometric modulator being configured to ensure that said collapse is permanent.

[0008] In another aspect, a sensor comprises an interferometric modulator which is configured to permanently actuate in response to a predetermined level of mechanical shock, wherein the actuation of the interferometric modulator is visually detectable.

[0009] In another aspect, a sensor comprises means for interferometrically modulating light and means for inducing permanent actuation of the light modulating means in response to a predetermined level of mechanical shock.

[0010] In another aspect, a display comprises an array of sensors, where each sensor comprises an interferometric modulator which is configured to permanently actuate in response to a predetermined level of mechanical shock, wherein the actuation of the interferometric modulator is visually detectable.

[0011] In another aspect, a method of manufacturing an interferometric modulator is provided. The method comprises providing a proof mass on a movable member of the interferometric modulator, the proof mass being configured to cause the interferometric modulator to collapse when exposed to a predetermined level of mechanical shock. The method further comprises treating the movable member or an optical stack of the interferometric modulator so as to ensure that adhesion will be permanent upon collapse.

[0012] In another aspect, a method of indicating exposure to an environmental stimulus is provided. The method comprises providing an interferometric modulator having a proof mass disposed on a movable member of the interferometric modulator, the proof mass being configured to cause the interferometric modulator to collapse when exposed to a predetermined level of shock, the interferometric modulator being configured to ensure that said collapse is permanent.

[0013] In another aspect, a sensor comprises an interferometric modulator which is configured to permanently actuate when exposed to a predefined level of radiation, wherein the actuation of the interferometric modulator is visually detectable.

[0014] In another aspect, a sensor comprises means for interferometrically modulating light and means for inducing permanent actuation of the light modulating means in response to a predefined level of radiation.

[0015] In another aspect, a display comprises an array of sensors, where each sensor comprises an interferometric modulator which is configured to permanently actuate when exposed to a predefined level of radiation, wherein the actuation of the interferometric modulator is visually detectable.

[0016] In another aspect, a method of manufacturing an interferometric modulator is provided. The method comprises providing a reactive layer on a movable member of the interferometric modulator, the reactive layer being configured to deform sufficiently to cause the interferometric modulator to collapse when exposed to a predetermined level of radiation. The method further comprises treating the movable member or an optical stack of the interferometric modulator so as to ensure that adhesion will be permanent upon collapse.

[0017] In another aspect, a method of indicating exposure to an environmental stimulus is provided. The method comprises providing an interferometric modulator having

a reactive layer disposed on a movable member of the interferometric modulator, the reactive layer being configured to deform when exposed to a predetermined level of radiation by an amount sufficient to cause the interferometric modulator to collapse, the interferometric modulator being configured to ensure that said collapse is permanent.

[0018] In another aspect, a sensor includes an interferometric modulator which is configured to permanently actuate in response to exposure to a predetermined combination of a first environmental stimulus and a second environmental stimulus.

[0019] In another aspect, a sensor comprises means for interferometrically modulating light, means for inducing collapse of the light modulating means in response to a first predefined environmental condition, and means for ensuring that said collapse is permanent if said collapse occurs in the presence of a second predefined environmental condition.

[0020] In another aspect, a display comprises an array of sensors, where each sensor includes an interferometric modulator which is configured to permanently actuate in response to exposure to a predetermined combination of a first environmental stimulus and a second environmental stimulus.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. 1 is an isometric view depicting a portion of one embodiment of an interferometric modulator display in which a movable reflective layer of a first interferometric modulator is in a relaxed position and a movable reflective layer of a second interferometric modulator is in an actuated position.

[0022] FIG. 2 is a system block diagram illustrating one embodiment of an electronic device incorporating a 3x3 interferometric modulator display.

[0023] FIG. 3 is a diagram of movable mirror position versus applied voltage for one exemplary embodiment of an interferometric modulator of FIG. 1.

[0024] FIG. 4 is an illustration of a set of row and column voltages that may be used to drive an interferometric modulator display.

[0025] FIG. 5A illustrates one exemplary frame of display data in the 3x3 interferometric modulator display of FIG. 2.

[0026] FIG. 5B illustrates one exemplary timing diagram for row and column signals that may be used to write the frame of FIG. 5A.

[0027] FIGS. 6A and 6B are system block diagrams illustrating an embodiment of a visual display device comprising a plurality of interferometric modulators.

[0028] FIG. 7A is a cross section of the device of FIG. 1.

[0029] FIG. 7B is a cross section of an alternative embodiment of an interferometric modulator.

[0030] FIG. 7C is a cross section of another alternative embodiment of an interferometric modulator.

[0031] FIG. 7D is a cross section of yet another alternative embodiment of an interferometric modulator.

[0032] FIG. 7E is a cross section of an additional alternative embodiment of an interferometric modulator.

[0033] FIG. 8A is a cross-section of a sensor according to an embodiment, shown in an unactuated state.

[0034] FIG. 8B is a cross-section of a sensor according to the embodiment of FIG. 8A, shown in an actuated (collapsed) state.

[0035] FIG. 9A is a cross-section of a sensor according to an alternative embodiment, shown in an unactuated state.

[0036] FIG. 9B is a cross-section of a sensor according to the embodiment of FIG. 9A, shown in an actuated (collapsed) state.

[0037] FIG. 10A is a cross-section of a sensor according to a further embodiment, shown in an unactuated state.

[0038] FIG. 10B is a cross-section of a sensor according to the embodiment of FIG. 10A, shown in an actuated (collapsed) state.

[0039] FIG. 11 is a cross-section view of a portion of a sensor having a sealing package according to an embodiment.

[0040] FIG. 12A is a partially cut away top view of the sensor of FIG. 11.

[0041] FIG. 12B is a partially cut away cross-section of the sensor of FIG. 11, shown with the sealing layer being removed.

[0042] FIG. 13 is a view of a sensor display according to an embodiment, shown in an unactuated state.

[0043] FIG. 14 is a view of the sensor display of FIG. 13, shown in an actuated state.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0044] The following detailed description is directed to certain specific embodiments of the invention. However, the invention can be embodied in a multitude of different ways. In this description, reference is made to the drawings wherein like parts are designated with like numerals throughout. As will be apparent from the following description, the embodiments may be implemented in any device that is configured to display an image, whether in motion (e.g., video) or stationary (e.g., still image), and whether textual or pictorial. More particularly, it is contemplated that the embodiments may be implemented in or associated with a variety of electronic devices such as, but not limited to, mobile telephones, wireless devices, personal data assistants (PDAs), hand-held or portable computers, GPS receivers/navigators, cameras, MP3 players, camcorders, game consoles, wrist watches, clocks, calculators, television monitors, flat panel displays, computer monitors, auto displays (e.g., odometer display, etc.), cockpit controls and/or displays, display of camera views (e.g., display of a rear view camera in a vehicle), electronic photographs, electronic billboards or signs, projectors, architectural structures, packaging, and aesthetic structures (e.g., display of images on a piece of jewelry). MEMS devices of similar structure to those described herein can also be used in non-display applications such as in electronic switching devices.

[0045] MEMS structures can be configured to deform and collapse when exposed to a given environmental condition or set of conditions. Depending on the adhesion forces involved, collapse can result in permanent adhesive failure, or “stiction,” in the structure. Although stiction is generally an undesirable trait in these devices, the tendency of certain structures to fail due to stiction under specific conditions can be used to advantage. MEMS devices are described herein which are configured to collapse and achieve permanent stiction when exposed to a predetermined environmental condition or set of conditions. These

devices may comprise interferometric modulators which, given their strong optical response upon collapse, are capable of indicating to an observer, in a non-reversible fashion and without the need for external sensing devices, whether the device has been exposed to the predetermined environmental condition or set of conditions at some point in the past. Such devices can be used in various applications, such as consumer-level packaging where conditions during shipping and/or storage must be monitored to ensure quality.

[0046] One interferometric modulator display embodiment comprising an interferometric MEMS display element is illustrated in Figure 1. In these devices, the pixels are in either a bright or dark state. In the bright (“on” or “open”) state, the display element reflects a large portion of incident visible light to a user. When in the dark (“off” or “closed”) state, the display element reflects little incident visible light to the user. Depending on the embodiment, the light reflectance properties of the “on” and “off” states may be reversed. MEMS pixels can be configured to reflect predominantly at selected colors, allowing for a color display in addition to black and white.

[0047] Figure 1 is an isometric view depicting two adjacent pixels in a series of pixels of a visual display, wherein each pixel comprises a MEMS interferometric modulator. In some embodiments, an interferometric modulator display comprises a row/column array of these interferometric modulators. Each interferometric modulator includes a pair of reflective layers positioned at a variable and controllable distance from each other to form a resonant optical gap with at least one variable dimension. In one embodiment, one of the reflective layers may be moved between two positions. In the first position, referred to herein as the relaxed position, the movable reflective layer is positioned at a relatively large distance from a fixed partially reflective layer. In the second position, referred to herein as the actuated position, the movable reflective layer is positioned more closely adjacent to the partially reflective layer. Incident light that reflects from the two layers interferes constructively or destructively depending on the position of the movable reflective layer, producing either an overall reflective or non-reflective state for each pixel.

[0048] The depicted portion of the pixel array in Figure 1 includes two adjacent interferometric modulators **12a** and **12b**. In the interferometric modulator **12a** on the left, a movable reflective layer **14a** is illustrated in a relaxed position at a predetermined distance

from an optical stack **16a**, which includes a partially reflective layer. In the interferometric modulator **12b** on the right, the movable reflective layer **14b** is illustrated in an actuated position adjacent to the optical stack **16b**.

[0049] The optical stacks **16a** and **16b** (collectively referred to as optical stack **16**), as referenced herein, typically comprise several fused layers, which can include an electrode layer, such as indium tin oxide (ITO), a partially reflective layer, such as chromium, and a transparent dielectric. The optical stack **16** is thus electrically conductive, partially transparent, and partially reflective, and may be fabricated, for example, by depositing one or more of the above layers onto a transparent substrate **20**. The partially reflective layer can be formed from a variety of materials that are partially reflective such as various metals, semiconductors, and dielectrics. The partially reflective layer can be formed of one or more layers of materials, and each of the layers can be formed of a single material or a combination of materials.

[0050] In some embodiments, the layers of the optical stack **16** are patterned into parallel strips, and may form row electrodes in a display device as described further below. The movable reflective layers **14a**, **14b** may be formed as a series of parallel strips of a deposited metal layer or layers (orthogonal to the row electrodes of **16a**, **16b**) deposited on top of posts **18** and an intervening sacrificial material deposited between the posts **18**. When the sacrificial material is etched away, the movable reflective layers **14a**, **14b** are separated from the optical stacks **16a**, **16b** by a defined gap **19**. A highly conductive and reflective material such as aluminum may be used for the reflective layers **14**, and these strips may form column electrodes in a display device.

[0051] With no applied voltage, the gap **19** remains between the movable reflective layer **14a** and optical stack **16a**, with the movable reflective layer **14a** in a mechanically relaxed state, as illustrated by the pixel **12a** in Figure 1. However, when a potential difference is applied to a selected row and column, the capacitor formed at the intersection of the row and column electrodes at the corresponding pixel becomes charged, and electrostatic forces pull the electrodes together. If the voltage is high enough, the movable reflective layer **14** is deformed and is forced against the optical stack **16**. A dielectric layer (not illustrated in this Figure) within the optical stack **16** may prevent shorting

and control the separation distance between layers **14** and **16**, as illustrated by pixel **12b** on the right in Figure 1. The behavior is the same regardless of the polarity of the applied potential difference. In this way, row/column actuation that can control the reflective vs. non-reflective pixel states is analogous in many ways to that used in conventional LCD and other display technologies.

[0052] Figures 2 through 5B illustrate one exemplary process and system for using an array of interferometric modulators in a display application.

[0053] Figure 2 is a system block diagram illustrating one embodiment of an electronic device that may incorporate aspects of the invention. In the exemplary embodiment, the electronic device includes a processor **21** which may be any general purpose single- or multi-chip microprocessor such as an ARM, Pentium®, Pentium II®, Pentium III®, Pentium IV®, Pentium® Pro, an 8051, a MIPS®, a Power PC®, an ALPHA®, or any special purpose microprocessor such as a digital signal processor, microcontroller, or a programmable gate array. As is conventional in the art, the processor **21** may be configured to execute one or more software modules. In addition to executing an operating system, the processor may be configured to execute one or more software applications, including a web browser, a telephone application, an email program, or any other software application.

[0054] In one embodiment, the processor **21** is also configured to communicate with an array driver **22**. In one embodiment, the array driver **22** includes a row driver circuit **24** and a column driver circuit **26** that provide signals to a display array or panel **30**. The cross section of the array illustrated in Figure 1 is shown by the lines 1-1 in Figure 2. For MEMS interferometric modulators, the row/column actuation protocol may take advantage of a hysteresis property of these devices illustrated in Figure 3. It may require, for example, a 10 volt potential difference to cause a movable layer to deform from the relaxed state to the actuated state. However, when the voltage is reduced from that value, the movable layer maintains its state as the voltage drops back below 10 volts. In the exemplary embodiment of Figure 3, the movable layer does not relax completely until the voltage drops below 2 volts. Thus, there exists a window of applied voltage, about 3 to 7 V in the example illustrated in Figure 3, within which the device is stable in either the relaxed or actuated state. This is referred to herein as the “hysteresis window” or “stability window.” For a display array

having the hysteresis characteristics of Figure 3, the row/column actuation protocol can be designed such that during row strobing, pixels in the strobed row that are to be actuated are exposed to a voltage difference of about 10 volts, and pixels that are to be relaxed are exposed to a voltage difference of close to zero volts. After the strobe, the pixels are exposed to a steady state voltage difference of about 5 volts such that they remain in whatever state the row strobe put them in. After being written, each pixel sees a potential difference within the “stability window” of 3-7 volts in this example. This feature makes the pixel design illustrated in Figure 1 stable under the same applied voltage conditions in either an actuated or relaxed pre-existing state. Since each pixel of the interferometric modulator, whether in the actuated or relaxed state, is essentially a capacitor formed by the fixed and moving reflective layers, this stable state can be held at a voltage within the hysteresis window with almost no power dissipation. Essentially no current flows into the pixel if the applied potential is fixed.

[0055] In typical applications, a display frame may be created by asserting the set of column electrodes in accordance with the desired set of actuated pixels in the first row. A row pulse is then applied to the row 1 electrode, actuating the pixels corresponding to the asserted column lines. The asserted set of column electrodes is then changed to correspond to the desired set of actuated pixels in the second row. A pulse is then applied to the row 2 electrode, actuating the appropriate pixels in row 2 in accordance with the asserted column electrodes. The row 1 pixels are unaffected by the row 2 pulse, and remain in the state they were set to during the row 1 pulse. This may be repeated for the entire series of rows in a sequential fashion to produce the frame. Generally, the frames are refreshed and/or updated with new display data by continually repeating this process at some desired number of frames per second. A wide variety of protocols for driving row and column electrodes of pixel arrays to produce display frames are also well known and may be used in conjunction with the present invention.

[0056] Figures 4, 5A, and 5B illustrate one possible actuation protocol for creating a display frame on the 3x3 array of Figure 2. Figure 4 illustrates a possible set of column and row voltage levels that may be used for pixels exhibiting the hysteresis curves of Figure 3. In the Figure 4 embodiment, actuating a pixel involves setting the appropriate

column to $-V_{\text{bias}}$, and the appropriate row to $+\Delta V$, which may correspond to -5 volts and +5 volts, respectively. Relaxing the pixel is accomplished by setting the appropriate column to $+V_{\text{bias}}$, and the appropriate row to the same $+\Delta V$, producing a zero volt potential difference across the pixel. In those rows where the row voltage is held at zero volts, the pixels are stable in whatever state they were originally in, regardless of whether the column is at $+V_{\text{bias}}$, or $-V_{\text{bias}}$. As is also illustrated in Figure 4, it will be appreciated that voltages of opposite polarity than those described above can be used, e.g., actuating a pixel can involve setting the appropriate column to $+V_{\text{bias}}$, and the appropriate row to $-\Delta V$. In this embodiment, releasing the pixel is accomplished by setting the appropriate column to $-V_{\text{bias}}$, and the appropriate row to the same $-\Delta V$, producing a zero volt potential difference across the pixel.

[0057] Figure 5B is a timing diagram showing a series of row and column signals applied to the 3x3 array of Figure 2 which will result in the display arrangement illustrated in Figure 5A, where actuated pixels are non-reflective. Prior to writing the frame illustrated in Figure 5A, the pixels can be in any state, and in this example, all the rows are at 0 volts, and all the columns are at +5 volts. With these applied voltages, all pixels are stable in their existing actuated or relaxed states.

[0058] In the Figure 5A frame, pixels (1,1), (1,2), (2,2), (3,2) and (3,3) are actuated. To accomplish this, during a "line time" for row 1, columns 1 and 2 are set to -5 volts, and column 3 is set to +5 volts. This does not change the state of any pixels, because all the pixels remain in the 3-7 volt stability window. Row 1 is then strobed with a pulse that goes from 0, up to 5 volts, and back to zero. This actuates the (1,1) and (1,2) pixels and relaxes the (1,3) pixel. No other pixels in the array are affected. To set row 2 as desired, column 2 is set to -5 volts, and columns 1 and 3 are set to +5 volts. The same strobe applied to row 2 will then actuate pixel (2,2) and relax pixels (2,1) and (2,3). Again, no other pixels of the array are affected. Row 3 is similarly set by setting columns 2 and 3 to -5 volts, and column 1 to +5 volts. The row 3 strobe sets the row 3 pixels as shown in Figure 5A. After writing the frame, the row potentials are zero, and the column potentials can remain at either +5 or -5 volts, and the display is then stable in the arrangement of Figure 5A. It will be appreciated that the same procedure can be employed for arrays of dozens or hundreds of rows and columns. It will also be appreciated that the timing, sequence, and levels of

voltages used to perform row and column actuation can be varied widely within the general principles outlined above, and the above example is exemplary only, and any actuation voltage method can be used with the systems and methods described herein.

[0059] Figures 6A and 6B are system block diagrams illustrating an embodiment of a display device **40**. The display device **40** can be, for example, a cellular or mobile telephone. However, the same components of display device **40** or slight variations thereof are also illustrative of various types of display devices such as televisions and portable media players.

[0060] The display device **40** includes a housing **41**, a display **30**, an antenna **43**, a speaker **45**, an input device **48**, and a microphone **46**. The housing **41** is generally formed from any of a variety of manufacturing processes as are well known to those of skill in the art, including injection molding and vacuum forming. In addition, the housing **41** may be made from any of a variety of materials, including, but not limited to, plastic, metal, glass, rubber, and ceramic, or a combination thereof. In one embodiment, the housing **41** includes removable portions (not shown) that may be interchanged with other removable portions of different color, or containing different logos, pictures, or symbols.

[0061] The display **30** of exemplary display device **40** may be any of a variety of displays, including a bi-stable display, as described herein. In other embodiments, the display **30** includes a flat-panel display, such as plasma, EL, OLED, STN LCD, or TFT LCD as described above, or a non-flat-panel display, such as a CRT or other tube device, as is well known to those of skill in the art. However, for purposes of describing the present embodiment, the display **30** includes an interferometric modulator display, as described herein.

[0062] The components of one embodiment of exemplary display device **40** are schematically illustrated in Figure 6B. The illustrated exemplary display device **40** includes a housing **41** and can include additional components at least partially enclosed therein. For example, in one embodiment, the exemplary display device **40** includes a network interface **27** that includes an antenna **43**, which is coupled to a transceiver **47**. The transceiver **47** is connected to a processor **21**, which is connected to conditioning hardware **52**. The conditioning hardware **52** may be configured to condition a signal (e.g., filter a signal). The

conditioning hardware **52** is connected to a speaker **45** and a microphone **46**. The processor **21** is also connected to an input device **48** and a driver controller **29**. The driver controller **29** is coupled to a frame buffer **28** and to an array driver **22**, which in turn is coupled to a display array **30**. A power supply **50** provides power to all components as required by the particular exemplary display device **40** design.

[0063] The network interface **27** includes the antenna **43** and the transceiver **47** so that the exemplary display device **40** can communicate with one or more devices over a network. In one embodiment, the network interface **27** may also have some processing capabilities to relieve requirements of the processor **21**. The antenna **43** is any antenna known to those of skill in the art for transmitting and receiving signals. In one embodiment, the antenna transmits and receives RF signals according to the IEEE 802.11 standard, including IEEE 802.11(a), (b), or (g). In another embodiment, the antenna transmits and receives RF signals according to the BLUETOOTH standard. In the case of a cellular telephone, the antenna is designed to receive CDMA, GSM, AMPS, or other known signals that are used to communicate within a wireless cell phone network. The transceiver **47** pre-processes the signals received from the antenna **43** so that they may be received by and further manipulated by the processor **21**. The transceiver **47** also processes signals received from the processor **21** so that they may be transmitted from the exemplary display device **40** via the antenna **43**.

[0064] In an alternative embodiment, the transceiver **47** can be replaced by a receiver. In yet another alternative embodiment, network interface **27** can be replaced by an image source, which can store or generate image data to be sent to the processor **21**. For example, the image source can be a digital video disc (DVD) or a hard-disc drive that contains image data, or a software module that generates image data.

[0065] Processor **21** generally controls the overall operation of the exemplary display device **40**. The processor **21** receives data, such as compressed image data from the network interface **27** or an image source, and processes the data into raw image data or into a format that is readily processed into raw image data. The processor **21** then sends the processed data to the driver controller **29** or to frame buffer **28** for storage. Raw data typically refers to the information that identifies the image characteristics at each location

within an image. For example, such image characteristics can include color, saturation, and gray-scale level.

[0066] In one embodiment, the processor **21** includes a microcontroller, CPU, or logic unit to control operation of the exemplary display device **40**. Conditioning hardware **52** generally includes amplifiers and filters for transmitting signals to the speaker **45**, and for receiving signals from the microphone **46**. Conditioning hardware **52** may be discrete components within the exemplary display device **40**, or may be incorporated within the processor **21** or other components.

[0067] The driver controller **29** takes the raw image data generated by the processor **21** either directly from the processor **21** or from the frame buffer **28** and reformats the raw image data appropriately for high speed transmission to the array driver **22**. Specifically, the driver controller **29** reformats the raw image data into a data flow having a raster-like format, such that it has a time order suitable for scanning across the display array **30**. Then the driver controller **29** sends the formatted information to the array driver **22**. Although a driver controller **29**, such as a LCD controller, is often associated with the system processor **21** as a stand-alone Integrated Circuit (IC), such controllers may be implemented in many ways. They may be embedded in the processor **21** as hardware, embedded in the processor **21** as software, or fully integrated in hardware with the array driver **22**.

[0068] Typically, the array driver **22** receives the formatted information from the driver controller **29** and reformats the video data into a parallel set of waveforms that are applied many times per second to the hundreds and sometimes thousands of leads coming from the display's x-y matrix of pixels.

[0069] In one embodiment, the driver controller **29**, array driver **22**, and display array **30** are appropriate for any of the types of displays described herein. For example, in one embodiment, driver controller **29** is a conventional display controller or a bi-stable display controller (e.g., an interferometric modulator controller). In another embodiment, array driver **22** is a conventional driver or a bi-stable display driver (e.g., an interferometric modulator display). In one embodiment, a driver controller **29** is integrated with the array driver **22**. Such an embodiment is common in highly integrated systems such as cellular phones, watches, and other small area displays. In yet another embodiment, display array **30**

is a typical display array or a bi-stable display array (e.g., a display including an array of interferometric modulators).

[0070] The input device **48** allows a user to control the operation of the exemplary display device **40**. In one embodiment, input device **48** includes a keypad, such as a QWERTY keyboard or a telephone keypad, a button, a switch, a touch-sensitive screen, or a pressure- or heat-sensitive membrane. In one embodiment, the microphone **46** is an input device for the exemplary display device **40**. When the microphone **46** is used to input data to the device, voice commands may be provided by a user for controlling operations of the exemplary display device **40**.

[0071] Power supply **50** can include a variety of energy storage devices as are well known in the art. For example, in one embodiment, power supply **50** is a rechargeable battery, such as a nickel-cadmium battery or a lithium ion battery. In another embodiment, power supply **50** is a renewable energy source, a capacitor, or a solar cell including a plastic solar cell, and solar-cell paint. In another embodiment, power supply **50** is configured to receive power from a wall outlet.

[0072] In some embodiments, control programmability resides, as described above, in a driver controller which can be located in several places in the electronic display system. In some embodiments, control programmability resides in the array driver **22**. Those of skill in the art will recognize that the above-described optimizations may be implemented in any number of hardware and/or software components and in various configurations.

[0073] The details of the structure of interferometric modulators that operate in accordance with the principles set forth above may vary widely. For example, Figures 7A-7E illustrate five different embodiments of the movable reflective layer **14** and its supporting structures. Figure 7A is a cross section of the embodiment of Figure 1, where a strip of metal material **14** is deposited on orthogonally extending supports **18**. In Figure 7B, the moveable reflective layer **14** is attached to supports at the corners only, on tethers **32**. In Figure 7C, the moveable reflective layer **14** is suspended from a deformable layer **34**, which may comprise a flexible metal. The deformable layer **34** connects, directly or indirectly, to the substrate **20** around the perimeter of the deformable layer **34**. These connections are herein referred to as support posts. The embodiment illustrated in Figure 7D has support post plugs **42** upon

which the deformable layer **34** rests. The movable reflective layer **14** remains suspended over the gap, as in Figures 7A-7C, but the deformable layer **34** does not form the support posts by filling holes between the deformable layer **34** and the optical stack **16**. Rather, the support posts are formed of a planarization material, which is used to form support post plugs **42**. The embodiment illustrated in Figure 7E is based on the embodiment shown in Figure 7D, but may also be adapted to work with any of the embodiments illustrated in Figures 7A-7C, as well as additional embodiments not shown. In the embodiment shown in Figure 7E, an extra layer of metal or other conductive material has been used to form a bus structure **44**. This allows signal routing along the back of the interferometric modulators, eliminating a number of electrodes that may otherwise have had to be formed on the substrate **20**.

[0074] In embodiments such as those shown in Figure 7, the interferometric modulators function as direct-view devices, in which images are viewed from the front side of the transparent substrate **20**, the side opposite to that upon which the modulator is arranged. In these embodiments, the reflective layer **14** optically shields the portions of the interferometric modulator on the side of the reflective layer opposite the substrate **20**, including the deformable layer **34**. This allows the shielded areas to be configured and operated upon without negatively affecting the image quality. Such shielding allows the bus structure **44** in Figure 7E, which provides the ability to separate the optical properties of the modulator from the electromechanical properties of the modulator, such as addressing and the movements that result from that addressing. This separable modulator architecture allows the structural design and materials used for the electromechanical aspects and the optical aspects of the modulator to be selected and to function independently of each other. Moreover, the embodiments shown in Figures 7C-7E have additional benefits deriving from the decoupling of the optical properties of the reflective layer **14** from its mechanical properties, which are carried out by the deformable layer **34**. This allows the structural design and materials used for the reflective layer **14** to be optimized with respect to the optical properties, and the structural design and materials used for the deformable layer **34** to be optimized with respect to desired mechanical properties.

[0075] In certain MEMS devices, such as interferometric modulators of the types described above, the large surface area to gap ratios and high surface energies create

conditions highly favorable to adhesion, due at least in part to Van der Waals and capillary forces. Depending on the particular configuration of the device and depending on the environmental conditions, the adhesion forces can surpass the mechanical restoring force of the movable layer, resulting in permanent, non-recoverable adhesion when the movable layer contacts the opposing surface. In general, permanent adhesion or “stiction” in a MEMS device is undesirable trait. However, it is possible to form MEMS structures configured to collapse and achieve stiction when exposed to a specific environmental condition or set of conditions.

[0076] By employing interferometric modulators in these structures, it is possible to design passive sensor devices capable of indicating to a human observer, without the need for external sensing electronics, whether they have been exposed to the specified environmental condition or set of conditions. By configuring such a device so as to ensure permanent stiction upon collapse – that is, so as to prevent spontaneous restoration to an original, uncollapsed state – such a device may be used to indicate even a one-time exposure to the specified environmental condition or set of conditions, regardless of any later change in the environment. In addition, the delicate nature of the films used in interferometric modulators makes intentional alteration of the sensor display impossible without destroying the sensor device permanently. This type of sensor is thus ideal for use in consumer applications which are sensitive to environmental conditions, such as food products (e.g. milk, eggs, wine) and medical products (e.g. blood, plasma, vaccines) which can degrade in certain environmental conditions, or applications involving sports activities (e.g. scuba diving, flying, mountain climbing) or work-related activities (e.g. welding, mining) where exposure to certain environmental conditions must be monitored. The ease of use of these devices makes them ideal when unambiguous identification of changes in environmental conditions have exceeded a pre-defined threshold. Such devices can also be used in multiples and can be configured with varying optical responses to create text, graphic, or color-based sensor displays.

[0077] Embodiments of the invention generally include a movable member designed to deform or otherwise collapse and achieve contact with an opposing surface in response to being exposed to a particular environmental condition, such as, for example, a

particular temperature or humidity threshold, a particular chemical species or concentration thereof, a particular level or type of radiation, a particular level of mechanical shock, or a combination of these or other environmental conditions. Embodiments may also be configured to ensure that, once collapsed, adhesion forces will exceed any mechanical restoring force required to restore the movable member to its original undeformed or uncollapsed state. In certain embodiments, the movable member may be provided with a package configured to seal an internal environment of the sensor from the external environment and thus protect the device in storage until the user exposes it to the environment that is to be sensed. The sealed internal environment can be configured to ensure that, if the movable member does collapse before the package is opened, such collapse will not be permanent. These and other embodiments can thus be activated by an end user upon opening of the package. Alternative embodiments can include a sealed internal environment configured with, for example, a selected high level of humidity, so as to ensure that permanent stiction will occur upon collapse.

Chemical/Humidity/Temperature Sensor

[0078] Figures 8A and 8B illustrate an environmental sensor **100** according to one embodiment of the invention. The sensor **100** comprises an optical stack **102** formed on a transmissive substrate **104**, where the optical stack **102** includes a partially reflective layer **106** and an electrically insulating layer **107**. The sensor **100** further comprises a movable member **108** spaced apart from the optical stack **102** by one or more posts **110** to define a gap **112**. In embodiments in which the movable member **108** comprises a reflective layer, the space between **106** and **108** functions as an interferometric cavity. An observer viewing the sensor **100** through the transmissive substrate **104** will thus be able to easily observe a change in the position of the movable member **108** relative to the optical stack **102**, as the light reflected by the sensor **100** is dependent on the height of the interferometric gap **112**.

[0079] As shown in Figure 8A, the movable member **108** includes an expansion layer **114** disposed on the side of the movable member **108** facing the optical stack **102**. The expansion layer **114** can be configured to expand in volume when exposed to a specific environmental condition occurring within the gap **112**, such as, for example, moisture, a particular level of acidity or alkalinity, or the presence of a particular chemical species. The

expansion layer **114** can further be configured to expand by an amount sufficient to induce bending in the movable member **108** such that the movable member **108** (and/or the expansion layer **114**) comes into contact with the optical stack **102**. Figure 8B shows the sensor **100** of Figure 8A in a collapsed state, the sensor having been exposed to the selected environmental condition.

[0080] The expansion layer **114** can comprise one or more of several materials exhibiting the desired properties for the particular application, such as, for example, cross-linked polyethylene oxide (a moisture absorber) or hydrogels. In alternative embodiments, a contraction layer can be disposed on the opposite side of the membrane. The contraction layer can be configured to contract when exposed to a specific environmental condition by an amount sufficient to induce bending in the movable member **108** such that the movable member **108** comes into contact with the optical stack **102**. Such a contraction layer may comprise, for example, a hygroscopic aerogel. The expansion or contraction layer can also comprise a polymeric material such as thin poly (hydroxyethyl methacrylate) (PHEMA) or poly (methyl methacrylate) (PMMA), which will expand when exposed to alcohols (methanol, isopropanol) as well as water vapor. A mechanochemically responsive polymeric film can also be used which expands or contracts in response to its ambient chemical environment. Another example of a suitable material is RTV silicone rubber, which can be configured to expand when exposed to a particular chemical analyte and contract when the analyte is removed. An expansion (or contraction) layer as described herein can be formed by, for example, applying the layer to the movable member **108** prior to its deposition.

[0081] Additionally or alternatively, embodiments can be configured to react in a specified way in response to temperature. Changes in temperature can induce strong variations in the as-deposited stress of micro-mechanical thin film structures, resulting in deflection of the thin film structure with respect to the substrate. Where the deflection response is known, the movable member **108** can thus be configured to deflect when exposed to a given temperature threshold by an amount sufficient to create contact with the opposing surface of the optical stack **102**. In alternative embodiments, the movable member **108** can comprise two or more films having different coefficients of thermal expansion, selected to induce deformation of the movable member sufficient to cause contact with the optical stack

in response to exposure to a given temperature. The movable member **108** can also be tethered or otherwise attached to a rigid substrate, and configured with a coefficient of thermal expansion selected to induce deformation or sagging sufficient to induce to cause contact with the optical stack in response to exposure to a given temperature.

[0082] In these and other embodiments, the movable member **108** and/or the optical stack **102** can be specially formed or treated so as to ensure that permanent stiction will occur when the movable member **108** contacts the optical stack **102**. Embodiments are thus configured to prevent the movable member **108** from restoring itself to its original position after making contact with the optical stack **102**, even when the temperature or humidity returns to normal or the deforming agent is no longer present. Embodiments can thus be tunable to indicate exposure to a wide range of sensitivities. A humidity sensor, for example, can be tuned to indicate exposure from 10% humidity or less, up to 90% humidity or more.

[0083] The tendency to adhere can be enhanced in a number of ways; for example, by driving charge into the surface dielectric film of the optical stack, thereby increasing electrostatic force upon contact, by utilizing dissimilar contact materials with greater mutual surface attraction, by roughening one or both of the contact surfaces, by coating one or both of the contact surfaces with an adhesive, or by increasing the size of the contact area between the two surfaces. In embodiments comprising an expansion layer disposed on the stack-facing surface of the movable member, the expansion layer may come into contact with the optical stack when the membrane deforms. Accordingly, the thickness and surface properties of the expansion layer material will influence adhesion between the surfaces. Where required, the tendency to adhere can be reduced by fabricating the device with smooth contact surfaces (having an RMS roughness < 1 nm, for example), by passivating the contact surfaces to reduce their surface energy, by coating them with self-assembled monolayers (SAMs) or atomic layer deposited (ALD) films, or by using similar contact materials (e.g. metal/metal, dielectric/dielectric) having less mutual attraction.

[0084] Adhesion can also be influenced by moisture levels. Embodiments can include a package sealed to the environment, for example with a known, low level of humidity, to ensure that permanent stiction will not occur until the sensor is activated by

opening the package to the environment and exposing it to a level of humidity allowing for permanent stiction to occur. Humidity levels as low as 100 ppmv, for example, can lead to permanent, non-recoverable adhesion on contact. The humidity threshold to achieve permanent adhesion can be further tailored as described above; thus, embodiments can be configured to cover a wide range of sensitivities. Further, embodiments can be configured to sense and indicate exposure to a particular combination of multiple stimuli, such as temperature and humidity. Alternatively, some embodiments can comprise a package sealed with a pre-defined and stable operating state that is only influenced by specific stimuli, such as temperature or shock, that may be coupled through the package to induce collapse of the membrane. For example, embodiments can be sealed with a known, high concentration of moisture or particular chemicals, to ensure that stiction will be permanent when an external stimulus is transmitted through the package.

Shock Sensor

[0085] With reference now to Figures 9A and 9B, an environmental sensor **200** according to an alternative embodiment is illustrated. The sensor **200** comprises an optical stack **202** formed on a transmissive substrate **204**, where the optical stack **202** includes a partially reflective layer **206** and an electrically insulating layer **207**. The sensor **200** further comprises a movable member **208** spaced apart from the optical stack **202** by one or more posts **210** to define a gap **212**. In embodiments in which the movable member **208** comprises a reflective layer, the space between **206** and **208** functions as an interferometric cavity. An observer viewing the sensor **200** through the transmissive substrate **204** will thus be able to easily observe a change in the position of the movable member **208** relative to the optical stack **202**, as the light reflected by the sensor **200** is dependent on the height of the interferometric gap **212**.

[0086] As shown in Figure 9A, a proof mass **214** is disposed on a side of the movable member **208**, such that a selected level of shock received in a direction generally normal to the surface of the movable member **208** will induce an acceleration of the proof mass **214** and force the movable member **208** into contact with the optical stack **202**. For example, as illustrated by the calculation below, for a MEMS structure requiring an actuation

force of an approximately 1 micro-newton (μN), a 10 μg proof mass will force the structure to collapse in response to a 10 g acceleration:

$$F = m \cdot a$$

$$m = \frac{F}{a}$$

$$m = \frac{1\mu\text{N}}{10 \cdot 9.8 \frac{\text{m}}{\text{s}^2}} \cong 10\mu\text{g}$$

[0087] The required volume for the proof mass can then be determined based on the density of the proof mass material as follows:

$$\rho = \frac{m}{V}$$

$$V = \frac{m}{\rho}$$

$$V = \frac{10\mu\text{g}}{8800 \frac{\text{kg}}{\text{m}^3}} \cong 1.2 \times 10^6 \mu\text{m}^3$$

[0088] In some embodiments, the proof mass comprises a high-density material, such as nickel ($\rho \approx 8800 \text{ kg/m}^3$). For a 10 g sensor as described above, a $1.2 \times 10^6 \mu\text{m}^3$ block of nickel (for example, having dimensions of $200 \mu\text{m} \times 200\mu\text{m} \times 30 \mu\text{m}$) can be used to induce collapse under a 10 g acceleration. In embodiments in which the movable member also comprises nickel, such a proof mass can be formed, for example, as follows: during fabrication of the MEMS device and before the movable member is removed from the sacrificial layer, the movable member can be masked so as to leave a $200 \mu\text{m} \times 200\mu\text{m}$ area exposed. The substrate can then be placed in a nickel electroplating bath and additional nickel can be plated on the exposed area up to the desired thickness of $30 \mu\text{m}$. Thus, the proof mass can comprise the same material as the movable member, and/or can be formed directly on the movable member. Alternatively, the proof mass can comprise a different material than the movable member, and/or can be adhered to the movable member, for example using an adhesive.

[0089] In other embodiments, the proof mass is manufactured on a separate, but similarly-sized substrate as the sensor. For example, a thick ($15\text{-}30\mu\text{m}$) layer of gold can be deposited on a thin ($\sim 100\text{-}200\mu\text{m}$) silicon substrate, patterned, and then aligned and attached,

using thermocompression bonding, to a movable membrane which is coated with sputtered gold ($\sim 1\text{-}3\mu\text{m}$). The thin silicon support can then be removed, for example by dissolving it in a KOH solution, before releasing the movable membrane.

[0090] Figure 9B shows the sensor **200** of Figure 9A in a collapsed state, the sensor having been exposed to the selected level of physical shock. In these and other embodiments, the movable member **208** and/or the optical stack **202** can be specially formed or treated, as described above in connection with Figures 8A-8B, so as to ensure that permanent stiction will occur when the movable member **208** contacts the optical stack **202**. Embodiments are thus configured to prevent the movable member **208** from restoring itself to its original position after making contact with the optical stack **202**, even after the physical shock has passed.

Radiation Sensor

[0091] With reference now to Figures 10A and 10B, an environmental sensor **300** according to a further embodiment is illustrated. The sensor **300** comprises an optical stack **302** formed on a transmissive substrate **304**, where the optical stack **302** includes a partially reflective layer **306** and an electrically insulating layer **307**. The sensor **300** further comprises a movable member **308** spaced apart from the optical stack **302** by one or more posts **310** to define a gap **312**. In embodiments in which the movable member **308** comprises a reflective layer, the space between **306** and **308** functions as an interferometric cavity. An observer viewing the sensor **300** through the transmissive substrate **304** will thus be able to easily observe a change in the position of the movable member **308** relative to the optical stack **302**, as the light reflected by the sensor **300** is dependent on the height of the interferometric gap **312**.

[0092] As shown in Figure 10A, the movable member **308** comprises a radiation-sensitive layer or coating **314** disposed on the side of the movable member **308** facing the optical stack **302**. The radiation-sensitive layer **314** can be configured to expand in volume when exposed to a particular type or level of radiation **315**. The radiation-sensitive layer **314** can further be configured to expand by an amount sufficient to induce bending in the movable member **308** such that the movable member **308** (and/or the expansion layer **314**) deflects across the gap **312** and comes into contact with the optical stack **302**. Figure 10B

shows the sensor **300** of Figure 10A in a collapsed state, the sensor having been exposed to the selected type or level of radiation.

[0093] The radiation-sensitive layer **314** can comprise, for example, an optically absorbing pigment such as carbon black, or a layer of chromium or indium tin oxide. Where the radiation-sensitive layer absorbs radiation and produces localized heating, such deformation can occur as a result of differential thermal expansion. Other embodiments can include a radiation-sensitive layer **314** designed to undergo a change in volume when exposed to radiation. Examples of such a material include polymer networks containing azobenzene liquid-crystalline (LC) moieties, which are capable of changing their macroscopic shape when exposed to light. Other polymer gels containing ionizable moieties, as well as certain inorganic materials such as vanadium dioxide, also display photosensitivity and can be incorporated into embodiments. In addition, several photosensitive polymeric materials exist which can be patterned lithographically into discrete “patches” within the boundary of each interferometric modulator to optimize their mechanical input to the movable member. One such material is PMMA, sold in a photoresist formulation commercially by MicroChem Corp, Newton, MA. This material can be spin-coated up to relatively high thicknesses (up to 5 μ m) in a standard clean room environment and subsequently patterned using deep UV illumination. It is also insensitive to the chemical etch of the release process used to remove the sacrificial layer and leave a suspended moveable member. By incorporating a radiation-sensitive coating **314** in a sensor **300** according to embodiments of the invention, such that permanent stiction will occur upon exposure of the sensor **300** to a predetermined type or level of radiation, a passive sensor is provided that directly displays a response to incident radiation without any additional components.

[0094] In certain embodiments, a polarizing coating or film **316** can be disposed on a side of the substrate **304** opposite the optical stack **302** to provide additional control of the direction of bending in the movable member **308**. For example, in embodiments comprising a coating **314** comprising a polymer network as described above, the coating **314** may be directionally sensitive to incident radiation. The polarizing film **316** can thus be configured to promote a preferred mechanical response from the coating **314**, and thus from the movable member **308**, as shown in Figure 10B.

[0095] In these and other embodiments, the movable member **308** and/or the optical stack **302** can be specially formed or treated, as described above in connection with Figures 8A-8B, so as to ensure that permanent stiction will occur when the movable member **308** contacts the optical stack **302**. Embodiments are thus configured to prevent the movable member **308** from restoring itself to its original position after making contact with the optical stack **302**, even after the deforming radiation is no longer present.

[0096] In another embodiment, an array of interferometric modulators with different stiction thresholds may be manufactured on a single substrate such that, for example, the highest level of humidity to which a device is exposed may be recorded. Continuing with the example, a user could determine that at some point in time since the device was activated it was exposed to a humidity level of 65%, but not more than 70%, based on some of the interferometric modulators reaching permanent stiction with others not having done so. As opposed to having a single threshold level, the maximum level may be recorded, for example with humidity, temperature (87 degrees but not 88 degrees), types of chemicals (exposure to carbon monoxide but not sulfur) or radiation (in degree or type – exposure to ultraviolet but not x-ray), force (exposure to 5 g but not 6 g), and so on.

Multiple-Stimuli Sensor

[0097] As mentioned earlier, embodiments can be configured to sense multiple stimuli simultaneously. Embodiments can be configured to sense any combination of energy inputs from the environment sufficient to induce a permanent change in the position of the movable member of the sensor.

[0098] For example, one embodiment can include a movable member comprising an expansion layer or contraction layer as described above, which is configured to cause a movable layer of the device to deform and cause the device to collapse when exposed to a particular level of acidity or alkalinity, or the presence of a particular chemical species. Such an embodiment can also be configured such that the collapse will only be permanent if it occurs at or above a particular temperature threshold. Additionally or alternatively, such an embodiment can be configured such that the collapse will only be permanent if it occurs at or above a particular humidity threshold.

[0099] Another embodiment can include a thin film stack configured with, for example, multiple layers having different coefficients of thermal expansion, as described above, so as to induce deformation and collapse of the movable member when the device is exposed to a predetermined temperature threshold. Such an embodiment can also be configured such that the collapse will only be permanent if it occurs at or above a particular humidity threshold.

[0100] A further embodiment can include a movable member comprising a radiation-sensitive layer as described above, which is configured to cause a movable layer of the device to deform and cause the device to collapse when exposed to a particular level or type of radiation. Such an embodiment can also be configured such that the collapse will only be permanent if it occurs at or above a particular temperature threshold. Additionally or alternatively, such an embodiment can be configured such that the collapse will only be permanent if it occurs at or above a particular humidity threshold.

[0101] A still further embodiment can include a proof mass as described above, which is configured to cause a movable layer of the device to deform and cause the device to collapse when exposed to a particular level of mechanical shock. Such an embodiment can be configured such that the collapse will only be permanent if it occurs at or above a particular temperature threshold. Additionally or alternatively, such an embodiment can be configured such that the collapse will only be permanent if it occurs at or above a particular humidity threshold.

Package

[0102] With reference now to Figures 11 and 12, an example of a sensor **400** according to another embodiment is described. The sensor **400** comprises an optical stack **402** formed on a transmissive substrate **404**, through which the state of the sensor **400** may be viewed. The sensor **400** also includes a movable member **408** spaced apart from the optical stack **402** by one or more posts **410** to define a gap. The movable member **408** can include a reactive member **414**, such as a chemical-reactive coating, a humidity, temperature, or radiation sensitive layer, or a proof mass configured to couple external shock, as described above. The sensor **400** can also include a protective layer **430** provided at or near the side of the movable member **408** facing away from the optical stack **402**. The protective layer **430**

can be configured to protect the active area of the sensor **400**, especially the movable member **408**, from the external environment until a user activates the sensor **400**. To achieve desired conditions in the internal environment of the sensor **400**, the protective layer **430** can be attached (that is, the sensor **400** can be encapsulated) under controlled ambient conditions. The internal environment can be configured with, for example, a low level of humidity selected to prevent permanent stiction from occurring in the sensor **400** should the movable member **408** collapse before being activated. In some embodiments, the protective layer **430** can be provided with an adhesive **432** protected by an additional peel-off backing layer, allowing the sensor **400** to be affixed to the surface of, for example, a shipping box or food package. The protective layer **430** can comprise metal, plastic, or any other suitable material capable of protecting the internal environment of the sensor **400** from one or more environmental influences.

[0103] The sensor **400** can also include one or more weakened areas or perforations **422** running through the substrate **404** to the optical stack **402**, to define one or more removable areas **426** of the substrate. A sealing layer **424** is disposed on a side of the substrate **404** and is configured to maintain the internal environment of the sensor **400**, by mechanically supporting the air gap and the perforations **422**. An encapsulating lid or shell with a perimeter seal (not shown) incorporating the protective layer described above can also be provided which provides mechanical support at the edges of the sensor **400** and which also protects the integrity of the package's internal environment.

[0104] As shown in Figure 11, the perforations **422** and removable areas **426** are provided in an optically inactive region of the sensor **400**, for example in an area between pixels (with a fixed layer **416** instead of a movable layer **408**), so as not to interfere with the optical function of the device. The perforations **422** provide weakened areas in the device such that, when the sealing layer **424** is peeled away or otherwise removed from the substrate **404**, the removable areas **426**, including a portion of the substrate **404** and the underlying layers of the optical stack **402**, along with any fixed layer **416**, will be broken free from and removed from the surrounding material. This process is illustrated in Figure 12B. Thus, when the sealing layer **424** is removed, the movable member **408**, including any reactive layer **414** disposed thereon, is exposed to the external environment, thus activating the sensor

400. In this way, the internal environment of the sensor **400** is protected from the external environment until activated by a user.

[0105] The perforations **422** and/or the removable areas **426** can be configured to expose one or more areas of the sensor **400** to the ambient environment, so as to allow the environment to influence the behavior of the device. The perforations **422** can be empty areas with no structural material, as illustrated in Figure 11, or can be areas comprising a weakened or frangible material. A plurality of perforations **422** and/or removable areas **426** can be provided in the sensor **400** in a distributed configuration, so as to evenly expose the optically active areas of the sensor **400** to the external environment. The perforation or perforations **422** can be provided in the substrate **404** in any suitable configuration, such as the annular configuration illustrated in Figure 12A. In certain embodiments, the perforations **422** can be formed by plasma or chemical etching to weaken or remove particular areas on the surface of the substrate **404**.

[0106] In some embodiments, the substrate and cap can be partially scribed or scored, so as to allow the user to ‘snap’ off an edge of the sensor package to activate the sensor, while preserving the integrity of the package during shipping and handling. In these embodiments, breaking the score line will open the seal between the substrate and the cap, allowing ambient environmental gases, water vapor, etc. to penetrate into the interferometric cavity and interact with the sensing elements inside.

[0107] As mentioned above, embodiments of the invention can be used in multiples and can be configured with varying optical responses to create text, graphic, or color-based sensor displays. Figures 13 and 14 illustrate an embodiment comprising an array of sensor devices as described above, configured to display “OK” in an original, uncollapsed state (Figure 13). Once exposed to a selected environmental threshold or condition, the array will permanently display “FAILED” (Figure 14). Since the collapse of the sensor devices in the array will alter the optical response of the devices in a manner detectable by a human observer, no external electronics or apparatus is required to sense the change.

[0108] In another embodiment the interferometric modulators can be arranged to display the highest level reached within a certain range, for example with humidity, radiation, temperature, force, etc. Rather than a pass/fail indicator, a range of values may be

represented by having images of numbers activate. For example, if the ambient environment of the device reaches 65% humidity, then a portion of the array designed to reach permanent stiction at 65% humidity will do so, with the resulting image showing “65%”. Other parts of the array may include other humidity demarcations at appropriate intervals.

[0109] While the above detailed description has shown, described and pointed out novel features of the invention as applied to various embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of the device or process illustrated may be made by those skilled in the art without departing from the spirit of the invention. As will be recognized, the present invention may be embodied within a form that does not provide all of the features and benefits set forth herein, as some features may be used or practiced separately from others.

WHAT IS CLAIMED IS:

1. A sensor, comprising:
an interferometric modulator, the modulator configured to permanently actuate when exposed to a predefined level of radiation, wherein the actuation of the interferometric modulator is visually detectable.
2. The sensor according to Claim 1, wherein said actuation occurs without requiring application of a voltage across the interferometric modulator.
3. The sensor according to any one of Claims 1 or 2, wherein the interferometric modulator comprises a radiation-reactive layer configured to cause said actuation when exposed to said level of radiation.
4. The sensor according to Claim 3, wherein the interferometric modulator comprises an optical stack and a movable layer, said radiation-reactive layer being disposed on the movable layer.
5. The sensor according to any one of Claims 1 to 4, further comprising a package configured to seal an internal environment of the interferometric modulator from an external environment, the internal environment being configured to prevent permanent actuation of the modulator, the package comprising at least one removable portion configured to expose the internal environment to the external environment upon removal to activate said sensor.
6. A sensor comprising:
means for interferometrically modulating light; and
means for inducing permanent actuation of the light modulating means in response to a predefined level of radiation.
7. The sensor according to Claim 6, wherein said actuation occurs without requiring application of a voltage across the light modulating means.
8. The sensor according to any one of Claims 6 or 7, wherein the inducing means comprises a proof mass configured to cause said actuation in response to said predefined level of radiation.

9. The sensor according to any one of Claims 6 to 8, further comprising means for activating the inducing means.

10. The sensor according to any one of Claims 6 to 9, wherein the activating means comprises a removable sealing layer disposed on the light modulating means.

11. A display comprising an array of sensors according to any one of Claims 1 to 10.

12. A method of manufacturing an interferometric modulator, the method comprising:

providing a reactive layer on a movable member of the interferometric modulator, the reactive layer being configured to deform sufficiently to cause the interferometric modulator to collapse when exposed to a predetermined level of radiation; and

treating the movable member or an optical stack of the interferometric modulator so as to ensure that adhesion will be permanent upon collapse.

13. The method according to Claim 12, wherein said treating comprises driving charge into a surface dielectric film of the optical stack.

14. The method according to any one of Claims 12 or 13, wherein said treating comprises roughening a contact surface of at least one of the movable member or the optical stack.

15. The method according to any one of Claims 12 to 14, wherein said treating comprises coating a contact surface of at least one of the movable member or the optical stack with an adhesive.

16. A method of indicating exposure to an environmental stimulus, the method comprising:

providing an interferometric modulator having a reactive layer disposed on a movable member of the interferometric modulator, the reactive layer being configured to deform when exposed to a predetermined level of radiation by an amount sufficient to cause the interferometric modulator to collapse, the interferometric modulator being configured to ensure that said collapse is permanent.

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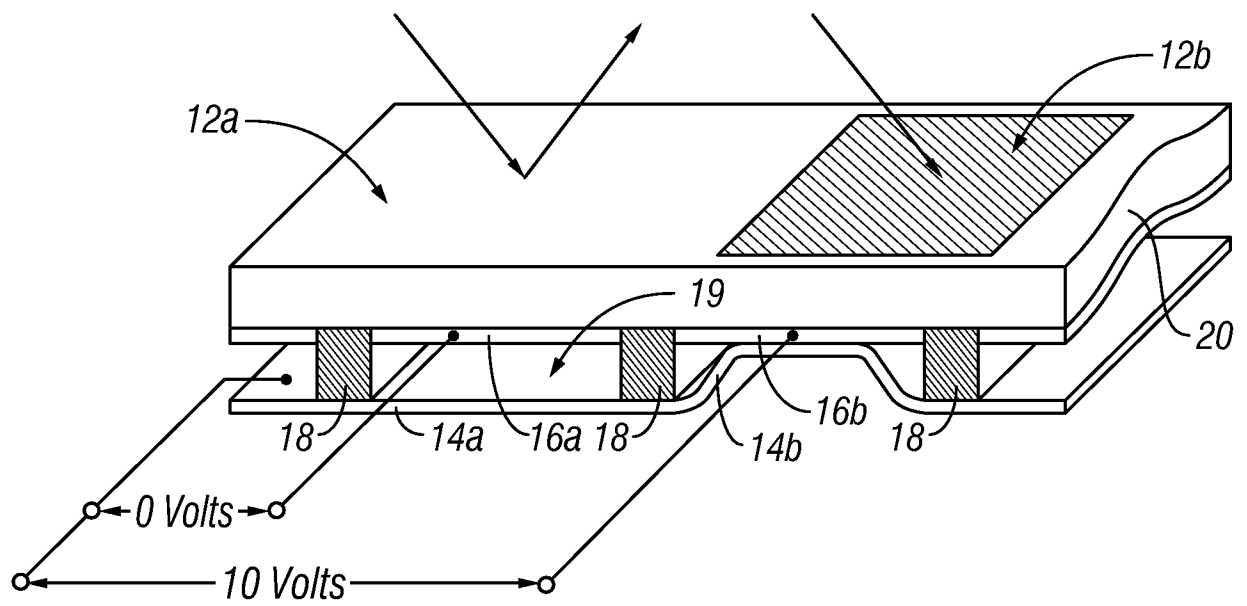


FIG. 1

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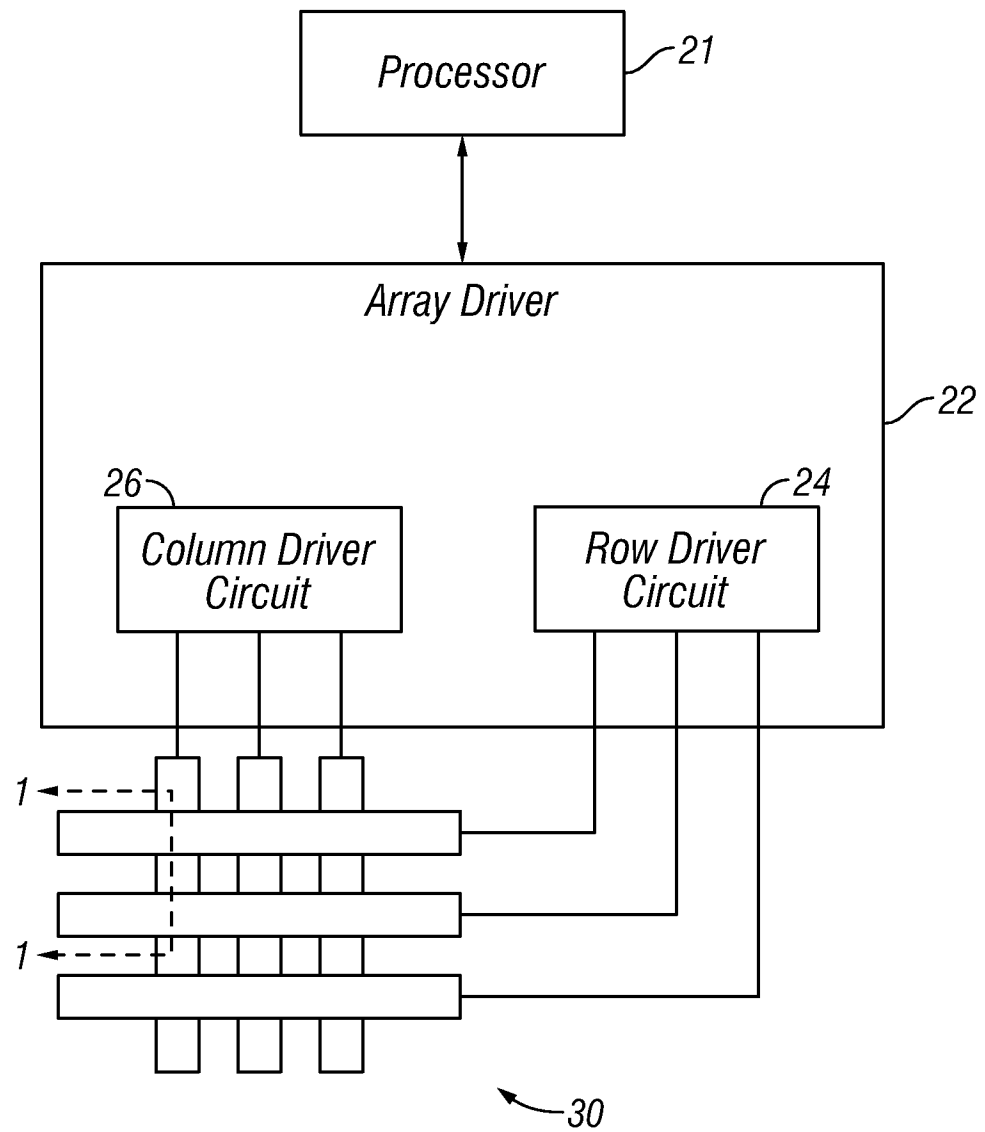


FIG. 2

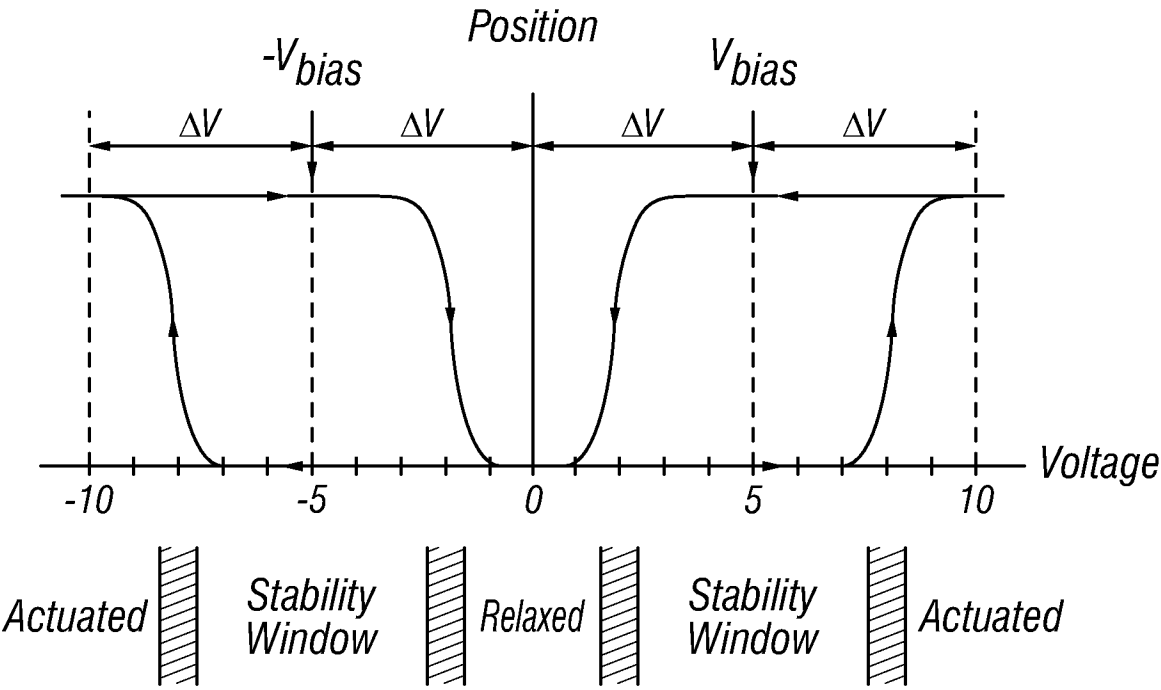


FIG. 3

		Column Output Signals	
		$+V_{bias}$	$-V_{bias}$
Row Output Signals	0	Stable	Stable
	$+\Delta V$	Relax	Actuate
	$-\Delta V$	Actuate	Relax

FIG. 4

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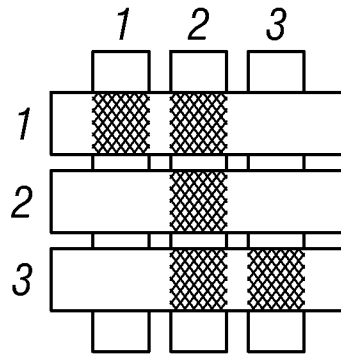


FIG. 5A

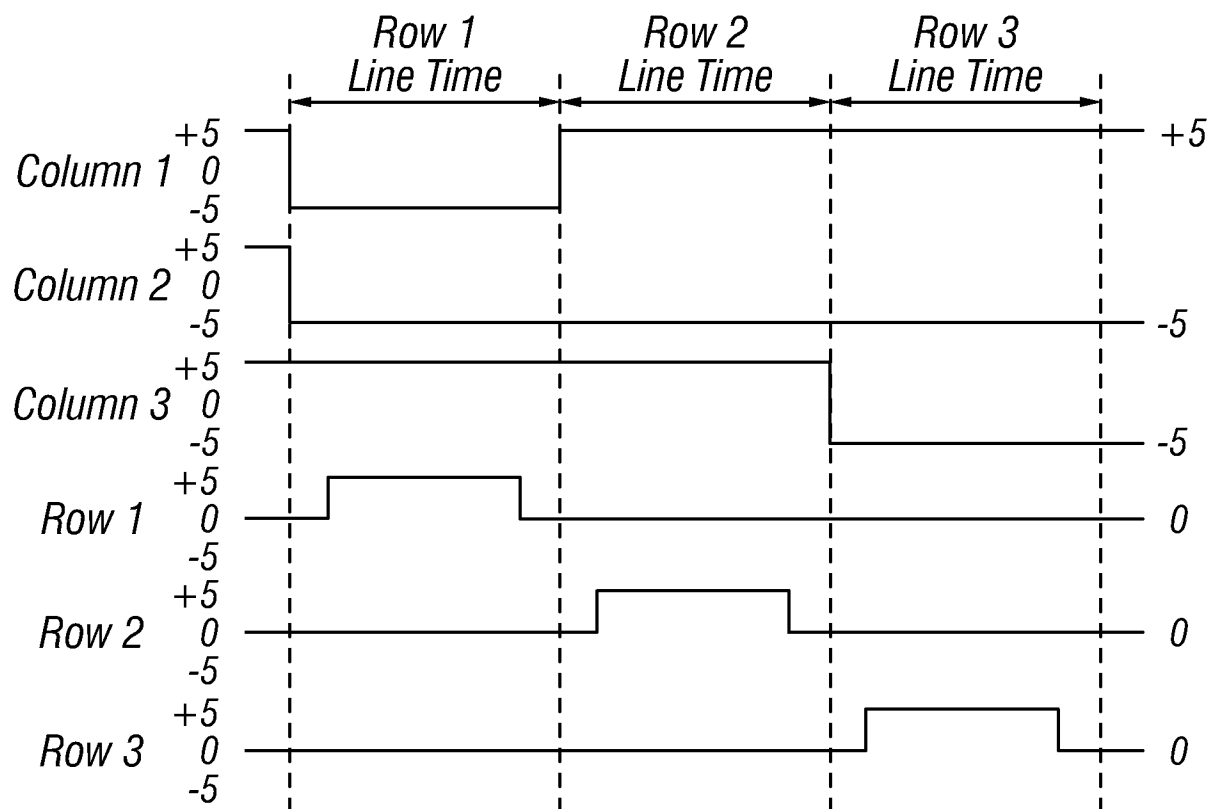


FIG. 5B

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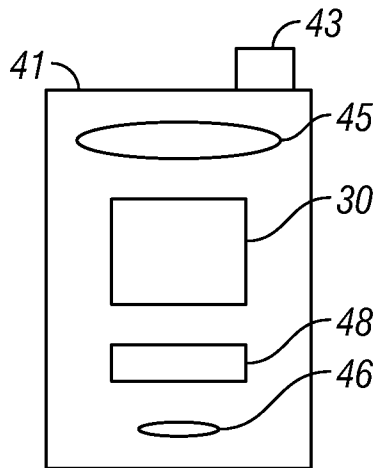


FIG. 6A

40

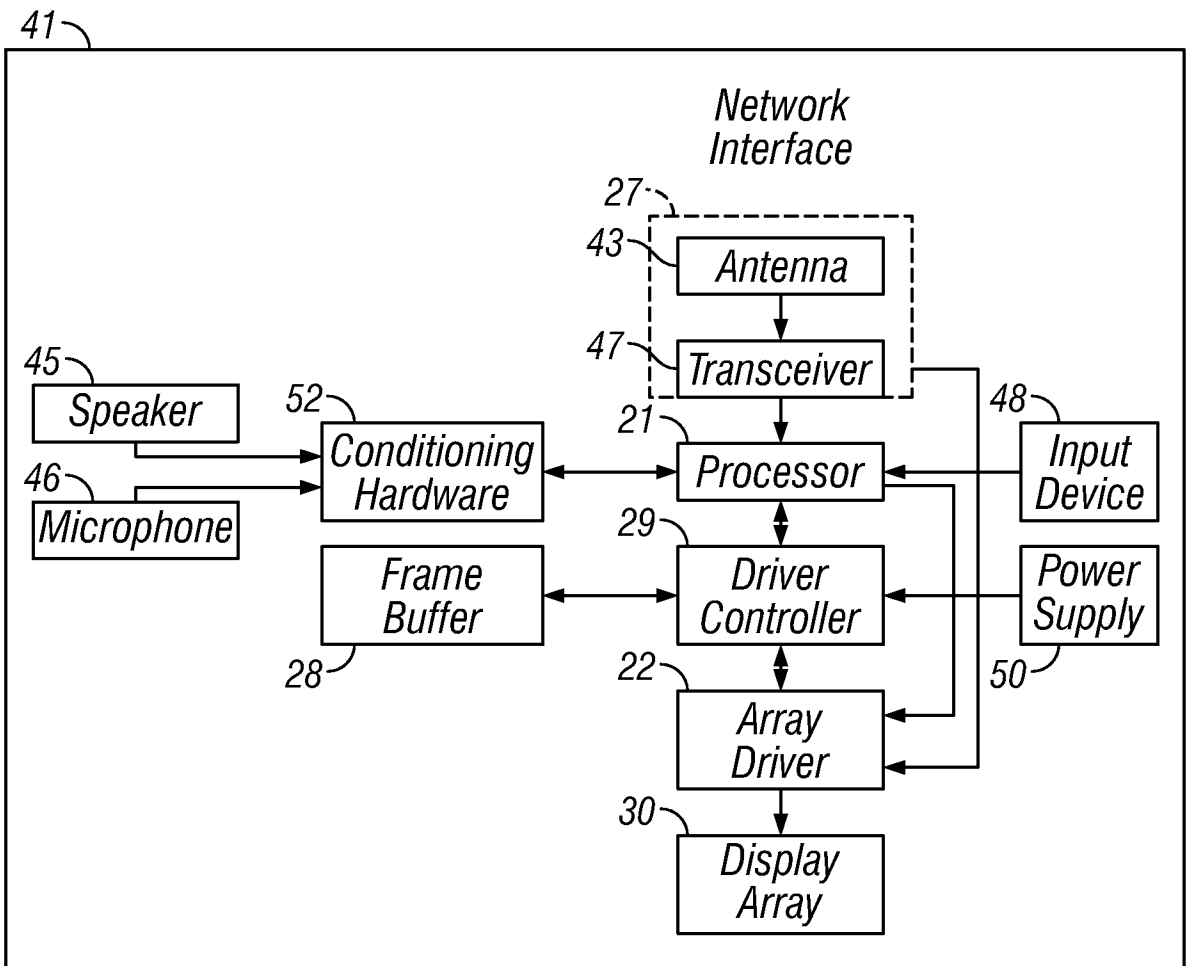


FIG. 6B

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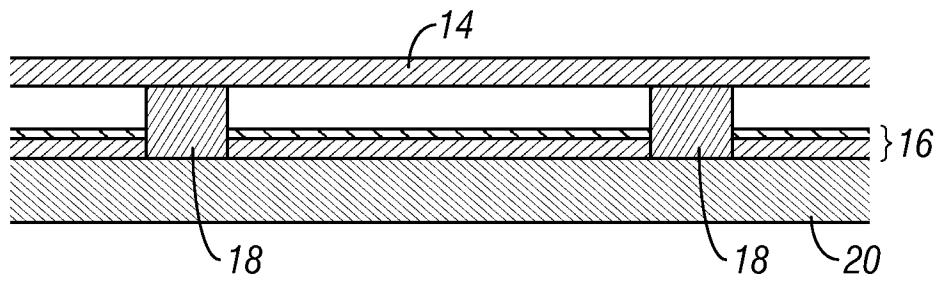


FIG. 7A

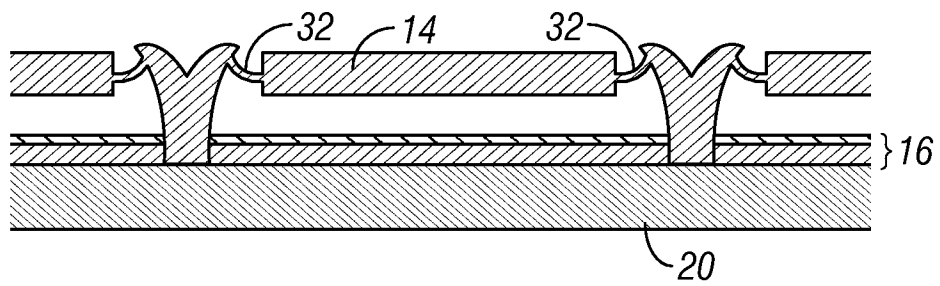


FIG. 7B

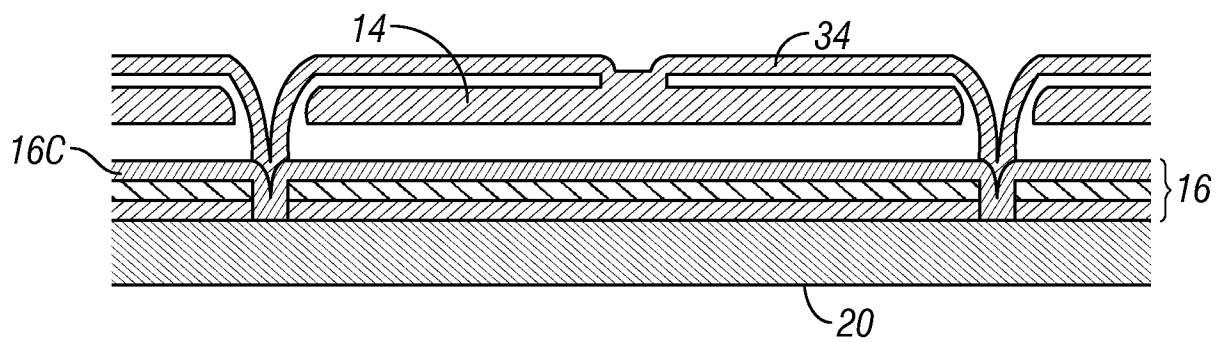


FIG. 7C

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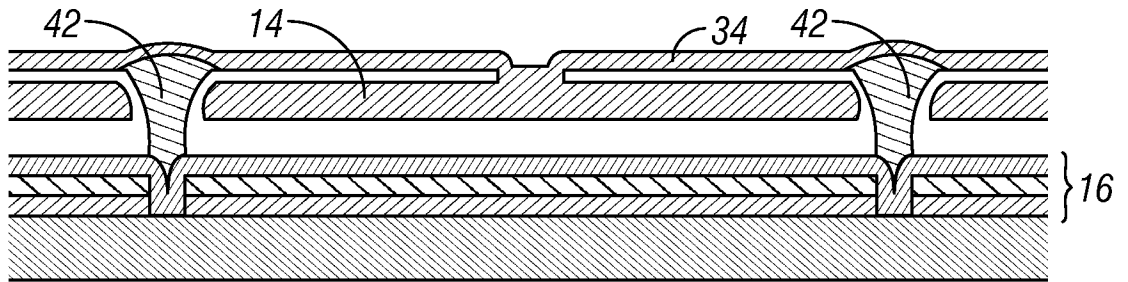


FIG. 7D

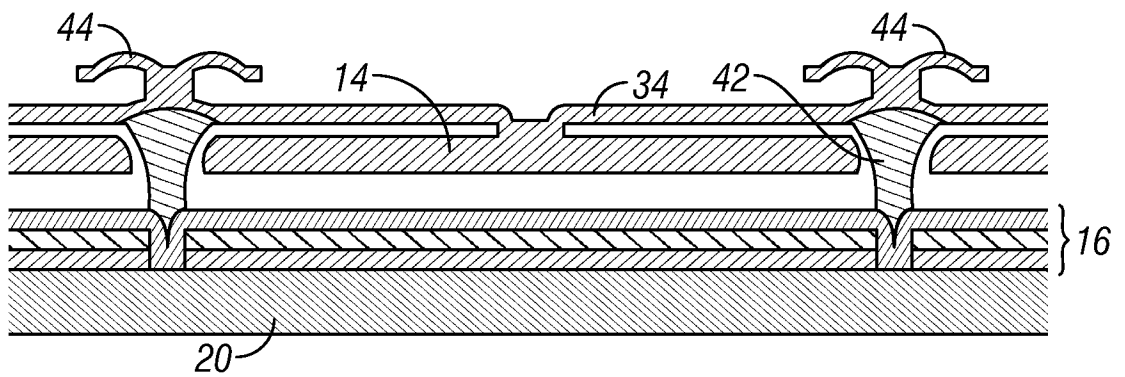


FIG. 7E

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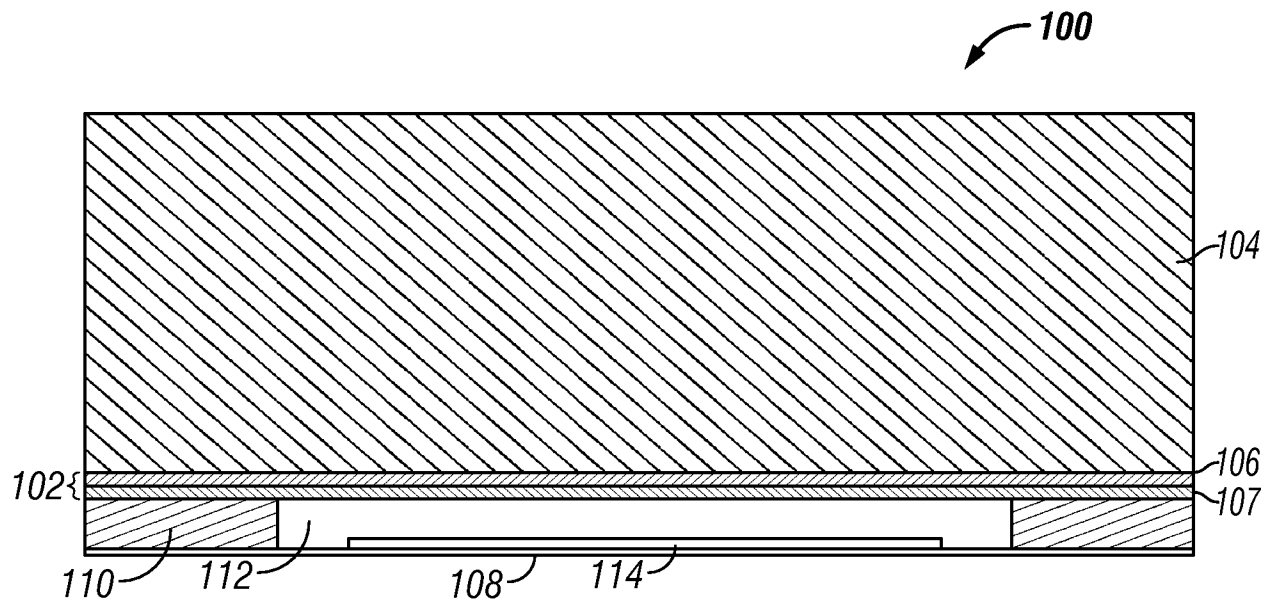


FIG. 8A

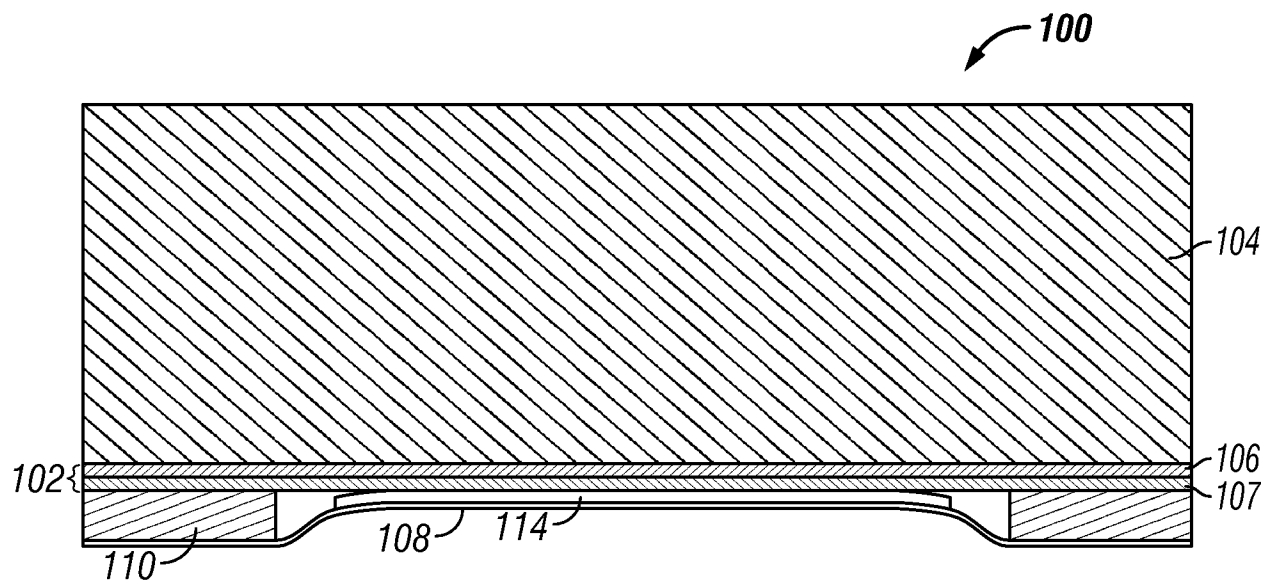


FIG. 8B

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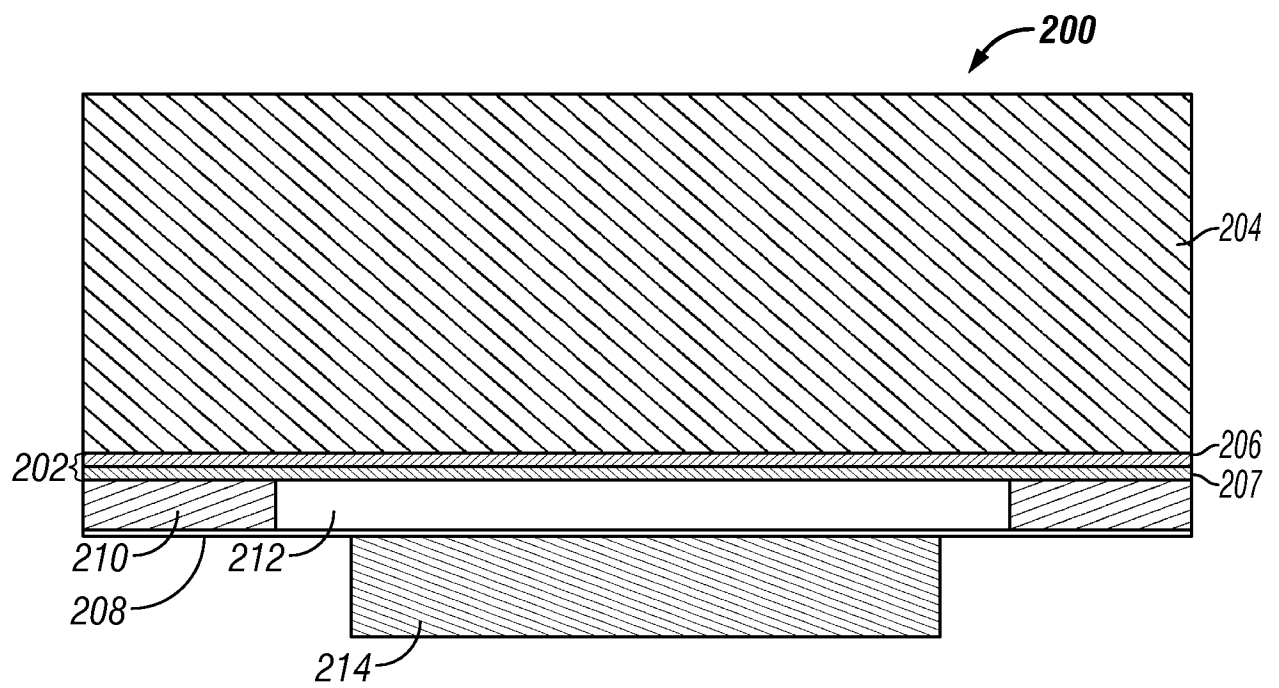


FIG. 9A

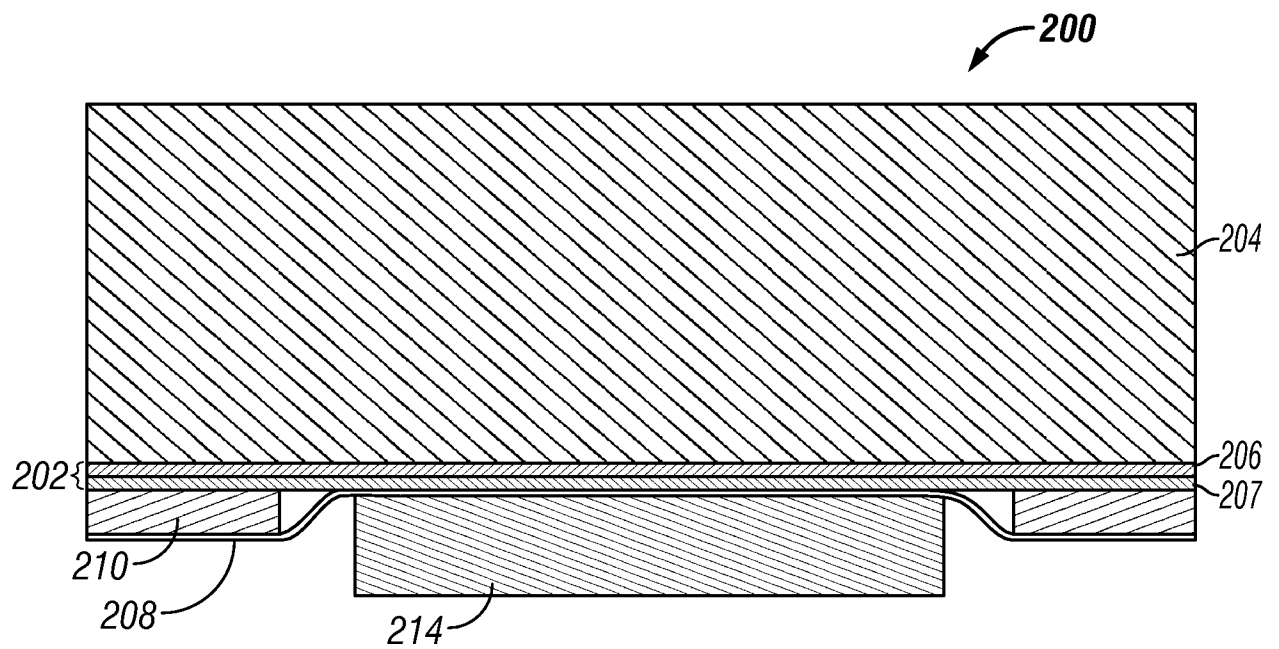


FIG. 9B

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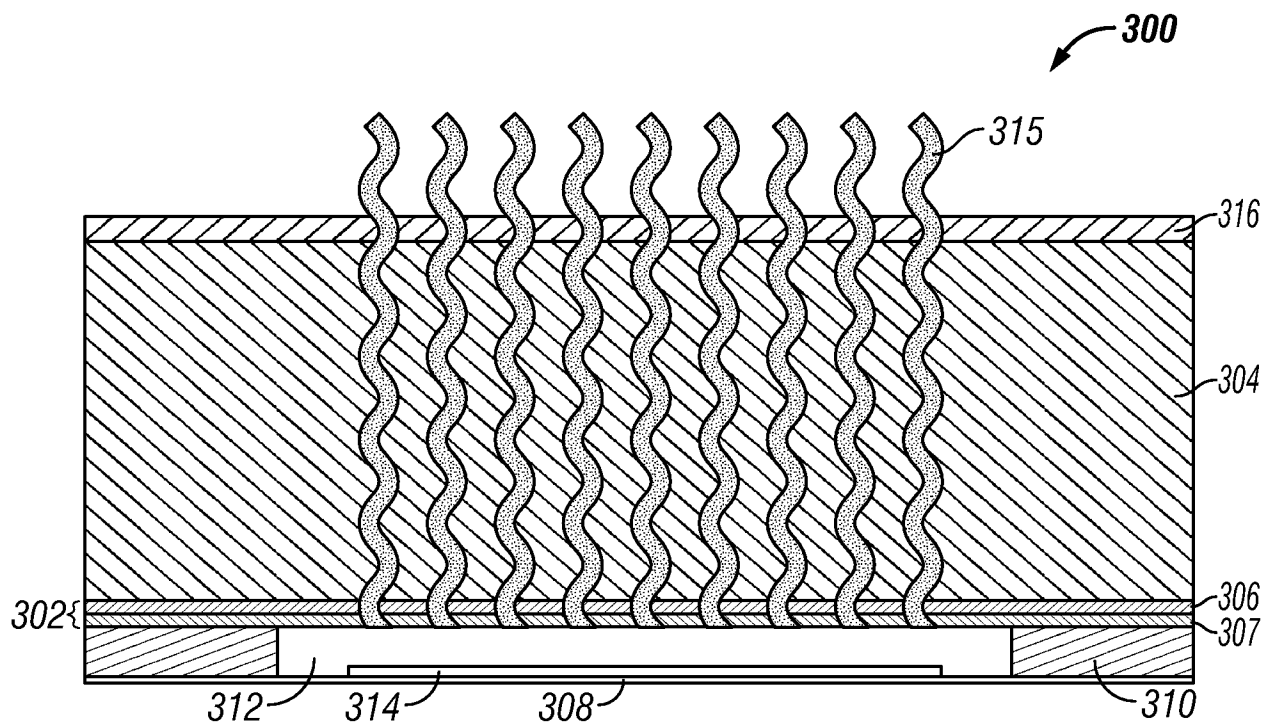


FIG. 10A

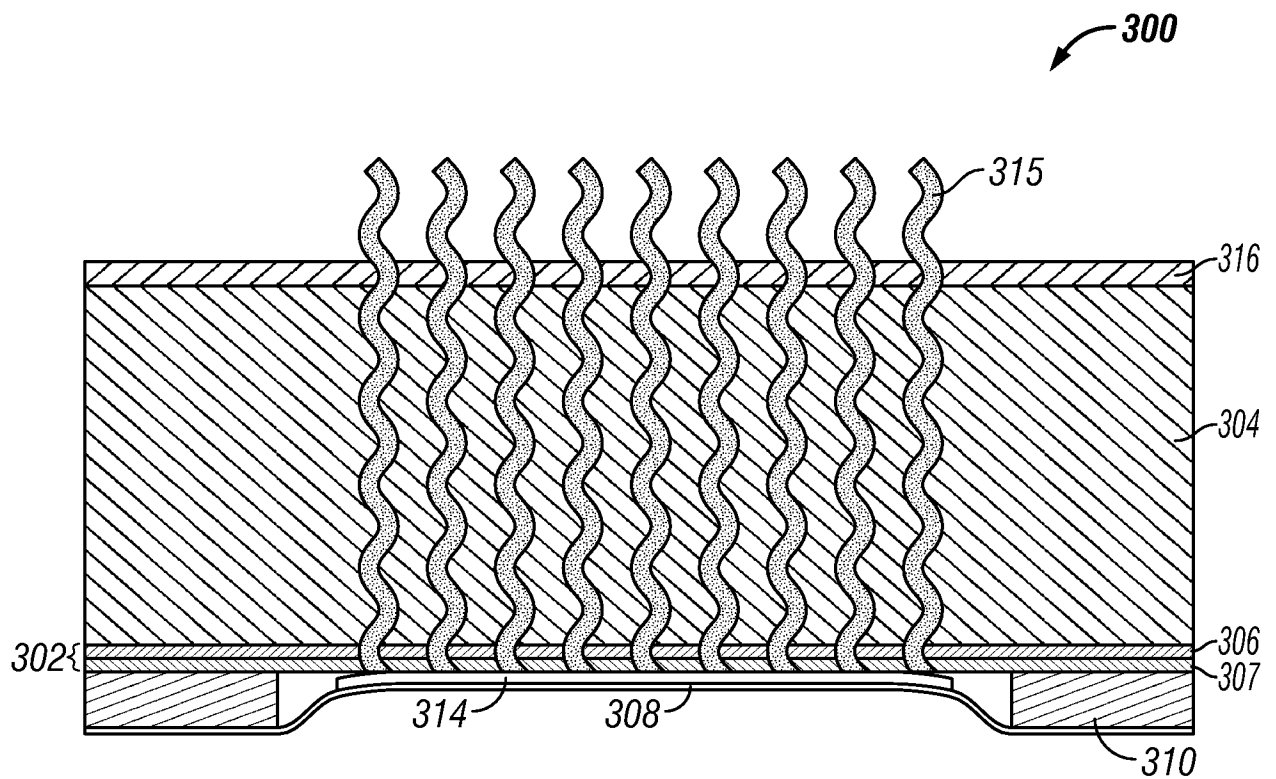


FIG. 10B

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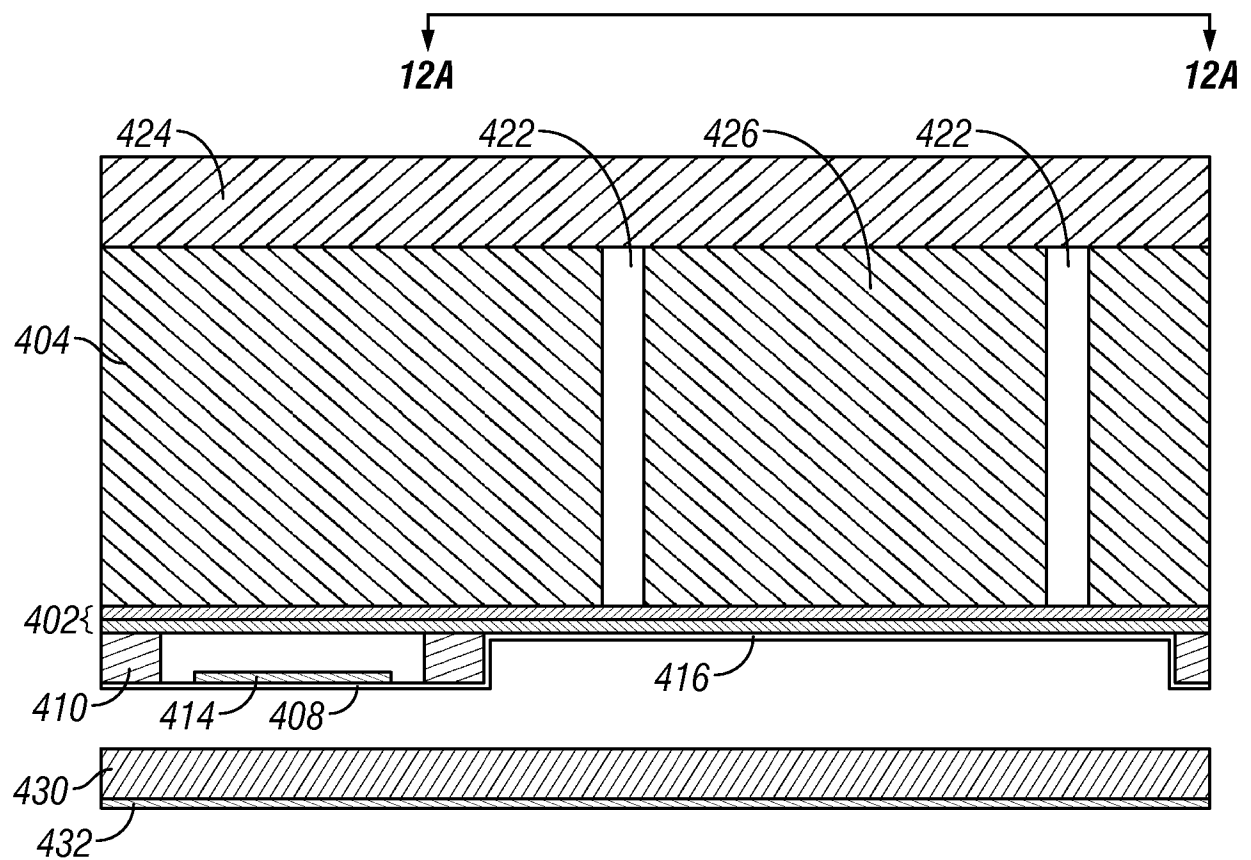


FIG. 11

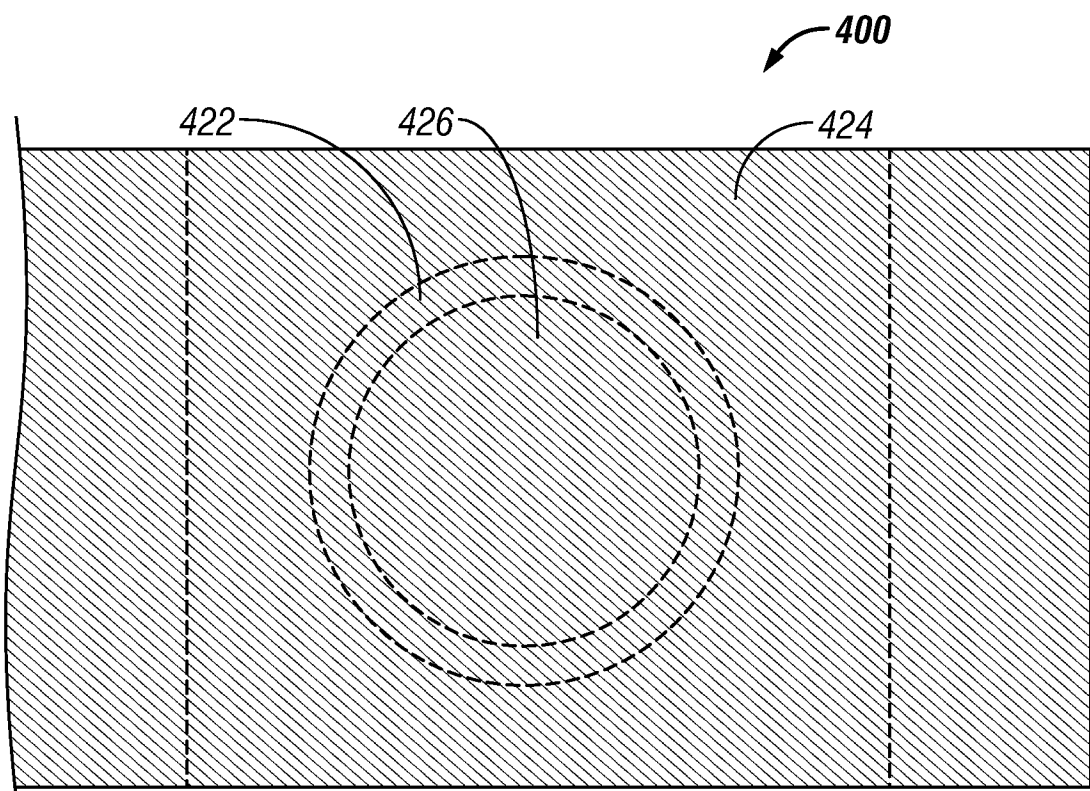


FIG. 12A

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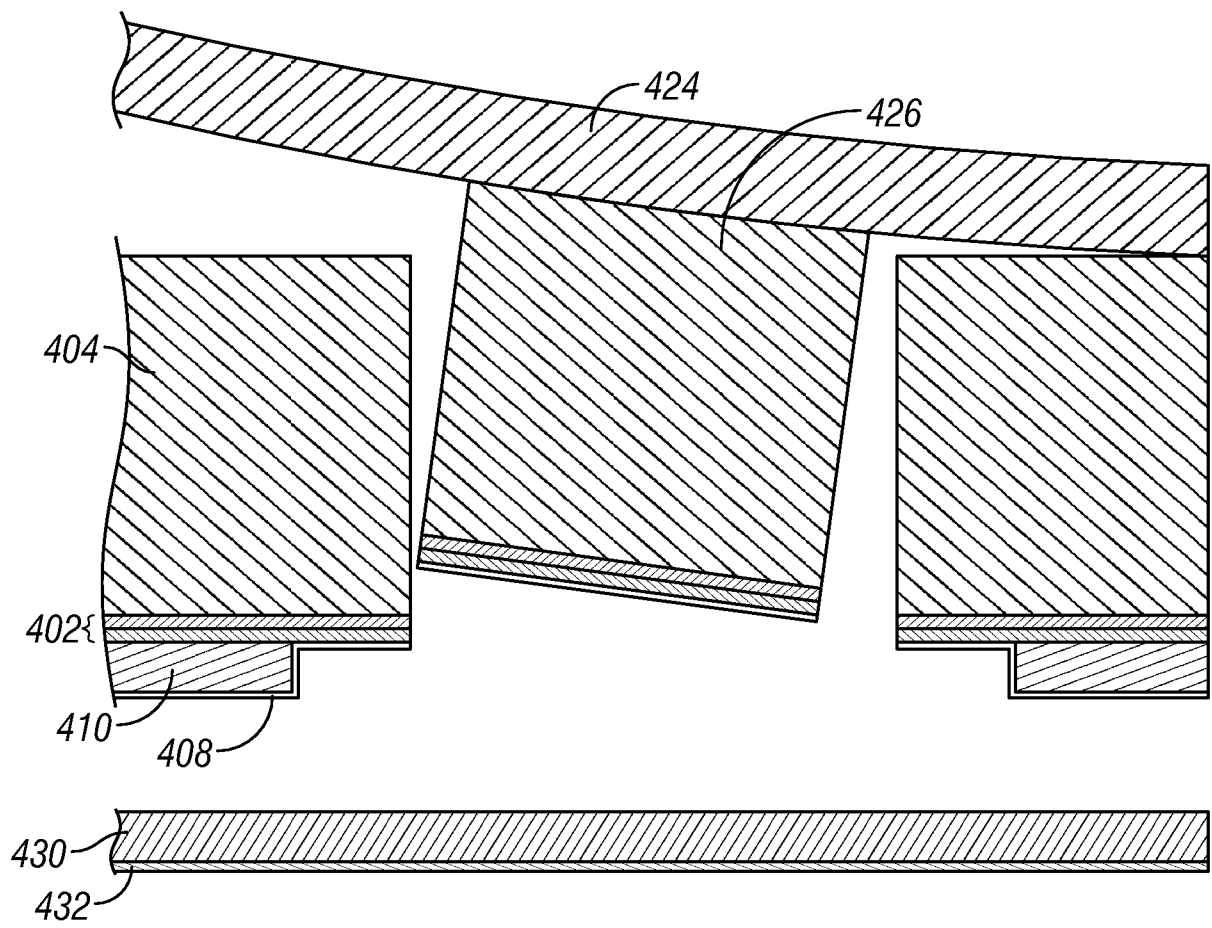


FIG. 12B

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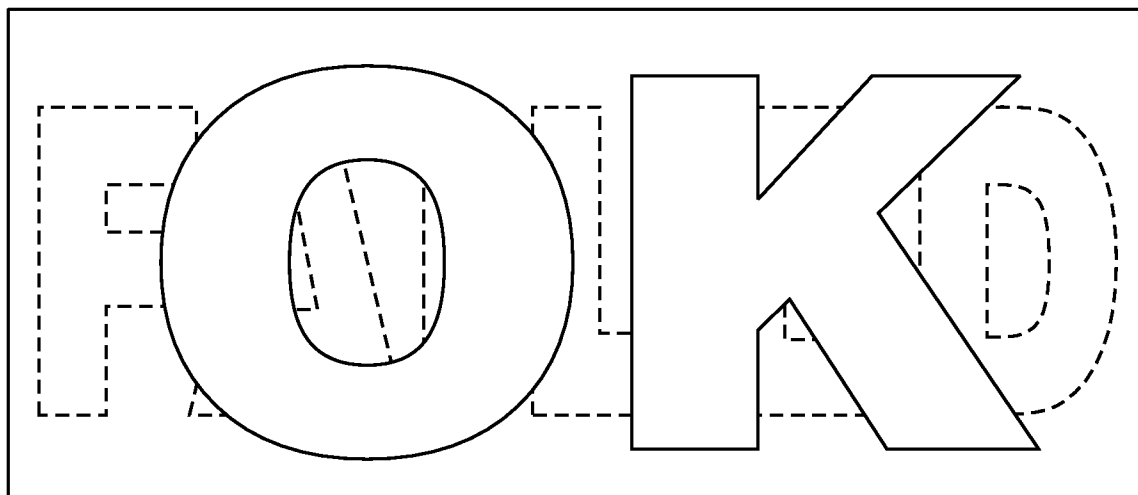


FIG. 13

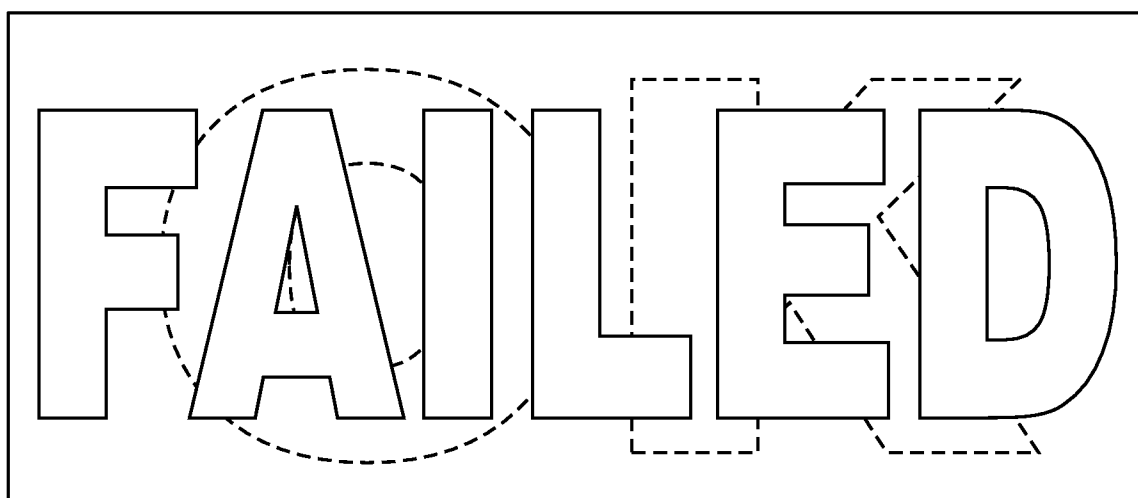


FIG. 14