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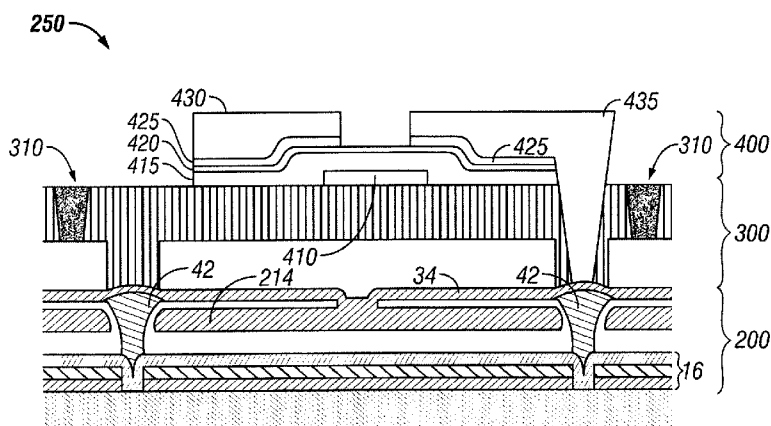


FIG. 6H

(57) Abstract: Methods and devices used for the encapsulation of MEMS devices, such as an interferometric modulator, are disclosed. Encapsulation is provided to MEMS devices to protect the devices from such environmental hazards as moisture and mechanical shock. In addition to the encapsulation layer (300) providing protection from environmental hazards, the encapsulation layer (300) is additionally planarized so as to function as a substrate for additional circuit elements formed above the encapsulation layer (300).

ENCAPSULATION METHODS FOR INTERFEROMETRIC MODULATOR AND MEMS DEVICES

Background

Field of the Invention

[0001] The field relates to microelectromechanical systems (MEMS), and more particularly to methods of encapsulation of MEMS devices.

Description of the Related Technology

[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 of Certain Embodiments

[0003] The system, method, and devices of the invention each have several aspects, no single one of which is solely responsible for its desirable attributes. Without limiting the scope of this invention, its more prominent features will now be discussed briefly. After considering this discussion, and particularly after reading the section entitled “Detailed Description of Certain Embodiments” one will understand how the features of this invention provide advantages over other display devices.

[0004] One aspect is a microelectromechanical system (MEMS) device, including a substrate, a MEMS element on the substrate, the MEMS element including a movable component, an encapsulation layer encapsulating the MEMS element, where the encapsulation layer is planarized, and an electronic element on or over the encapsulation layer.

[0005] Another aspect is a method of manufacturing a microelectromechanical system (MEMS) device, the method including forming a MEMS element on a substrate, the MEMS element including a gap, forming an encapsulation layer encapsulating the MEMS element, planarizing the encapsulation layer, and forming an electronic element on the encapsulation layer.

[0006] Another aspect is a microelectromechanical system (MEMS) device, including means for supporting a MEMS element, the MEMS element including a movable component, means for encapsulating the MEMS element, where the encapsulating means is planarized, and means for processing electronic signals on or over the encapsulating means.

Brief Description of the Drawings

[0007] Figure 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.

[0008] Figure 2 is a system block diagram illustrating one embodiment of an electronic device incorporating a 3x3 interferometric modulator display.

[0009] FIGS. 3A and 3B are system block diagrams illustrating an embodiment of a visual display device comprising a plurality of interferometric modulators.

[0010] Figure 4A is a cross section of the device of Figure 1.

[0011] Figure 4B is a cross section of an alternative embodiment of an interferometric modulator.

[0012] Figure 4C is a cross section of another alternative embodiment of an interferometric modulator.

[0013] Figure 4D is a cross section of yet another alternative embodiment of an interferometric modulator.

[0014] Figure 4E is a cross section of an additional alternative embodiment of an interferometric modulator.

[0015] Figure 5 is a cross section of a MEMS device comprising a encapsulation layer, which is planarized.

[0016] Figures 6A-6H are cross sections of a MEMS device showing processing steps used to manufacture the MEMS device of Figure 5.

Detailed Description of Certain Embodiments

[0017] 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.

[0018] Embodiments provide methods and devices which provide encapsulation to MEMS devices to protect the devices from such environmental hazards as moisture and mechanical shock. In addition to the encapsulation layer providing protection from environmental hazards, the encapsulation layer is additionally planarized so as to function as a substrate for additional circuit elements formed above the encapsulation layer.

[0019] 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.

[0020] 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.

[0021] 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**.

[0022] 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.

[0023] 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.

[0024] 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.

[0025] Figures 2 through 5B illustrate one exemplary process and system for using an array of interferometric modulators in a display application.

[0026] 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.

[0027] 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.

[0028] Figures 3A and 3B 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.

[0029] 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.

[0030] 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.

[0031] The components of one embodiment of exemplary display device 40 are schematically illustrated in Figure 3B. 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.

[0032] 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.

[0033] 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.

[0034] 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.

[0035] 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.

[0036] 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**.

[0037] 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.

[0038] 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).

[0039] 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.

[0040] 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.

[0041] 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.

[0042] The details of the structure of interferometric modulators that operate in accordance with the principles set forth above may vary widely. For example, Figures 4A-4E illustrate five different embodiments of the movable reflective layer 14 and its supporting structures. Figure 4A 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 4B, the moveable reflective layer 14 is attached to supports at the corners only, on tethers 32. In Figure 4C, 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 4D 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 4A-4C, 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 4E is based on the embodiment shown in Figure 4D, but may also be

adapted to work with any of the embodiments illustrated in Figures 4A-4C, as well as additional embodiments not shown. In the embodiment shown in Figure 4E, 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.

[0043] In embodiments such as those shown in Figure 4, 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 4E, 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 4C-4E 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.

[0044] The following description is directed to methods and devices used for the encapsulation of MEMS devices, such as the interferometric modulators described above. The encapsulation layers described herein are applied to interferometric modulators, however, in other embodiments encapsulation layers can be applied to other MEMS devices.

[0045] Figure 5 is an illustration of an exemplary embodiment of a MEMS device **100** comprising substrate **110** with MEMS element **120** thereon. Over the MEMS element **120** is encapsulation layer **130** with an electronic element **140** thereon.

[0046] Substrate **110** supports the other components, and may, in some embodiments, be transparent or partially transparent. The substrate may be formed of, for example, glass, plastic, another material, or a combination thereof. The substrate provides a means for supporting MEMS element **120**.

[0047] MEMS element **120** may be any MEMS device. For example, the MEMS element may be an interferometric modulator, a switch, or another MEMS element, or combination thereof. In some embodiments, the MEMS element comprises a gap and/or a moveable component. In some embodiments, the MEMS element may be any of the interferometric modulators described above and shown in Figures 4A-4E.

[0048] The MEMS element **120** is encapsulated by encapsulation layer **130**. Encapsulation layer **130** may provide a hermetic seal for the interferometric modulator in order to protect it from environmental agents such as moisture and oxygen. The seal also allows for pressure within the MEMS element to be maintained independent from external pressure of the ambient environment. Thus, the MEMS element may be fabricated to maintain an environment that differs from the ambient environment. For example, during manufacturing, the encapsulation layer **130** can be manufactured with a via **150** that provides an electrical connection from the electronic element **140** to the MEMS element **120**. In some embodiments the encapsulation layer seals all interferometric modulators in an array from the ambient environment, while in other embodiments only a portion of the interferometric modulators are sealed by the encapsulation layer. For example, an array may comprise some interferometric modulators which do not move. Such interferometric modulators may have a reflective layer manufactured at a known fixed position, and may not need to have encapsulation layer.

[0049] The encapsulation layer **130** may be formed of BCB, acrylic, polyimide, silicon oxide, silicon nitride, AlOx, oxynitride, etc.

[0050] When the moveable components of the MEMS element **120** move between various states, optional orifices within the MEMS element **120** (not shown in the

cross-section of Figure 5) allow for gasses to flow between around or through the MEMS element 120. The viscosity of the gasses within the device may slow the movement. Sealing the interferometric modulator array at the time of manufacturing with the encapsulation layer 130 allows for deliberate customization of the environment of the MEMS element 120. Because of the permanent nature of the encapsulation provided by encapsulation layer 130, the environment within each MEMS element 120 can persist throughout the lifetime of the array. For example, inducing a vacuum before sealing will substantially remove the gasses from the MEMS element 120, so that during use, the movement of the moveable components is not impeded by the cavity atmosphere. It should be realized that interferometric modulator arrays are typically sealed from the ambient environment by sealing a backplate to protect the array from the outside environment. While this type of sealant may still be used, it may also be unnecessary because the encapsulation layer 130 can also serve to protect the interior cavities from being affected by the ambient environment. Similarly, embodiments of the invention may also include the use of a desiccant to reduce the moisture levels within the MEMS element 120. However, the use of such desiccant may be unnecessary in view of the fact that the MEMS element 120 may be hermetically sealed by the encapsulation layer 130. The encapsulation layer 130 provides a means for sealing the MEMS element 120. The encapsulation layer 130 also provides a means for supporting the electronic element 140.

[0051] As shown in Figure 5, in some embodiments, the encapsulation layer 130 comprises a via 150 which makes an electrical connection between the MEMS element 120 and the electronic element 140. The electronic element 140 may comprise passive and/or active elements, such as routing wires, resistors, capacitors, inductors, diodes, and transistors. These elements may also include variable elements, such as variable resistors and variable capacitors. The type of electronic element is not limited and other types of electronic elements may also be used. The electronic element may comprise display driver circuitry for at least one of rows, columns, portions of rows and/or columns, and individual deformable layers. The electronic element may additionally or alternatively comprise sense circuitry, used to determine the state of individual deformable layers or groups (such as rows or columns) of deformable layers. ESD protection, EM shielding, and interconnect routing may also be included in the

electronic element. In some embodiments the electronic element may also comprise digital signal processing (DSP) functions such as data filtering and control information decoding. In some embodiments, the electronic element may comprise RF functions such as an antenna and a power amp, as well as data converters. The type and function of the electronic element is not limited and other types and functions may be implemented. In some embodiments, the electronic element provides a means for electrically communicating with the MEMS element.

[0052] In order to prepare the encapsulation layer **130** for the electronic element **140**, the upper surface of the encapsulation layer **130** may be planarized. A planarization process may be performed to modify the upper surface of the encapsulation layer **130** so that it is substantially planar. Planarization allows the electronic element **140** to be formed without the effects of topological irregularities which would exist in the encapsulation layer **130** without the planarization. For some electronic elements, such as TFT's, topological irregularities can significantly affect performance parameters. Accordingly, when an array of electronic elements **140** is to be formed on an encapsulation layer **130** above an array of MEMS elements **110**, planarization of the encapsulation layer **130** results in more consistent performance of the TFT's across the array.

[0053] Figures 6A-6E are cross sections of a MEMS device showing processing steps used to manufacture the MEMS device of Figure 5. These figures show processing steps for the interferometric modulator shown in Figure 4D. The processing steps may be analogously applied to other interferometric modulator embodiments, for example, any of the interferometric modulators shown in Figures 4A-4C, and 4E. Other processing steps can be used in addition to or alternatively.

[0054] Figure 6A is a cross section of MEMS device **250** at a particular point in the manufacturing process. MEMS device **250** at the point show has a MEMS element **200** built on substrate **210**. MEMS element **200** includes moveable layer **214** supported on posts **242** and spaced apart from optical stack **216** by a gap. Moveable layer **214** may be similar to layer **14** described above, posts **242** may be similar to support post plugs **42** described above, and optical stack **216** may be similar to optical stack **16** described

above. Also shown in Figure 6A is sacrificial layer **220**. The sacrificial layer **220** is used to form the MEMS element **200**, and is removed later in the manufacturing process.

[0055] Figure 6B is a cross section of MEMS device **250** at a second point in the manufacturing process. A second sacrificial layer **225** has been formed on the MEMS element **200**. In Figure 6C the second sacrificial layer **225** has been etched in preparation for forming an encapsulation layer.

[0056] Figure 6D is a cross section of MEMS device **250** showing MEMS element **200** covered by encapsulation layer **300**. The encapsulation layer **300** can be formed of BCB, acrylic, polyimide, silicon oxide, silicon nitride, AlOx, oxynitride, etc. After formation the encapsulation layer **300** is typically non-planar, as indicated by irregular sections **305**.

[0057] Because the encapsulation layer **300** forms a substrate for electronic elements placed thereon, the topological irregularities can affect the performance of some electronic elements. It is advantageous to perform a planarization process on the encapsulation layer **300** to substantially remove the topological irregularities. Figure 6E shows the encapsulation layer **300** after planarization. The planarization process may include a mechanical polishing (MP) process, a chemical mechanical planarization (CMP) process, or a spin-coating process.

[0058] In these embodiments, the encapsulation layer **300** is spaced apart from the relaxed state position of the moveable layer **214** by the second sacrificial layer **225**. The introduction of such a sacrificial layer may improve reliability of the device. During operation, the moveable layer **214** may forcefully move from an actuated position close to the optical stack **216** to the relaxed position away from the optical stack **216**. Maintaining a space above the moveable layer **214** allows for the moveable layer **214** to “overshoot” the final relaxed state because of the mechanical restorative force. Without sufficient space, the deformable layer would collide with the encapsulating layer **300**, potentially damaging the structure and shortening the life of the encapsulating layer **300** and/or the mechanical interferometric modulator structure.

[0059] Figure 6F shows MEMS device **250** where the encapsulation layer **300** has holes **310**, and the sacrificial layers **220** and **225** have been removed. In some embodiments, the sacrificial layers **200** and **225** are removed through the holes **310** in the

encapsulation layer **300**. In some embodiments, the holes are used to create a desired environment for the MEMS element **200**. For example, as discussed above, a substantial vacuum, or low pressure environment can be established with the holes **310**.

[0060] Figure 6G shows MEMS device **250** where the holes **310** in the encapsulation layer **300** have been plugged. In some embodiments, the plugs are formed of a dielectric material. In some embodiments, the plugs are conductive. In some embodiments, the encapsulation layer **300** with plugged holes **310** forms a hermetic seal for the MEMS element **200**.

[0061] Figure 6H shows MEMS device **250** with electronic element **400** formed on the encapsulation layer **300**, which has been planarized. In this embodiment, electronic element **400** is a thin film transistor (TFT) having gate **410**, insulator layer **415**, semiconductor layer **420**, source/drain layer **425**, drain electrode **430**, and source electrode **435**. In this embodiment source electrode **435** is connected to moveable layer **214** through encapsulation layer **300**. The electronic element **400** may comprise an interconnect layer and may comprise a connector configured to connect the MEMS device to another device. The electronic element **400** may comprise either or both of an active element and a passive element.

[0062] In various embodiments of the manufacturing process, the steps described above happen in a different order. For example, the encapsulation layer **300** may be planarized after the material of the sacrificial layer(s) is removed. The holes **310** may be plugged before the encapsulation layer **300** is planarized. The electronic element **400** may be formed after the encapsulation layer **300** is planarized, and before the material of the sacrificial layer(s) is removed. Accordingly, the atmosphere of the MEMS element **200** may be modified and the holes **310** plugged after the formation of the electronic element **300**. In some embodiments, the holes may be plugged with conductive material which connects the electronic element **400** with the MEMS element **200**.

[0063] While the above detailed description has shown, described, and pointed out novel features 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 microelectromechanical system (MEMS) device, comprising:
 - a substrate;
 - a MEMS element on the substrate, the MEMS element comprising a movable component;
 - an encapsulation layer encapsulating the MEMS element, wherein the encapsulation layer is planarized; and
 - an electronic element on or over the encapsulation layer.
2. The device of Claim 1, wherein the encapsulation layer is planarized with a chemical mechanical planarization method.
3. The device of Claim 1 or 2, wherein the encapsulation layer is planarized with a mechanical polishing method.
4. The device of any of the preceding claims, wherein the MEMS element comprises an interferometric modulator.
5. The device of any of the preceding claims, wherein the MEMS element comprises a moveable component configured to move between first and second positions, the first position being nearer the encapsulation layer than the second position.
6. The device of any of the preceding claims, wherein the encapsulation layer is spaced apart from the MEMS element.
7. The device of any of the preceding claims, wherein the encapsulation layer comprises a hole.
8. The device of Claim 7, wherein the hole is plugged.
9. The device of Claim 7 or 8, wherein the hole is plugged with a dielectric material.
10. The device of any of Claims 7 to 9, wherein the hole is plugged with a conductive material.
11. The device of Claim 10, wherein the conductive material is electrically connected to the MEMS element.
12. The device of any of the preceding claims, wherein the electronic element comprises an interconnect layer.

13. The device of any of the preceding claims, wherein the electronic element comprises a connector.

14. The device of any of the preceding claims, wherein the electronic element comprises an active device.

15. The device of any of the preceding claims, wherein the electronic element comprises a passive device.

16. The device of any of the preceding claims, wherein the electronic element comprises a thin film transistor.

17. A method of manufacturing a microelectromechanical system (MEMS) device, the method comprising:

- forming a MEMS element on a substrate, the MEMS element comprising a gap;
- forming an encapsulation layer encapsulating the MEMS element;
- planarizing said encapsulation layer; and
- forming an electronic element on the encapsulation layer.

18. The method of Claim 17, wherein forming the encapsulation layer comprises forming a hole.

19. The method of Claim 17 or 18, wherein forming the MEMS element comprises depositing a sacrificial layer, and the method further comprises removing the sacrificial layer through the hole.

20. The method of any of Claims 17 to 19, wherein the electronic element is formed prior to removing the sacrificial layer.

21. The method of any of Claims 17 to 20, further comprising:
- modifying the environment of the MEMS element; and
 - plugging the hole.

22. The method of any of Claims 18 to 20, further comprising plugging the hole.

23. The method of Claim 22, further comprising plugging the hole, wherein the encapsulation layer is planarized after the hole is plugged.

24. The method of any of Claims 17 to 23, further comprising electrically connecting the MEMS element with the electronic element through the encapsulation layer.

25. A microelectromechanical system (MEMS) device, comprising:
means for supporting a MEMS element, the MEMS element comprising a movable component;
means for encapsulating the MEMS element, wherein the encapsulating means is planarized; and
means for processing electronic signals on or over the encapsulating means.

26. The device of Claim 25, wherein the supporting means comprises a substrate, the encapsulating means comprises an encapsulation layer, and the processing means comprises an electronic element.

27. The device of Claim 25 or 26, wherein the encapsulating means is planarized with a chemical mechanical planarization method.

28. The device of any of Claims 25 to 27, wherein the encapsulating means is planarized with a mechanical polishing method.

29. The device of any of Claims 25 to 28, wherein the MEMS element comprises an interferometric modulator.

30. The device of any of Claims 25 to 29, wherein the encapsulating means comprises a hole.

31. The device of any of Claims 25 to 30, wherein the hole is plugged.

32. The device of any of Claims 25 to 31, wherein the processing means is electrically connected to the MEMS element through the hole.

33. The device of any of Claims 25 to 32, wherein the electronic element comprises a connector.

34. The device of any of Claims 25 to 33, wherein the processing means comprises a thin film transistor.

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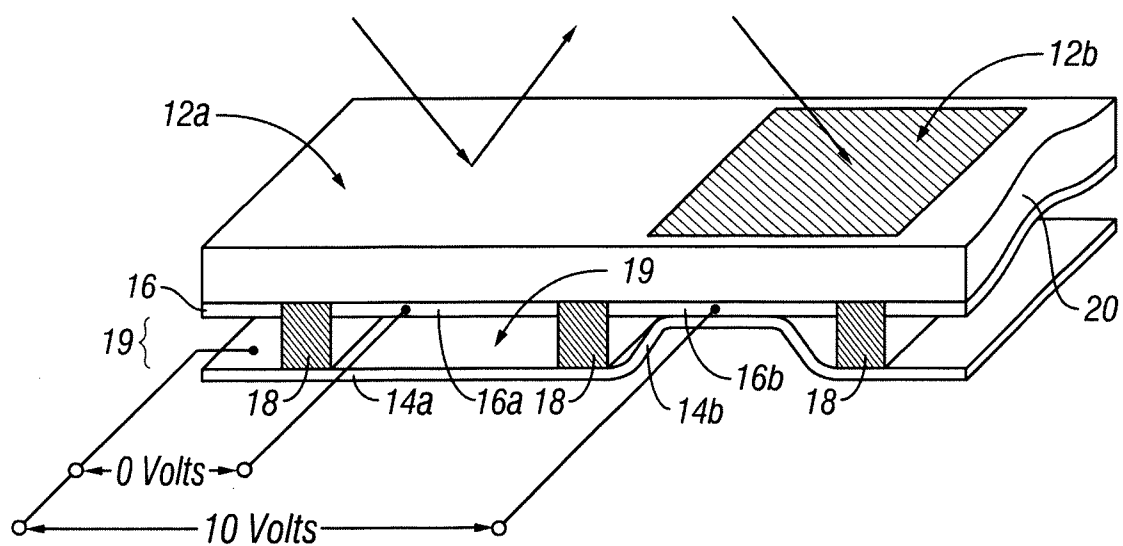


FIG. 1

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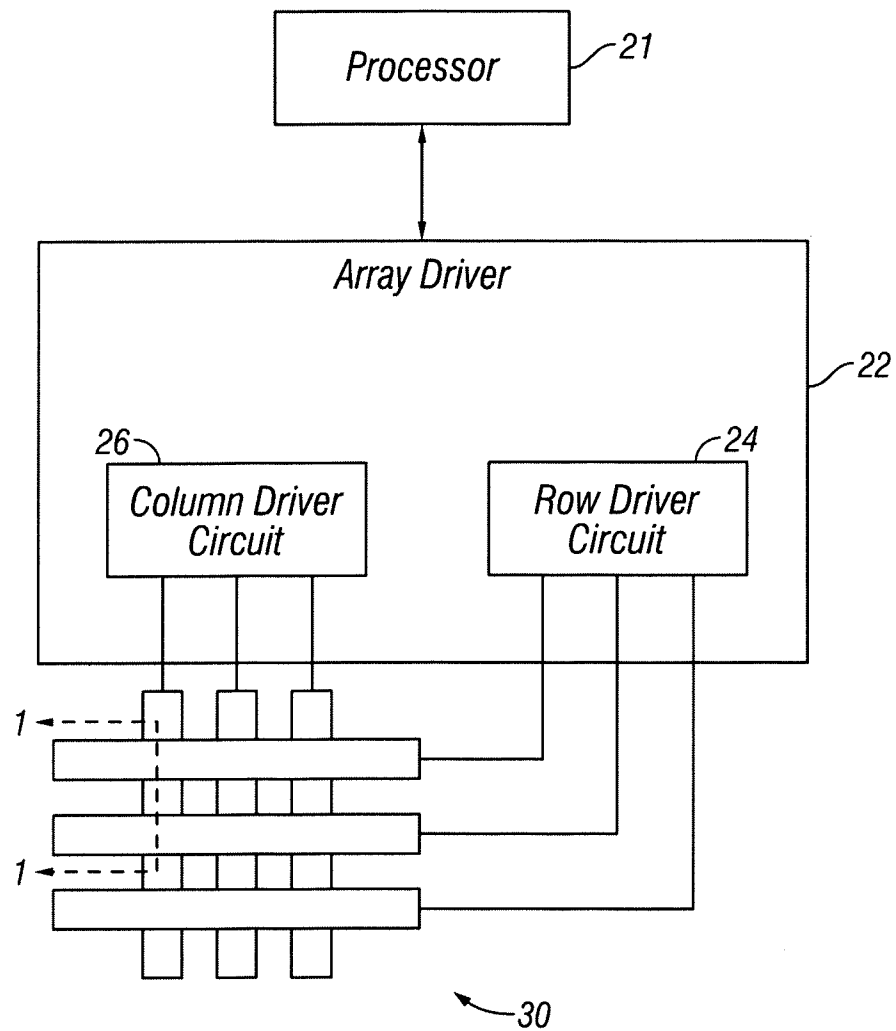


FIG. 2

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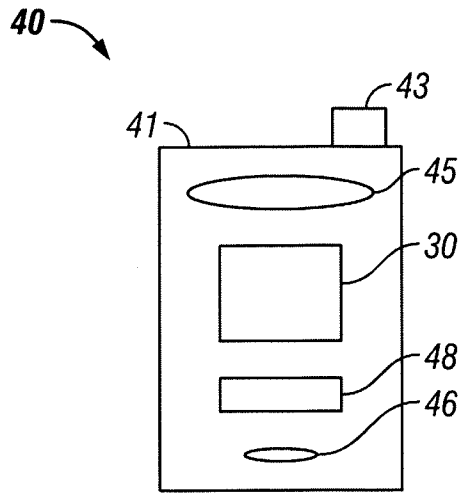


FIG. 3A

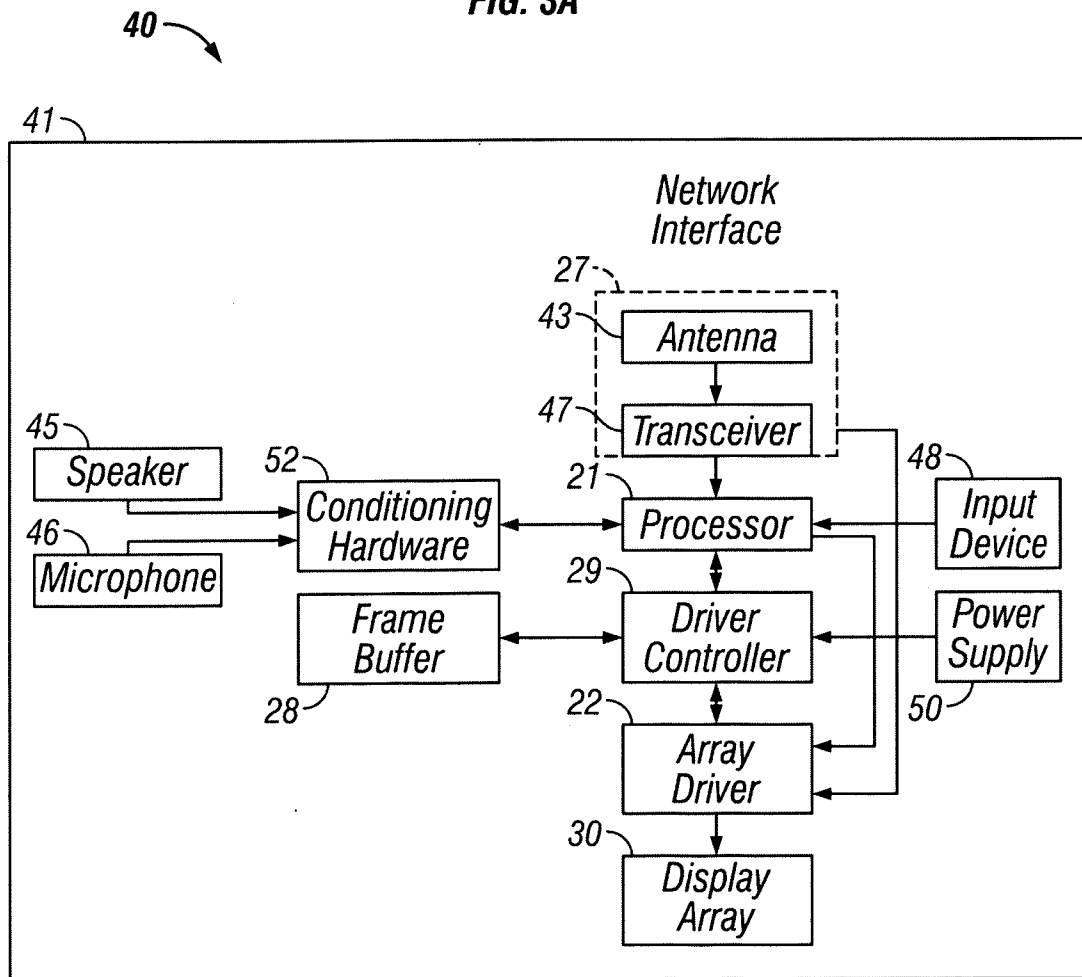


FIG. 3B

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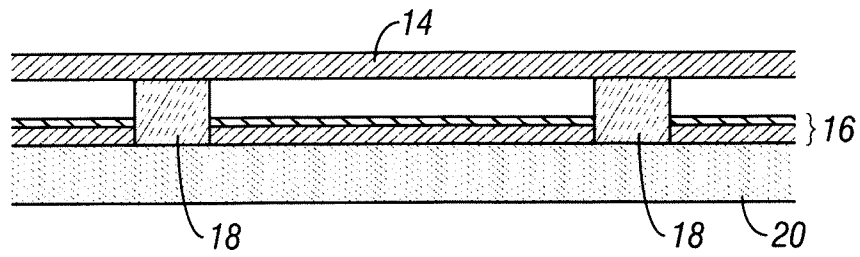


FIG. 4A

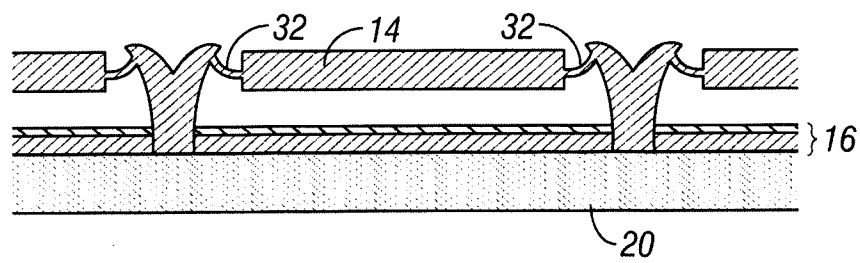


FIG. 4B

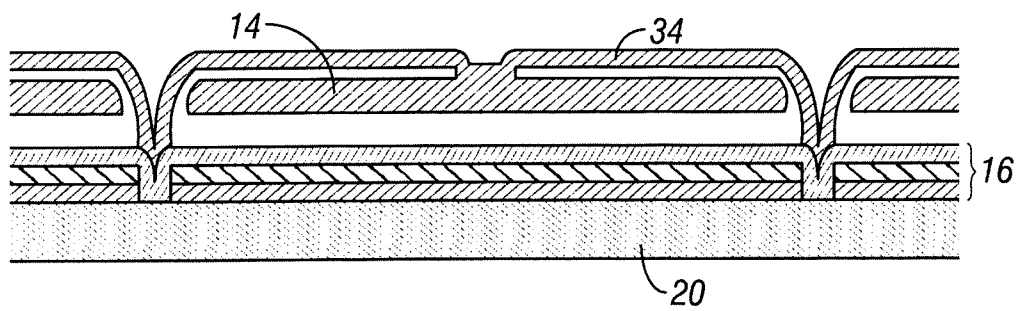


FIG. 4C

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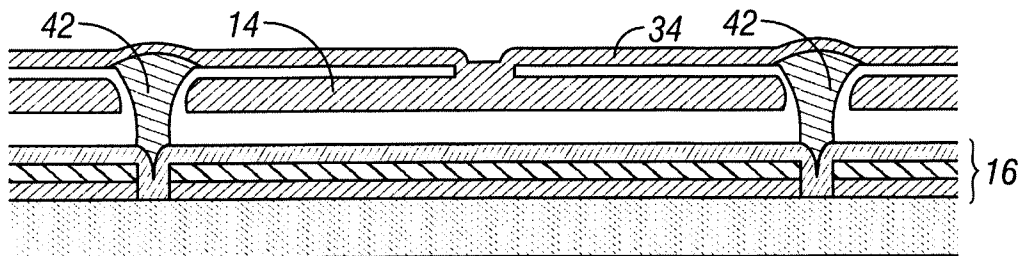


FIG. 4D

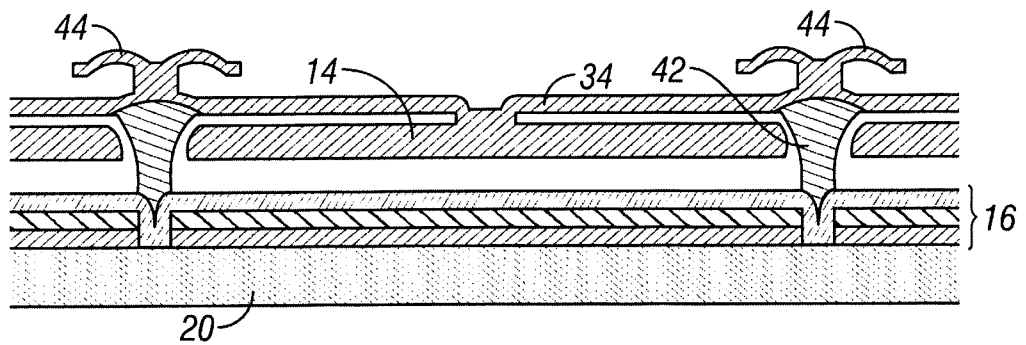


FIG. 4E

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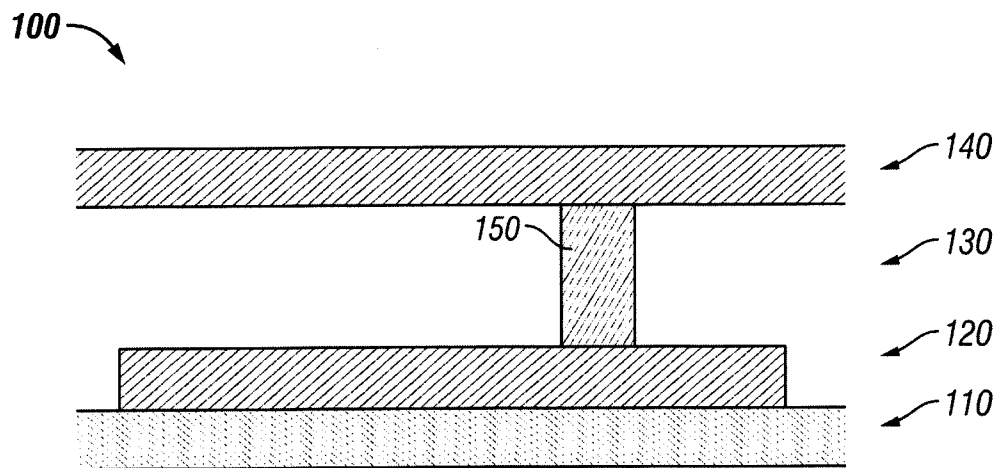


FIG. 5

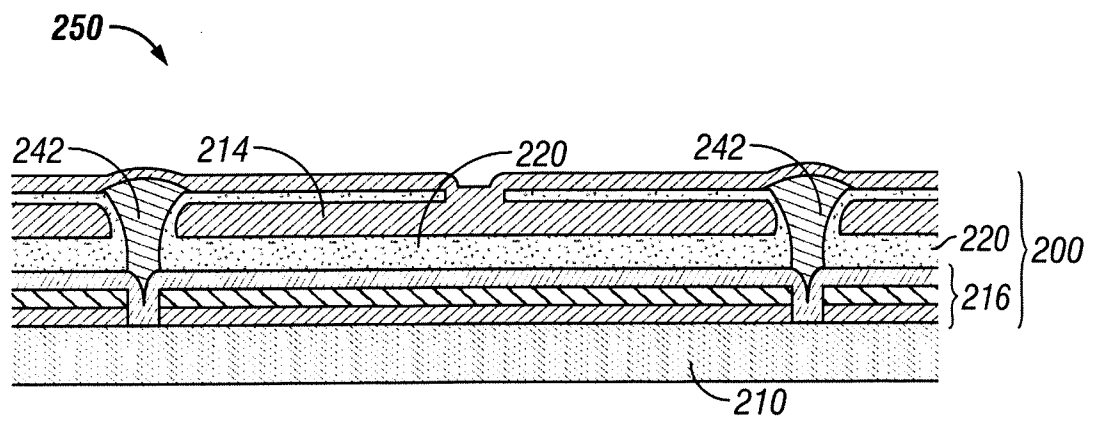


FIG. 6A

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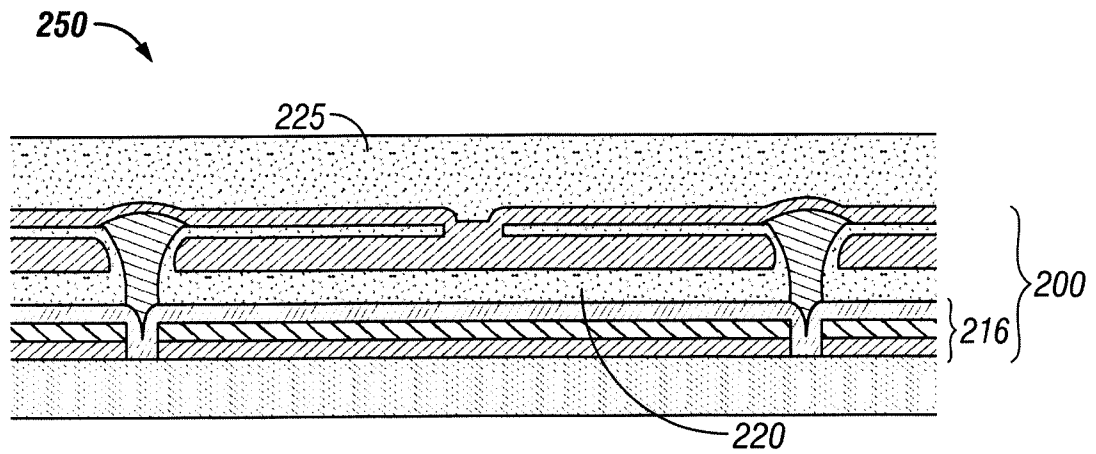


FIG. 6B

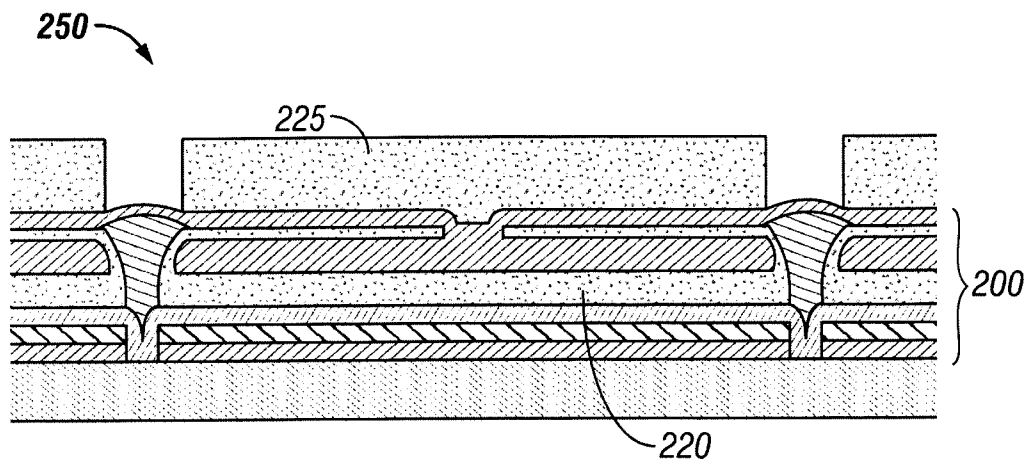


FIG. 6C

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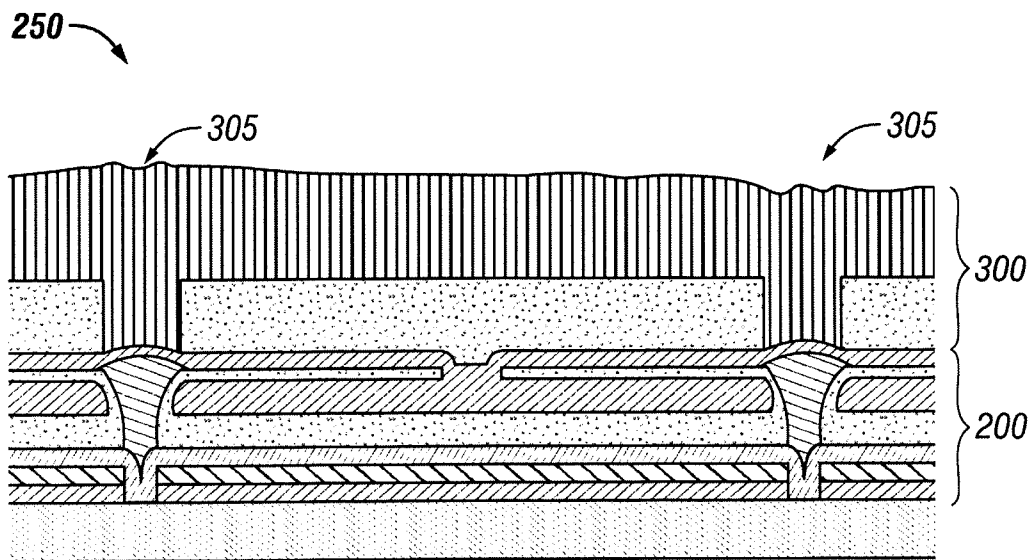


FIG. 6D

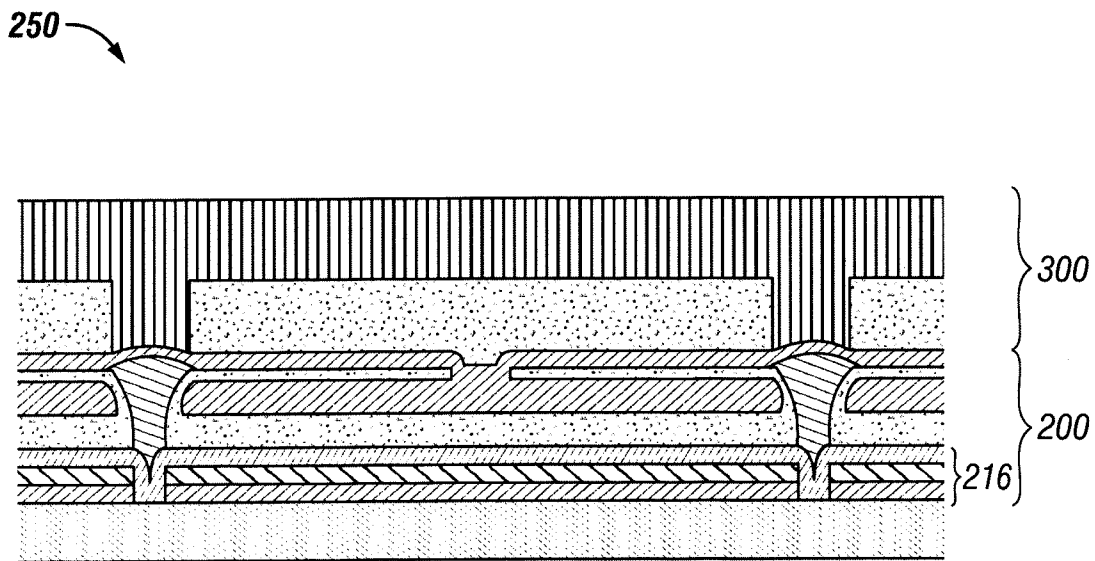


FIG. 6E

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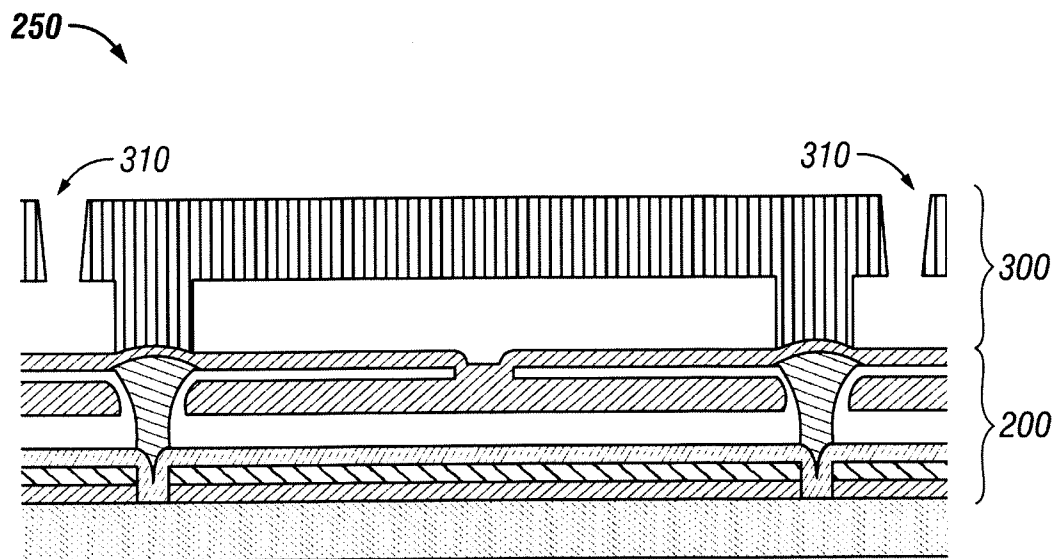


FIG. 6F

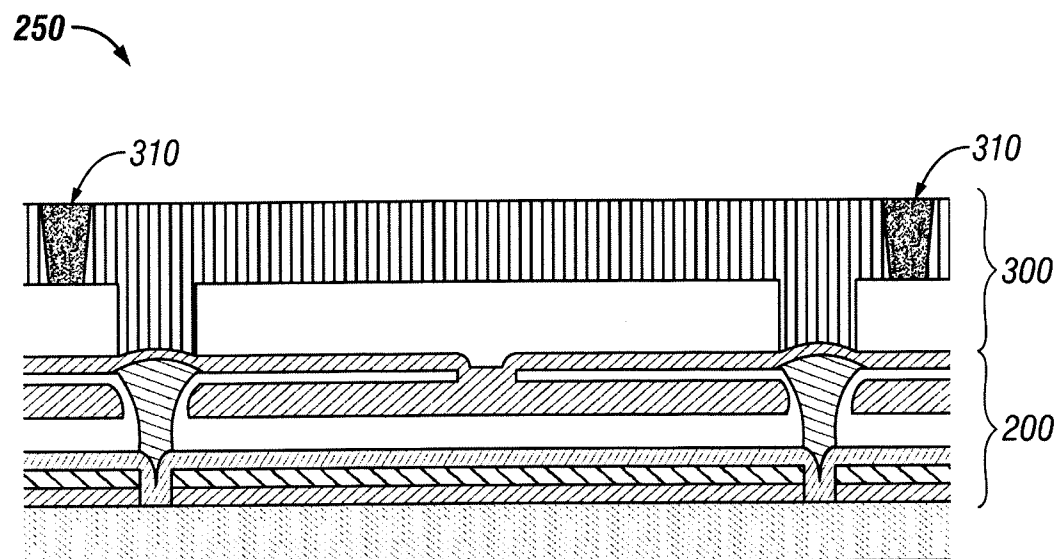


FIG. 6G

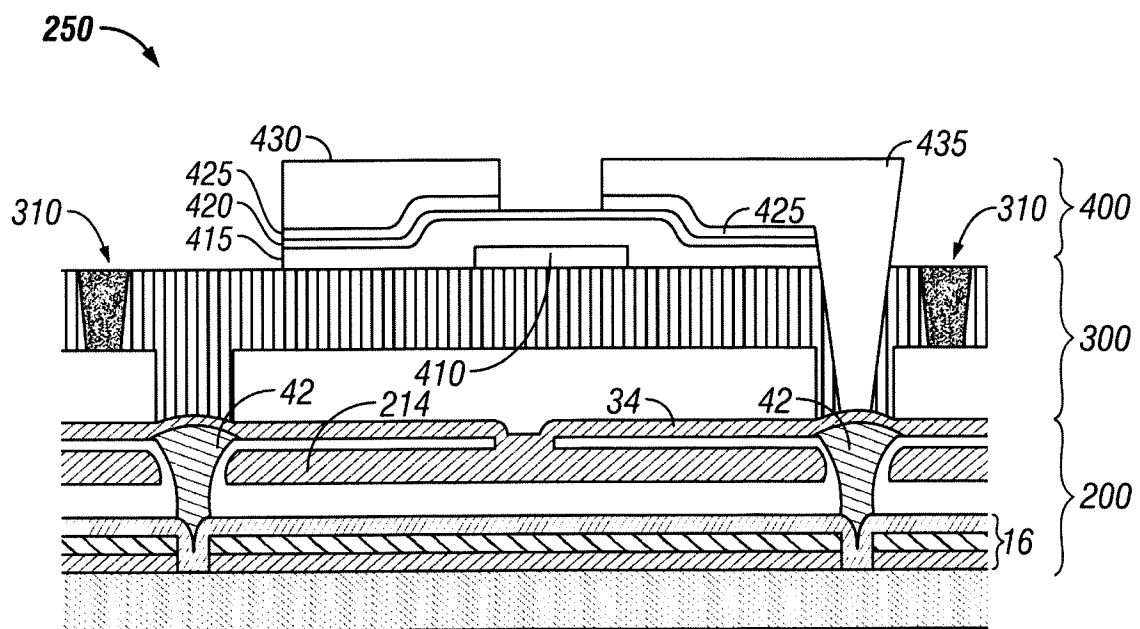


FIG. 6H