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Arney et al.

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[45] Date of Patent: Sep. 15, 1998

[54] METHOD AND APPARATUS FOR AN IMPROVED MICROMECHANICAL MODULATOR

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[73] Assignee: **Lucent Technologies Inc.**, Murray Hill, N.J.

[21] Appl. No.: **805,255**

[22] Filed: **Feb. 24, 1997**

Related U.S. Application Data

[62] Division of Ser. No. 565,453, Feb. 1, 1996, Pat. No. 5,751, 469.

[51] **Int. Cl.**[6] **G02B 26/00**

[52] **U.S. Cl.** **359/291**; 216/72

[58] **Field of Search** 359/290, 291; 216/72

[56] **References Cited**

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OTHER PUBLICATIONS

Zhang et al., Digest IEEE Int. Conf. on Solid State Sensors and Actuators, pp. 520–523, 1991.

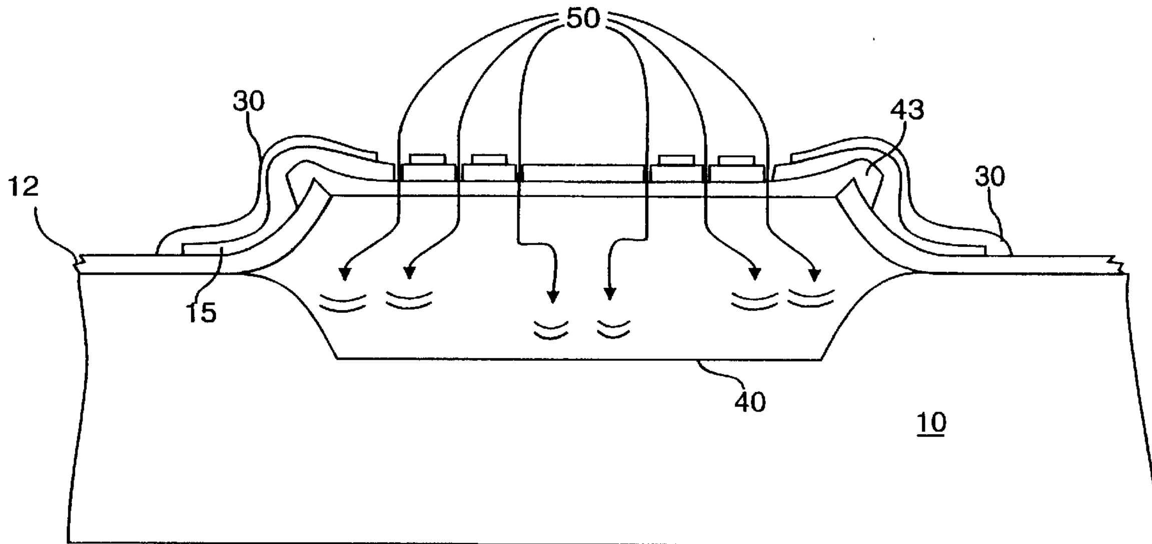
Primary Examiner—Georgia Y. Epps

Assistant Examiner—Dawn-Marie Bey

[57] **ABSTRACT**

An improved modulator and methods for making the modulator are disclosed. A membrane, preferably circular in shape, is formed over a region of a substrate in such a way that a gap results between the membrane and substrate forming a modulator cavity. The membrane forms a continuous surface over the cavity. In particular, the membrane is not supported by discrete support arms, but rather extends beyond the modulator cavity. Preferably, holes are formed in the membrane to aid in damping its motion and to allow access to underlying layers during modulator formation. According to the method, the modulator is formed by forming a means for creating a gap between the substrate and the membrane, forming a membrane, forming a lateral conduit to aid in removing the means for creating the gap and, finally, by removing the means for creating the gap.

19 Claims, 12 Drawing Sheets



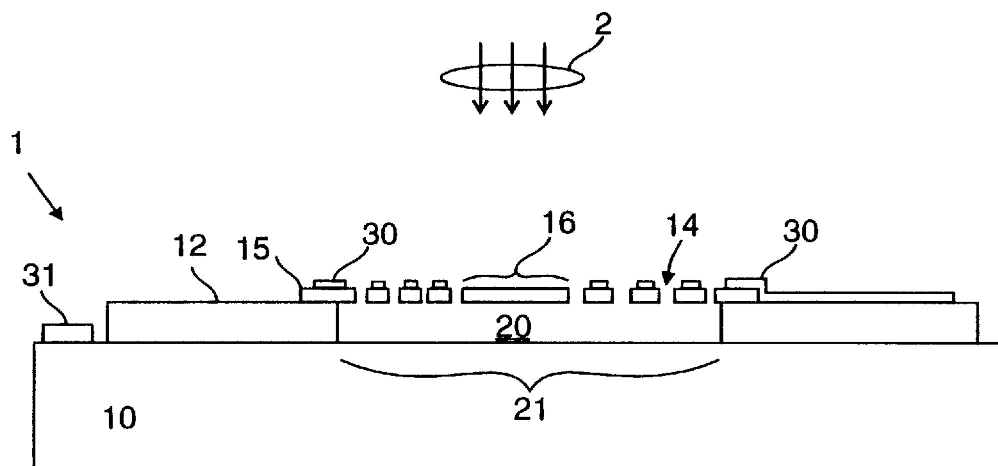


FIG. 1

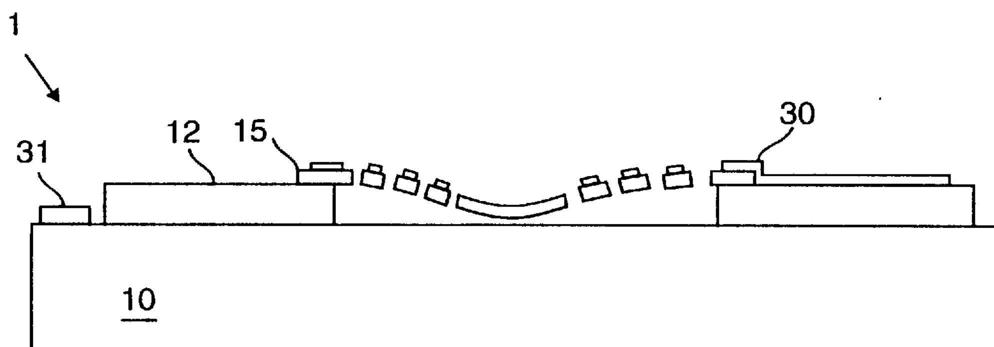


FIG. 3

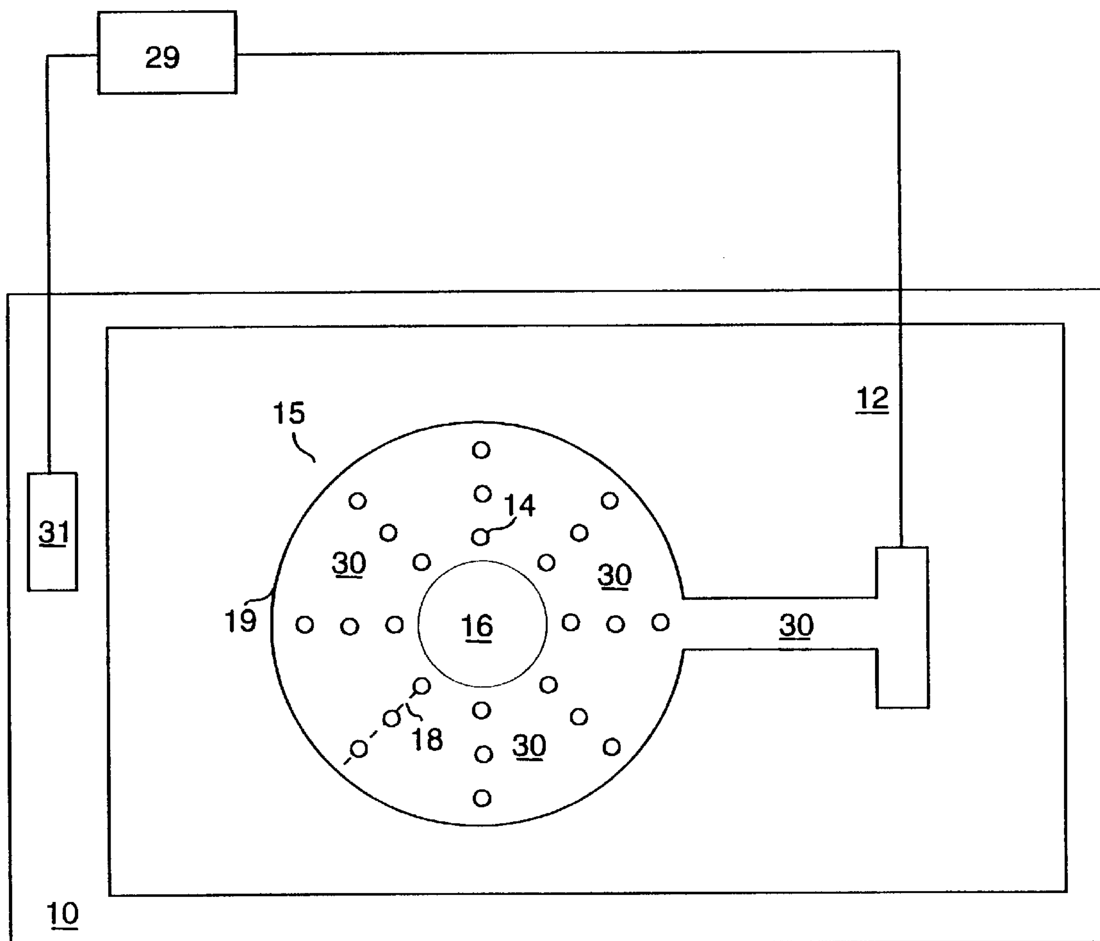


FIG. 2

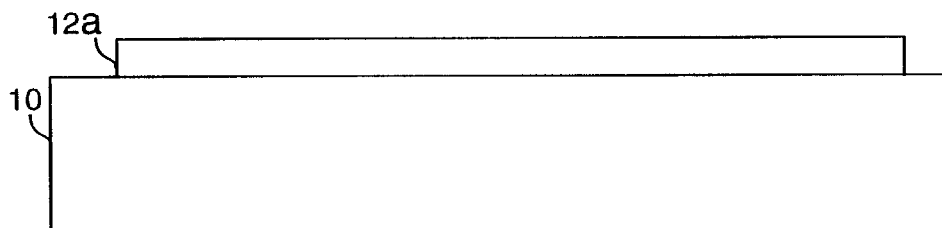


FIG. 4

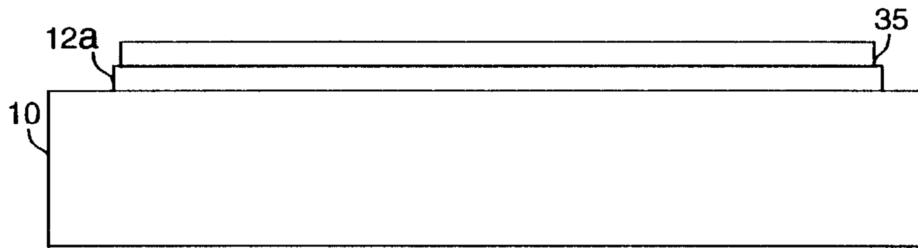


FIG. 5

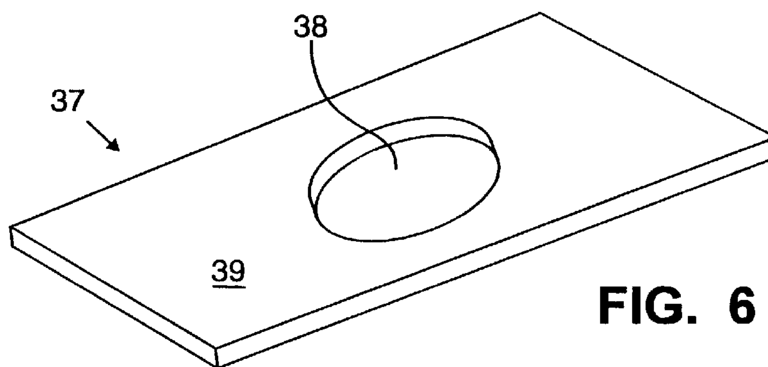


FIG. 6

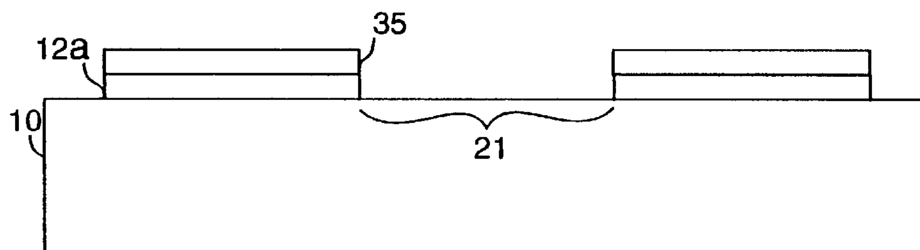


FIG. 7

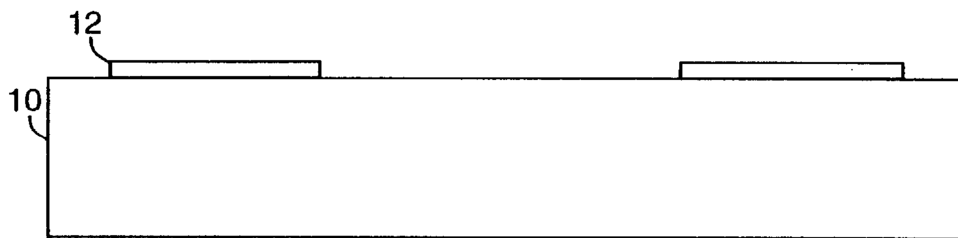


FIG. 8

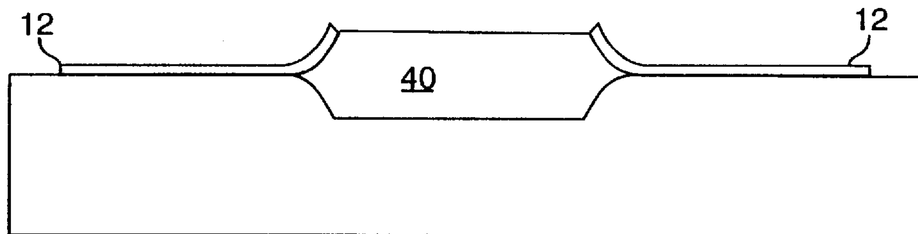


FIG. 9a

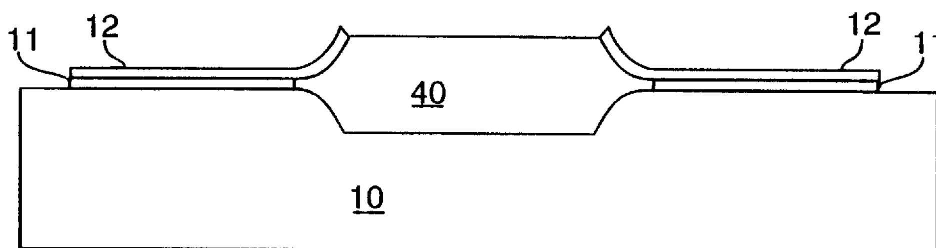


FIG. 9b

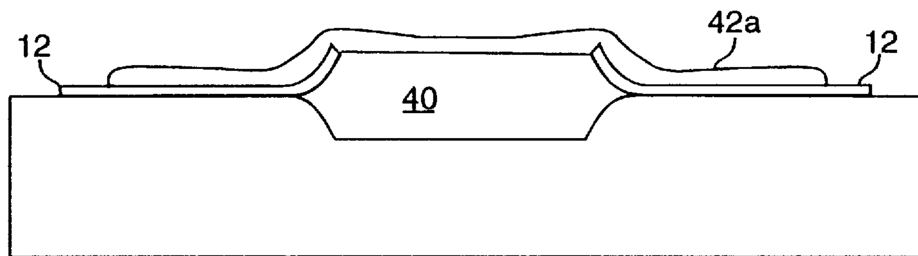


FIG. 10

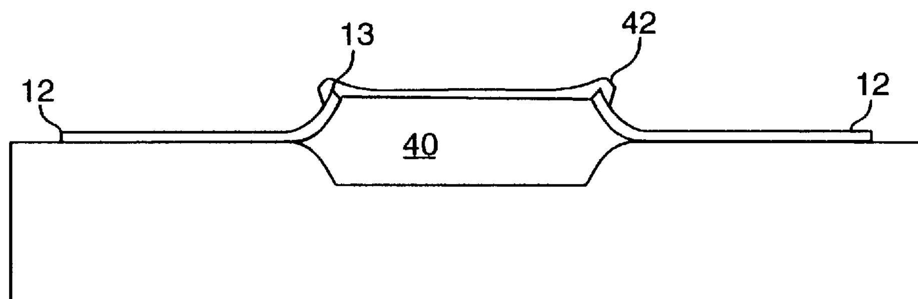


FIG. 11

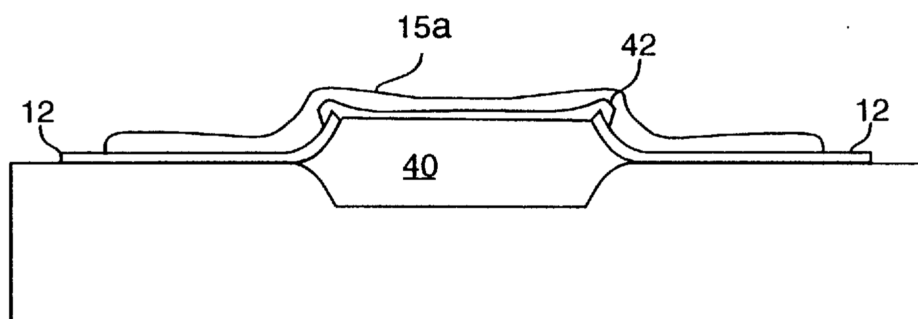


FIG. 12

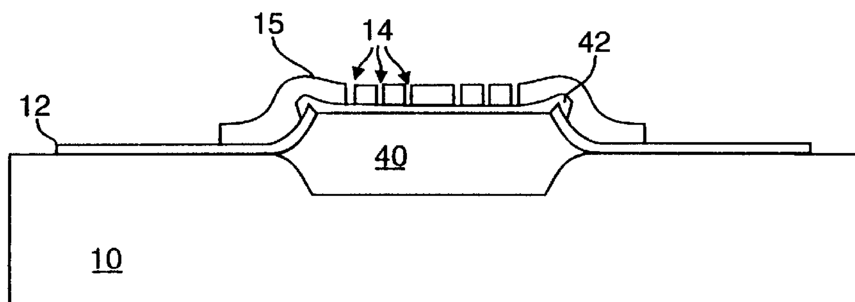


FIG. 13

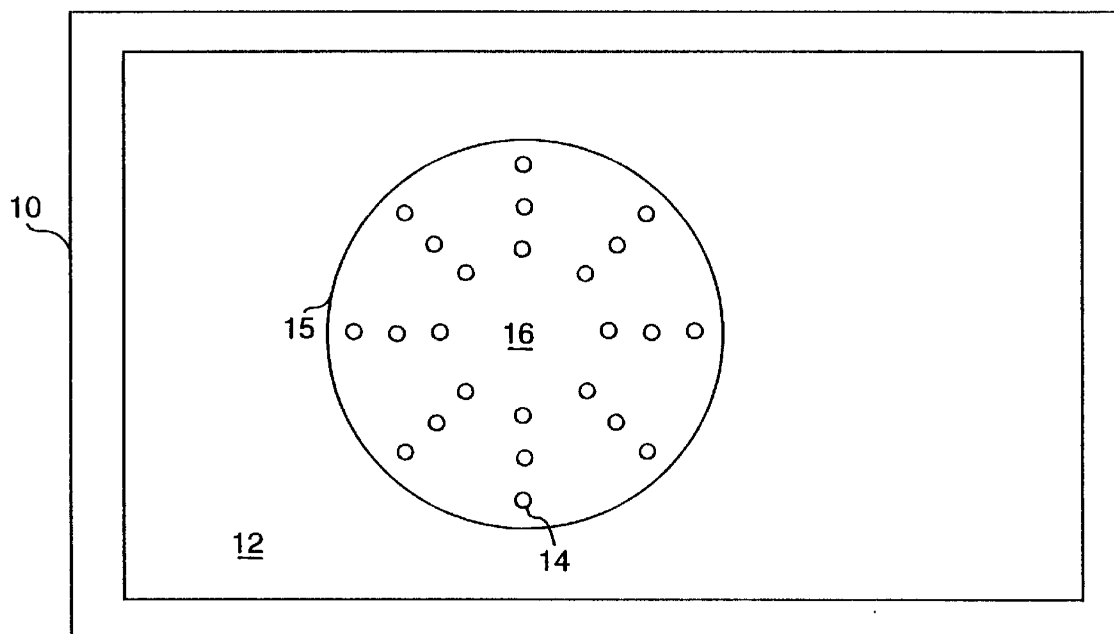


FIG. 14

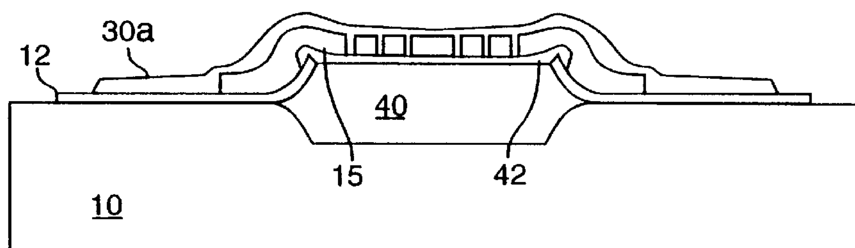


FIG. 15

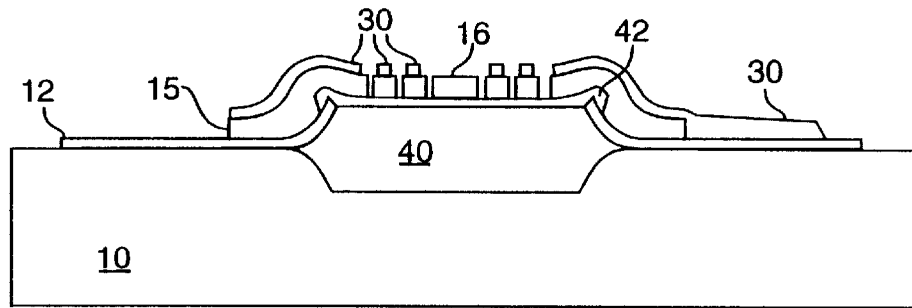


FIG. 16

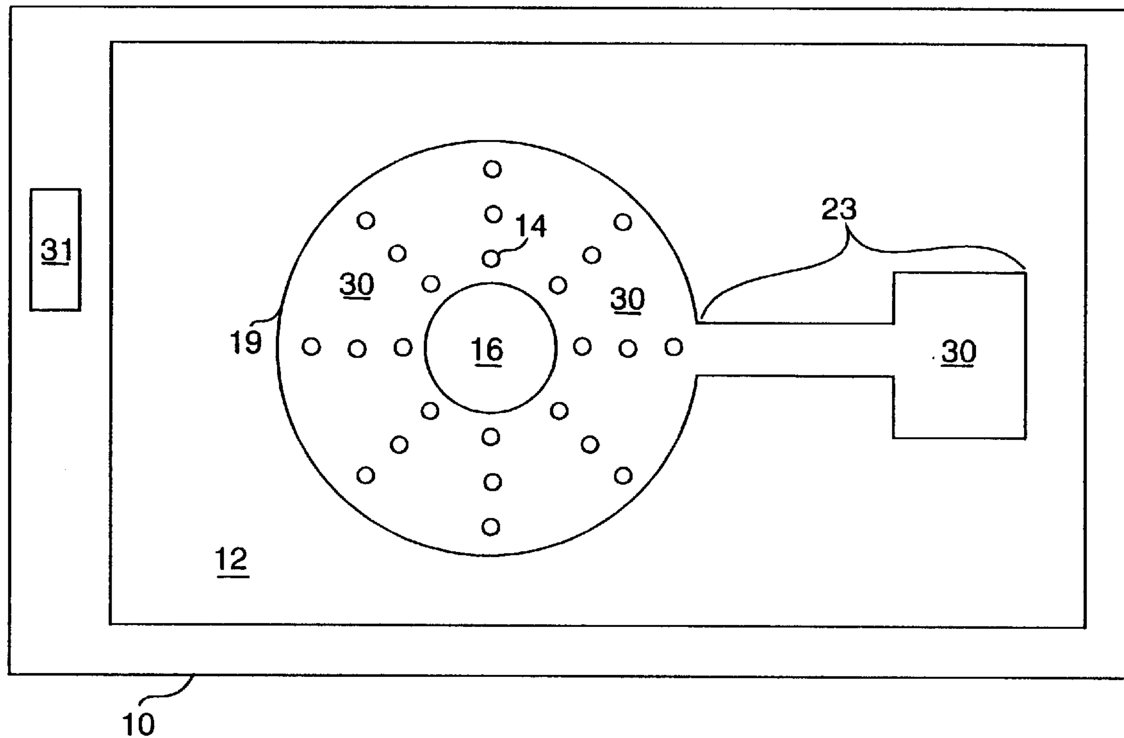


FIG. 17

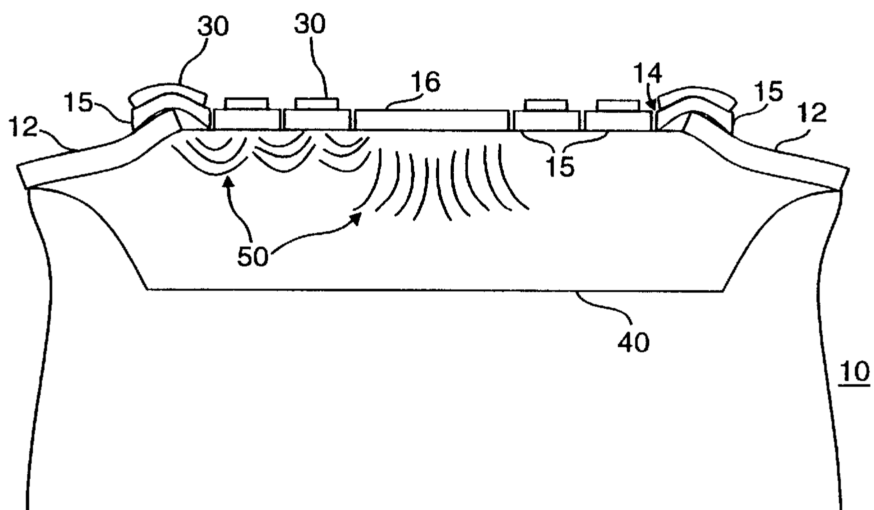


FIG. 18A

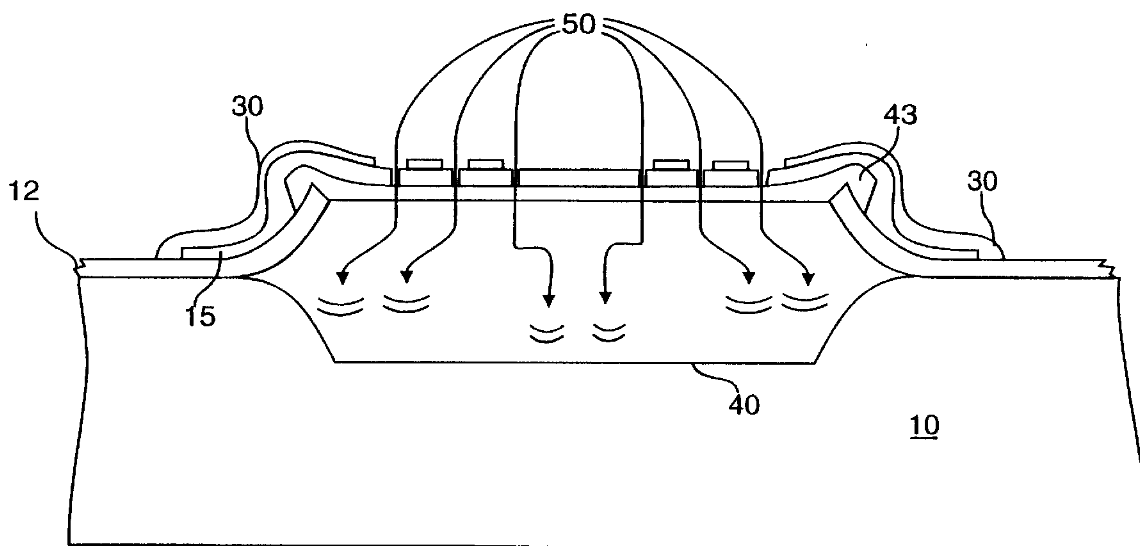


FIG. 18B

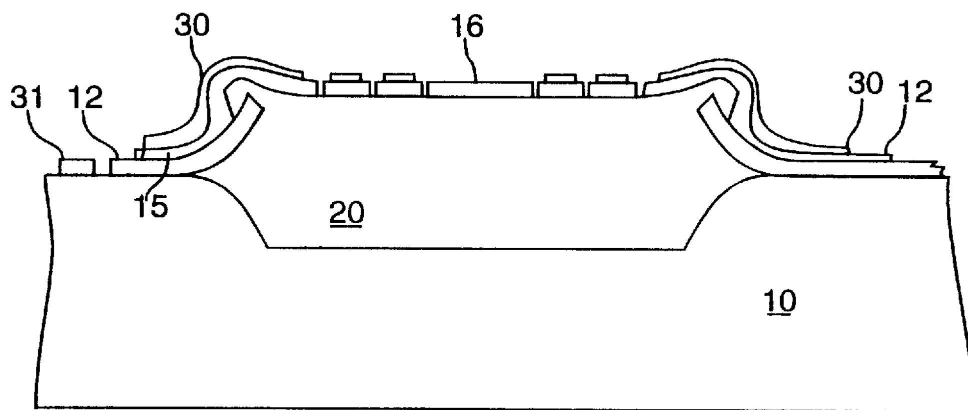


FIG. 19

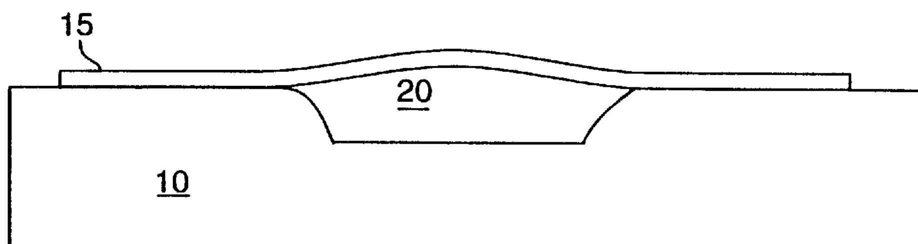


FIG. 20

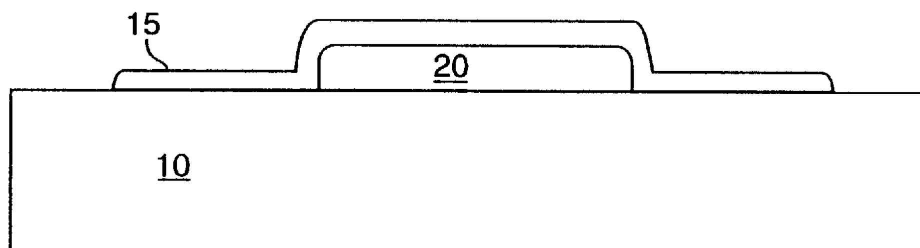


FIG. 21

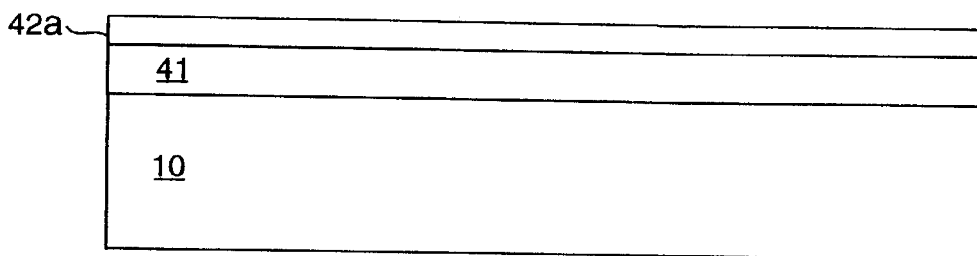


FIG. 22

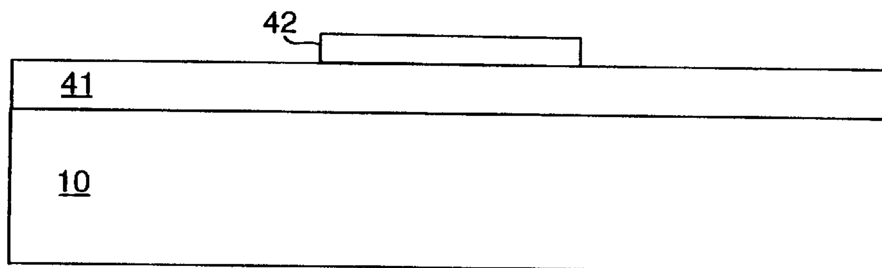


FIG. 23

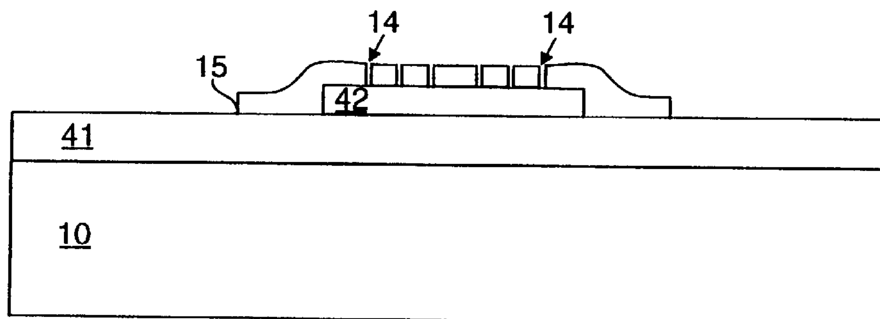


FIG. 24

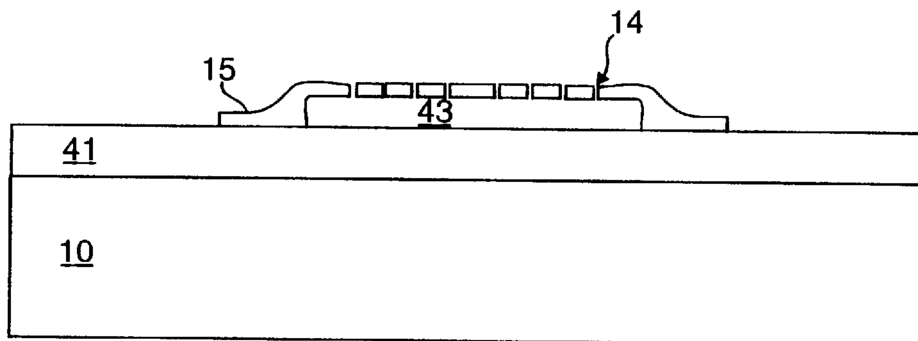


FIG. 25

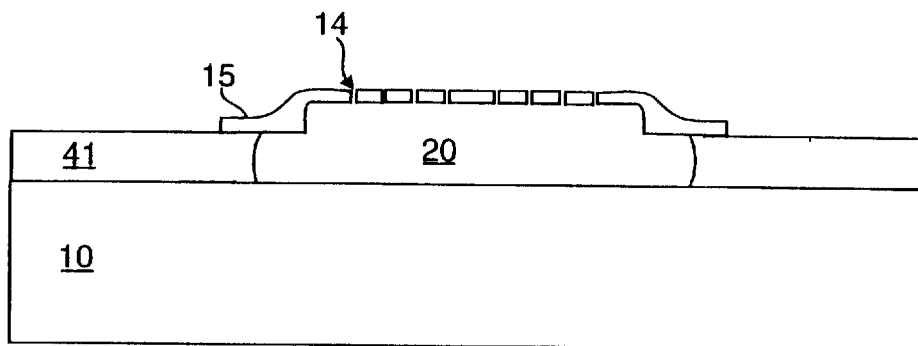


FIG. 26

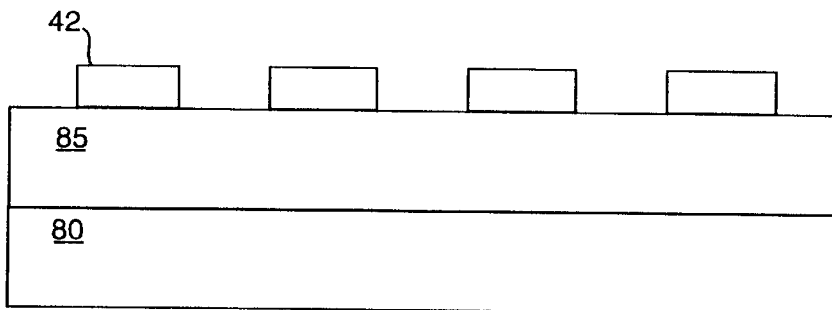


FIG. 27

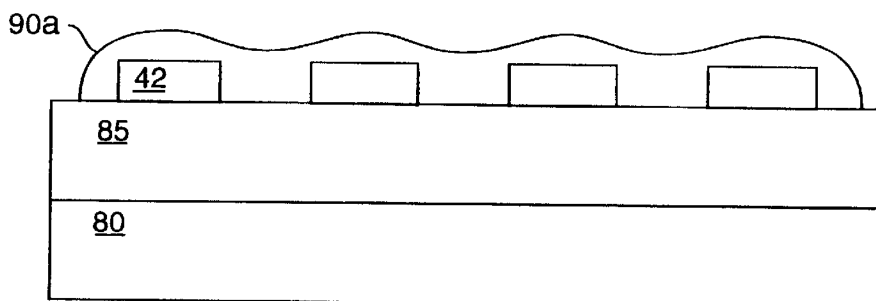


FIG. 28

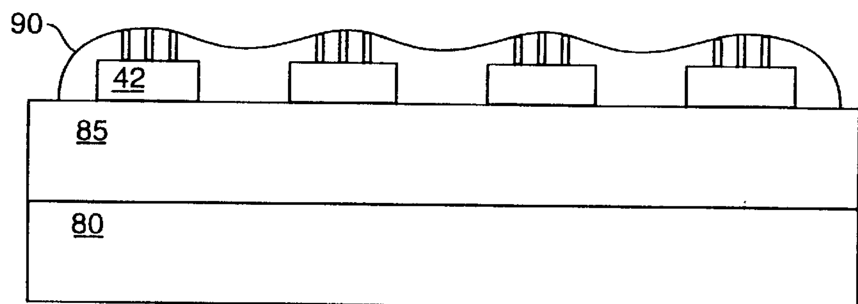


FIG. 29

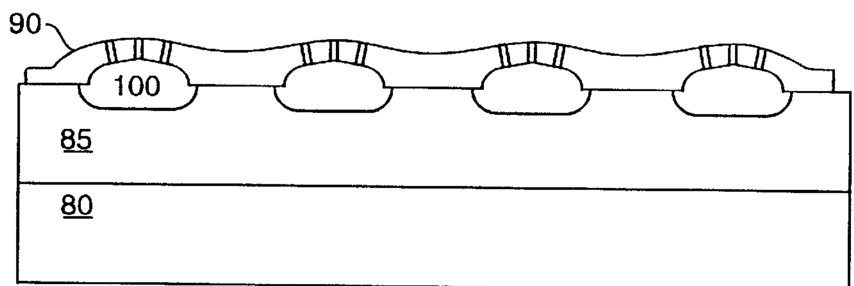


FIG. 30

METHOD AND APPARATUS FOR AN IMPROVED MICROMECHANICAL MODULATOR

This is a division of application Ser. No. 08/565,453, filed Feb. 1, 1996, now U.S. Pat. No. 5,751,469.

FIELD OF THE INVENTION

The present invention relates to micromechanical optical modulators. More particularly, the present invention relates to a micromechanical optical modulator utilizing a circularly-shaped membrane.

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to U.S. Pat. Nos. 5,500,761; 5,636,052; 5,589,974 and 5,654,819 and to co-pending U.S. patent application Ser. No. 08/578,123 filed Dec. 26, 1995 all of which are assigned to the assignee of the present invention.

BACKGROUND OF THE INVENTION

It is desirable in optical wavelength-division-multiplexing networks to have inexpensive optical modulators that have high contrast and wide optical bandwidths. One potentially suitable optical modulator is the surface-normal micromechanical optical modulator. This device has a variable air gap defined by two layers of material, typically a membrane and a substrate. Varying the air gap by causing the membrane to move alters the optical properties of the device. Typically, such modulators have two states corresponding to two different membrane positions. In one state, a minimal portion of the optical energy incident upon the modulator is returned in the surface normal direction. In the second state, a significantly greater portion of the incident optical energy is so directed. The aforementioned modulator is typically actuated, i.e., the air gap is changed, by electrostatic forces.

Typical prior art modulators utilize uniformly-thick membranes having a rectangularly-shaped central region supported over a substrate via support arms. See, for example, Aratani et al., "Process and Design Considerations for Surface Micromachined Beams for a Tunable Interferometer Array in Silicon," Proc. IEEE Micro. ElectroMech. Workshop, Ft. Lauderdale, Fla., Feb. 7–10, 1993, pp. 230–235. The foregoing reference, as well as any other articles, patent applications or patents mentioned in this specification are incorporated herein by reference.

The support arms of the aforementioned modulators are usually also rectangular in shape and relatively narrow compared to the portion of the membrane they are supporting. Due to the sharp corners resulting from the rectangular shapes of the central region and support arms, and to the relatively narrow support arms, very high stresses can be concentrated in the support arms. Such stresses may cause the support arms to fail rendering the modulator inoperable.

Thus, there is a need for an improved membrane design that minimizes stress concentrations leading to improved modulator reliability and performance and that further simplifies modulator fabrication and packaging.

SUMMARY OF THE INVENTION

An improved micromechanical modulator utilizing a novel membrane configuration, and methods for fabricating the modulator, are disclosed. In one embodiment, a membrane, preferably circular in shape, is formed over a region of a substrate in such a way that a gap results between the membrane and substrate forming a cavity. The membrane forms a continuous surface over the cavity. In particular, the membrane is not supported by discrete support arms, but rather extends beyond the perimeter of the cavity. Thus, the membrane covers the cavity in a manner analogous to the way a drum head covers the body of a drum. Preferably, holes are formed in the membrane to aid in damping its motion. Also, the holes are used during modulator fabrication, as described below.

Modulators according to the present invention may be formed using known deposition and patterning techniques. In one embodiment, at least one layer of material is deposited on a silicon substrate and patterned, defining a preferably circular region of bare substrate where the gap will be formed, i.e., defining the modulator cavity. The nascent modulator is exposed to conditions suitable for thermally oxidizing the bare substrate within the circular region. The oxidation conditions are controlled to precisely limit the lateral and vertical extent of the oxidation within the substrate. In this manner, the thickness of the resulting gap and the dimensions of the modulator cavity can be precisely defined.

A rapidly-etchable layer of material is deposited on the oxidized silicon. Such a material is capable of being etched at a much faster rate than the underlying oxide. The rapidly-etchable layer is patterned into the shape selected for the membrane and then a membrane-forming layer of material is deposited and patterned, preferably into a circular shape.

During membrane patterning, small holes are formed that extend completely through the membrane. As mentioned above, such holes aid in damping membrane vibration and also provide access to the underlying layers, such as the rapidly-etchable layer and the oxidized silicon, that must be removed in subsequent steps to form the gap. No holes are placed in a region near the center of the membrane which forms an optical window. If the membrane is non-conductive, a layer of conductive material is deposited on the membrane, leaving the optical window uncovered.

An etch is then introduced through the holes in the membrane. The etch first removes the rapidly-etchable layer. Once removed, a lateral conduit exists between the oxide layer and the membrane layer that allows the etch to flow over the entire surface of the oxide layer. After flowing over the surface of the oxide, the etch proceeds in an essentially vertical direction through the oxide. Providing a lateral conduit for this purpose is particularly advantageous. If the rapidly-etchable layer was not present so that a conduit was not formed, the etch would have to proceed in a somewhat lateral direction under the regions of the membrane where there are no holes, such as the optical window. Since the oxidized substrate may be as much as 350 microns in diameter, i.e., the size of the modulator cavity, yet typically about a micron or less in thickness, a vertical etch will be completed much more rapidly than a lateral etch. Such a rapid etch is desirable since membrane features are susceptible to attack while the underlying oxide is being etched. Removing the oxide layer creates the gap hence forming the modulator.

BRIEF DESCRIPTION OF THE DRAWINGS

Further features of the invention will become more apparent from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawings, in which like elements have like reference numerals and in which:

FIG. **1** is a cross-sectional side view of a modulator according to the present invention;

FIG. **2** is a top view of the modulator of FIG. **1**;

FIG. **3** illustrates the modulator of FIGS. **1** and **2** under bias;

FIG. **4** shows a substrate with a cavity-defining layer disposed thereon;

FIG. **5** shows a layer of erodible material disposed upon the arrangement of FIG. **4**;

FIG. **6** is an exemplary embodiment of a mask used for patterning a circular feature in a layer of material;

FIG. **7** shows the layers of FIG. **5** patterned to define a modulator cavity;

FIG. **8** shows the arrangement of FIG. **7** after the erodible material is stripped from the cavity-defining layer;

FIG. **9***a* shows the arrangement of FIG. **8** after local oxidation of the substrate within the nascent modulator cavity;

FIG. **9***b* illustrates a further embodiment of the present method wherein a pad oxide is used to minimize stress on the cavity-defining layer during oxide growth;

FIG. **10** shows a rapidly-etchable layer disposed on the arrangement of FIG. **9***a;*

FIG. **11** shows the rapidly-etchable layer patterned;

FIG. **12** shows the membrane-forming layer disposed on the arrangement of FIG. **11**;

FIG. **13** is an illustration of the arrangement of FIG. **12** with the membrane-forming layer patterned into a membrane;

FIG. **14** is a top-view of the arrangement of FIG. **13**;

FIG. **15** shows a layer of conductive material disposed on top of the membrane;

FIG. **16** shows the conductive material appropriately patterned;

FIG. **17** is a top-view of the arrangement of FIG. **16** showing the patterned conductive layer;

FIG. **18***a* is an illustration of the oxidized substrate being etched in an embodiment wherein the rapidly-etchable layer was not deposited on the oxidized substrate;

FIG. **18***b* is an illustration of the oxidized substrate being etched in the preferred embodiment wherein the rapidly-etchable layer was deposited on the oxidized substrate;

FIG. **19** shows the arrangement of FIG. **16** with the rapidly-etchable layer and the oxidized substrate removed, forming a modulator according to the present invention;

FIG. **20** is another embodiment of a modulator according to the present invention;

FIG. **21** is a further embodiment of a modulator according to the present invention;

FIG. **22** shows an oxide layer and a rapidly-etchable layer disposed on a substrate in an additional embodiment of a method according to the present invention;

FIG. **23** shows the rapidly-etchable layer patterned into a shape suitable for forming a lateral conduit;

FIG. **24** shows a membrane layer disposed on the patterned rapidly-etchable layer;

FIG. **25** is an illustration of a lateral conduit that is formed as the rapidly-etchable layer is removed;

FIG. **26** shows the oxide layer removed resulting in a gap between the membrane and the substrate;

FIG. **27** shows a first and a second device layer and a rapidly-etchable material disposed on the second device layer, which material is patterned into discrete regions;

FIG. **28** shows a third device layer disposed on the regions of rapidly-etchable material;

FIG. **29** shows holes patterned in the third device layer and lateral conduits formed as the regions of rapidly-etchable material are removed; and

FIG. **30** shows gaps formed between the second and third device layer as a portion of the second device layer underneath each lateral conduit is etched.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIGS. **1** and **2** show a preferred embodiment of a micromechanical modulator **1** according to the present invention. As shown in FIG. **1**, the device comprises a substrate **10** and membrane **15**.

The membrane **15** and substrate **10** are spaced from each other defining a gap **20** between them. In a preferred embodiment, a plurality of holes **14** are provided in the membrane, preferably radially arranged as illustrated in FIG. **2**. The holes **14** aid in damping membrane vibration and are also used during modulator fabrication, as described later in this specification. The holes **14** are patterned in the membrane **15** beginning outside of a centrally located region **16** and radiate toward the periphery **19** of the membrane **15**. The centrally located region **16** forms an "optical window". The optical window is typically in optical communication with an optical waveguide or fiber that delivers an optical signal **2** to the modulator. The holes **14** are absent from the optical window since their presence in that region of the membrane would deleteriously effect the optical properties of the modulator **1**.

In contrast to typical modulator designs, the present modulator is not supported by discrete support arms. Rather, the membrane **15** overlaps the periphery of the modulator cavity **21** along most of such periphery. In a preferred embodiment, the membrane **15** overlaps the periphery of the modulator cavity **21** at substantially every point along such periphery. Such an arrangement reduces the concentration of stress which may develop in the narrow support arms and near sharp corners. High-stress points may act as nucleation sites for fractures. Such fractures may result in modulator failure.

In a preferred embodiment, the membrane **15** is circular, as shown in FIG. **2**. Such a circular membrane has neither of the aforementioned stress concentrators and may be fabricated to have a higher intrinsic stress level than would otherwise be possible. Modulators using such a higher-stress membrane will have a higher resonant frequency and a higher bit rate than modulators utilizing a lower-stress membrane.

The substrate **10** and the membrane **15** are preferably suitably conductive so that a biasing signal may be applied across them generating an electrostatic force. This force causes the membrane **15** to move toward the substrate, as shown in FIG. **3**. As the membrane moves from its unbiased position, the reflectivity of the modulator **1** to the incident optical signal **2** changes. In particular, in a first embodiment, the modulator **1** exhibits its minimum reflectivity when the membrane is in its unbiased position. The minimum reflectivity of the modulator is preferably zero. As the membrane moves to its biased position, the modulator preferably exhibits its maximum reflectivity. In a second embodiment, the modulator **1** exhibits its maximum reflectivity when the membrane is in its unbiased position. As the membrane moves to its biased position, the modulator preferably exhibits its minimum reflectivity. Minimum reflectivity for the second embodiment is again preferably zero.

The biasing signal can be supplied by a controlled voltage source **29**. A contact **31** may be formed on the substrate **10** to facilitate electrical connection with the controlled voltage source **29**. The controlled voltage source is also electrically connected to the membrane **15**. The modulator may suitably be formed on a semiconductor chip or wafer.

Preferably, the substrate **10** is formed of a conductive material, which is either transparent or absorbing over the operating optical bandwidth. Suitable materials include, but are not limited to, silicon, gallium arsenide, indium phosphide, germanium or indium tin oxide (ITO) coated glass. If a semiconductor is used for the substrate, it should preferably be appropriately doped. For example, if the substrate is silicon, it is preferably doped with any Group III or Group V element, typically phosphorous or boron. Such doping should enhance device speed.

If the substrate is formed of a material that is insufficiently conductive for a modulator according to the present invention, conductivity can be increased or imparted by doping the substrate with suitable materials. Doping methods include ion implantation, selective diffusion and other methods known to those skilled in the art.

The membrane **15** is preferably comprised of a single layer of material which is transparent at the operating wavelengths of the modulator. If the substrate **10** is silicon, which is the preferred material, then the membrane **15** is preferably silicon nitride. It should be understood that the improved modulator of the present invention may be based on any one of a variety of different operating principles. As such, the preferred or required characteristics of the membrane of the present modulator may vary as a function of the selected operating principle. For example, if the present modulator comprises at least one quarter-wave thick membrane according to the teachings of U.S. Pat. Nos. 5,500,761; 5,636,052; 5,589,974 and 5,654,819, then the membrane **15** is further characterized by a refractive index which is approximately equal to the square root of the refractive index of the substrate **10**. If, however, the modulator is a phase-mismatched Fabry-Perot cavity modulator as described in U.S. patent application Ser. No. 08/578,123, then the membrane **15** is characterized by a refractive index which is greater than the square root of the refractive index of the substrate **10**. It will be appreciated that the membrane **15** according to the present invention may be required to possess other characteristics for other modulator designs. Such differences not withstanding, all embodiments of modulators according to the present invention will have a membrane that overlaps the periphery of the modulator cavity. In some preferred embodiments, such a membrane may have a circular shape and may additionally possess damping holes.

As previously noted, if the membrane **15** is not suitably conductive for a modulator according to the present invention, a layer **30** of conductive material may be deposited on it, as shown in FIGS. **1**, **2** and **3**. It should be appreciated that if the membrane **15** is comprised of a suitably conductive material, such as doped amorphous or polycrystalline silicon or ITO, then the conductive layer **30** is not required. Any suitably conductive material may be used to form the conductive layer **30**, including, without limitation, aluminum, platinum, tungsten, conducting silicon, ITO, gold, or alloys of these materials such as, without limitation, chromium/gold or titanium/gold. Further, silicides or appropriately-doped amorphous silicon or polycrystalline silicon is suitable for use as the conductive layer. It will be appreciated that if the conductive layer **30** is optically opaque over the operating bandwidth of the modulator, then it must not be disposed on the centrally located region **16** of the membrane **15** that forms the optical window.

As previously noted, an improved modulator according to the present invention can be based on any one of a variety of operating principles. As such, the thickness of the membrane **15** and the size of the gap **20** may vary with the selected operating principle. Such parameters can be determined by referencing a description of a modulator based on the selected operating principle. See, for example, U.S. Pat. Nos. 5,500,761; 5,636,052; 5,589,974 and 5,654,819 and Ser. No. 08/578,123.

As previously described, the membrane **15** includes a plurality of holes **14**. In the embodiment shown in FIG. **2**, the holes **14** are aligned along a plurality of radii **18**. In a preferred embodiment, the holes should be arranged along a square or hexagonal array. The holes are sized and spaced to optimize damping of the membrane **15**.

Maximum damping is achieved when the distance, d, between holes **14** is given by:

$$d=2[(Ph^2)/(12\pi\mu_{eff}f)]^{0.5} \qquad [1]$$

where: P is the pressure of the gas through which the membrane **15** moves; h is the distance between the membrane and the substrate, i.e., the gap **20**, f is the natural resonant frequency of the modulator and μ_{eff} is the effective gas viscosity. The effective gas viscosity may be expressed in terms of the gas viscosity μ by the formula:

$$\mu_{eff}=\mu/\{1+[6(2-\sigma)\lambda/\sigma h]\} \qquad [2]$$

where: σ is the accommodation coefficient, as described further below, and λ is the mean-free-path of the gas. The following example uses the foregoing expressions to calculate the spacing, d, for holes **14** in a membrane **15**.

In the following example, the gas surrounding the modulator is assumed to be air at a temperature of 20° C. and at a pressure of one atmosphere. Further, the modulator is designed for an operating frequency of 1 MHz and has a gap between the membrane and substrate of 1 micron. The accommodation coefficient, σ, is a measure of how effectively a surface scatters gas molecules that impinge the surface. The accomodation coefficient typically has a value near 1, which will be the value used for the present example. At the prevailing temperature and pressure conditions, the mean-free-path, λ, of air is 0.09 microns and the viscosity, μ, of air is 1.8×10^{-4} grams per centimeter second. Substituting the foregoing values into [2], μ_{eff} equals 1.2×10^{-4} grams per centimeter second. The pressure, P, is 1×10^6 dynes per square centimeter and frequency is 1×10^6 Hertz. Substituting the foregoing values into [1], d equals 28 microns.

The diameter of the holes **14** should be in the range of about 2 to about 4 times the gap between the membrane and substrate, i.e, about 2h to about 4h, and no more than about one-third of d, the hole spacing. Thus, for the foregoing example, a suitable hole diameter may range from about 2 microns to about 4 microns.

Expression [1] provides the hole spacing for maximum membrane damping. Depending upon the specifics of a given application, a maximally-damped membrane might not, however, be an optimally-damped membrane. It is possible, for example, that a calculated hole spacing and hole size may result in an over-damped membrane **15**. Damping is optimized at a quality factor, Q, in the range of about 0.7 to 0.8, which allows the modulator to achieve the highest bit rates. The quality factor, which may be calculated

in ways known to those skilled in the art, is inversely proportional to the damping of the membrane. Thus, as damping increases, Q decreases proportionally. The damping can be reduced by decreasing the number of holes **14** in the membrane **15**. In particular, the holes should be reduced in proportion to the desired increase in Q.

It will be appreciated from expression [1] that the type of gas used in the modulator cavity and its pressure also affect membrane damping. Generally, heavier gases provide more damping than lighter gases, e.g., xenon provides more damping then helium. Thus, damping can be adjusted by adjusting gas pressure or changing the type of gas used in the modulator cavity.

The resonant frequency, f, of a circular membrane can be determined by the following expression: $f=0.766/D(S/\rho)^{1/2}$, where S is the stress in the membrane, ρ is the average density of the membrane and D is the diameter of the membrane, and hence the diameter of the modulator cavity, such as the modulator cavity **21**. In calculating the stress, S, and density, ρ, of the membrane, the presence of the conductive layer **30** and any other layers should be taken into account. With optimal damping, the modulator bit rate is about twice the resonant frequency of the membrane **15**.

The above expression can be used to size the membrane **15** or modulator cavity **21** for a modulator operating at a given bit rate by simply selecting a membrane material, calculating the membrane's density and stress and then solving for D. For example, the diameter of a membrane according to the present invention is given below as a function of membrane resonant frequency based on a silicon nitride membrane having a stress, S, of 600 Megapascals (MPa) and a density, ρ, of 3.1 grams per cubic centimeter (gms/cc).

f (MHz)	D (microns)
1.0	336
1.5	224
2.0	168
2.5	134
3.0	112

The diameter of the optical window **16** can suitably range in size from about 10 to 150 microns, consistent with the size of the membrane **15**. Preferably, the optical window **16** is sized to facilitate optical communication with an optical fiber delivering the optical signal to, and receiving the optical signal from, the modulator. Preferably, the maximum diameter of the optical window **16** is about 35 percent of the membrane diameter. Thus, for the above example, a 3 MHz (6 Mbit/sec) modulator could be made with a 40 micron diameter optical window. If higher-stress silicon nitride is used than in the above example, an even larger optical window could be accomodated, simplifying further the alignment with an optical fiber.

A method according to the present invention for forming the modulator described herein is described below. The method comprises (1) forming a means for creating a gap between the substrate and the membrane, (2) forming a membrane, (3) forming a lateral conduit to aid in removing the means for creating the gap and, finally, (4) removing the means for creating the gap. While steps (3) and (4) occur, for the most part, sequentially, both steps may be accomplished by the single step of delivering an etch to the nascent modulator. Further details of embodiments of the method are described below.

The substrate **10**, which may be in the form of a wafer, is assumed to be silicon for the purposes of the following description. The substrate **10** is assumed to be suitably prepared, i.e, doped, as appropriate, with phosphorus or boron, and cleaned. In one embodiment, a cavity defining layer **12*a*** of material is deposited on the substrate **10**, as shown in FIG. **4**. The layer **12*a*** will be assumed to be silicon nitride for the purposes of the following description. It will be appreciated by those skilled in the art that to the extent a different material is used for the layer **12*a*,** the following procedures may require modification, such as, for example, using a different etch. Such modifications are within the capabilities of those skilled in the art.

Preferably, the layer **12*a*** of silicon nitride is deposited using low pressure chemical vapor deposition (LPCVD). LPCVD is well known to those skilled in the art. The silicon nitride is deposited at temperatures ranging from about 800° to 840° centigrade (C). The silicon nitride so deposited has a tensile stress of about 1000 MPa. The layer **12*a*** is typically deposited to a thickness of about 1000 to 1500 angstroms (Å). After deposition, the layer **12*a*** is patterned into the shape of the optical cavity, such as the optical cavity **21**.

Standard photolithographic techniques may be used to pattern the layer **12*a*,** which are illustrated in FIGS. **5–8**. As shown in FIG. **5**, a layer **35** of selectively erodible material such as photoresist or photo-definable polyimide, for example, is deposited on the layer **12*a***. Exposing the layer **35** to appropriate radiation, typically ultraviolet light, causes a change in the solubility of the exposed region of the layer. Exposure may increase or decrease solubility depending upon the nature of the erodible material. After exposure, the erodible material is "developed" wherein it is treated with a solvent that removes erodible material of higher solubility. An appropriately patterned mask, such as the mask **37** shown in FIG. **6**, is used so that regions of the layer **35** may be selectively exposed. Such selective exposure allows the pattern of the mask to be reproduced in underlying layers forming desired features in those layers. For example, the mask **37** has a circular region **38** that is either transparent or opaque to such radiation, and a region **39** that has the opposite property, depending upon the nature of the erodible material. As the layer **35** is selectively irradiated through the mask **37**, a circular region of the layer **35** having higher solubility than the surrounding region results. Solvent is then applied to remove the higher solubility material, and a circular region extending through the layer **35** and stopping at the layer **12*a*** results. The patterned layer **35** may now serve as a template for patterning the layer **12*a***.

The layer **12*a*** is etched using an appropriate etching technique. For example, if the layer **12*a*** is silicon nitride, it can be etched using a dry etch such as plasma ion etching or reactive ion etching utilizing fluorine chemistry such as CF_4, CHF_3 or SF_6, for example. Other suitable etching methods known to those skilled in the art may alternatively be used. The nascent modulator, after etching the layer **12*a*,** is shown in FIG. **7**. Etching the layer **12*a*** defines the modulator cavity **21**. For clarity, prior to patterning, modulator-forming layers will be given the designation "a" as well as a numerical identifier, e.g., the layer **12*a*.** After patterning, the designation "a" will be dropped, e.g., the layer **12**.

The remaining erodible material **35** is stripped from the patterned layer **12** using solvents or a mixture of sulfuric acid and peroxide ("piranha") or plasma ash. FIG. **8** is an illustration of the nascent modulator with the erodible material **35** removed from the cavity defining layer **12**. For convenience, the aforementioned steps of depositing an erodible material, patterning, developing, etching and stripping will be collectively referred to herein as "patterning".

The silicon substrate and the cavity defining layer **12** are then thermally oxidized using either steam, wet or dry methods known to those skilled in the art. Preferably, steam oxidation is used. Oxidation temperature is preferably within the range of about 950° to about 1150° C. The lateral extent of the oxidation is defined by the opening in the layer **12,** which further defines the modulator cavity **21**. The

vertical extent of the oxidation is a function of the amount of time that the silicon is exposed to the oxidation environment. The aforementioned method for oxidizing a selective portion of silicon is referred to as local oxidation of silicon (LOCOS). LOCOS is well understood by those skilled in the art.

A volumetric expansion occurs as oxygen combines with silicon. As a result, approximately one-half of the LOCOS oxide **40** grows above the original silicon surface as shown in FIG. **9***a*. Furthermore, the oxidation proceeds somewhat beyond the modulator cavity **21** resulting in the characteristic "bird's beak" shape at each end of the LOCOS oxide **40**. As shown in FIG. **9***a,* the LOCOS oxide lifts a small portion of the cavity defining layer **12**. A layer **11** of oxide shown in FIG. **9***b,* referred to as a "pad oxide," may be used for stress relief as the LOCOS oxide **40** forces itself laterally under the cavity defining layer **12**. The pad oxide **11** is believed to flow under the layer **12** as the LOCOS oxide **40** intrudes. If the pad oxide **11** is present, it is deposited or grown before depositing the layer **12***a*. The thickness of the LOCOS oxide **40** is the primary determinant of the size of the gap **20** when the membrane **15** is in the unbiased state. Thus, a gap determining layer or means for creating a gap between the substrate and membrane is formed.

After the LOCOS oxide **40** is grown to the appropriate thickness, a rapidly-etchable layer **42***a* is deposited. The layer **42***a* is formed of a material that etches very rapidly compared to the LOCOS oxide **40**. In a preferred embodiment, the material is a glass that etches very quickly in hydrofluoric acid (HP) or buffered HF (BBF) or diluted HF or diluted BHF. Suitable glasses include phosphorosilicate glass (PSG), boron-phosphoro-silicate glass (BPSG), phosphoro-tetraorthosilicate (PTEOS) or boron-phosphoro-tetraorthosilicate (BPTEOS). Plasma-enhanced chemical vapor deposition silicon nitride or silicon oxide, and spin-on-glass may also suitably be used as the rapidly-etchable layer. In an alternate preferred embodiment, discussed in more detail later in this specification, the rapidly-etchable layer may be amorphous silicon or polycrystalline silicon. Regardless of the material chosen, the layer **42***a* is preferably deposited as a smooth layer having a uniform thickness.

If the layer **42***a* is a glass, it is preferably deposited at low temperatures using LPCVD. Deposition temperature is preferably about 450° C. The layer **42***a* is preferably deposited to a thickness ranging from about 500 to about 5000 Å. Then it may be annealed to control its density and etching properties, at, for example, 900° C. for 1 hr in nitrogen. After deposition, the layer **42***a* is patterned using the standard photolithographic steps previously described.

As shown in FIG. **11**, the patterned rapidly-etchable layer **42** preferably slightly oversizes the upturned edge **13** of the cavity-defining layer **12**. Alternatively, the patterned rapidly-etchable layer **42** may slightly undersize the edge **13** so that the upper surface of the LOCOS oxide **40** is not completely covered. Depositing the rapidly-etchable layer **42***a* facilitates forming a lateral conduit **43** for distributing etch solution across the surface of the underlying LOCOS oxide, as described in more detail below. Such a feature is particularly advantageous.

A membrane-forming layer **15***a* is next deposited as shown in FIG. **12**. Preferably, the membrane-forming layer **15***a* is silicon nitride that is deposited using LPCVD. The membrane forming layer **15***a* is deposited to the thickness required for membrane **15**. As previously noted, membrane thickness can be determined according to the teachings of the aforementioned patent specifications or according to other references as appropriate for the selected operating principle of the modulator. Further, the refractive index and stress of the membrane forming layer **15***a* are controlled. It is within the capabilities of those skilled in the art to suitably control the aforementioned parameters.

The membrane-forming layer **15***a* is preferably patterned into the membrane **15** using standard photolithographic procedures. The plurality of holes **14**, shown in FIGS. **13** and **14**, are patterned in the membrane **15** during the aforementioned step. Note that the membrane-forming layer **15***a* need not be removed "in the field", i.e., beyond the modulator cavity **21**. A layer **30***a* of conductive material, shown in FIG. **15**, is deposited, if required, on the patterned membrane **15**. The layer **30***a* is then patterned. Alternatively, the layer **30***a* can be deposited before patterning the underlying membrane-forming layer **15***a*. In a further preferred embodiment, the layer **30***a* can be deposited and patterned after the release etch step, described below.

As shown in FIG. **16**, the conductive material preferably undersizes the membrane **15** so that portions of the membrane **15** adjacent the holes **14** are not covered by the conductive layer **30**. If the conductive material is optically opaque, it should not be deposited within the optical window of the membrane **15**. Those skilled in the art will appreciate that the layer **30** can be directly patterned using the "liftoff" method.

The conductive layer **30** preferably extends beyond the membrane **15** to a region **23**, as illustrated in FIG. **17**. The controlled voltage source **29** is preferably electrically connected to the conductive layer **30** in the region **23**. It will be appreciated that the region **23** may be patterned into any suitable shape. A contact **31** for electrically connecting the substrate **10** to the controlled voltage source **29** can be deposited and patterned on the substrate during the deposition and patterning of the conductive layer **30**.

To form the gap **20**, the rapidly-etchable layer **42** and LOCOS oxide **40** underlying the membrane **15** must be removed. This step is referred to as a "release" etch, since the membrane **15** is released, i.e., free to move, after the underlying layers are removed. If the rapidly-etchable layer **42** is formed from one of the preferred glasses, then the etch is preferably HF, BHF, or dilute versions of HF and BBF. These preferred etching vehicles may attack other features of the modulator, such as the conductive layer **30**, and the membrane **15**, depending upon the materials chosen and the amount of time spent in the etch bath. A protective layer of photoresist is preferably deposited on the conductive layer **30**, however, photoresist will lift from the underlying material in EF or even in BHF during longer etch times. As previously noted, degradation of the conductive layer **30** may be avoided by depositing and patterning the conductive layer **30** after the release etch.

It will be appreciated that an etch cannot be delivered to the layers underlying the membrane **15** of the present modulator in the same manner as for modulators having membranes supported by support arms. In particular, there is usually a sufficient amount of open area between the support arms of typical modulators so that etches can be delivered to layers underlying the membrane. In the present modulator, however, the membrane **15** completely covers the optical cavity. Thus, etch must be delivered to the layers underlying the membrane in a different manner. In one embodiment of the present invention, etch is delivered to the underlying layers via the holes **14** in the membrane **15**. Other techniques or means for delivering the etch, such as holes through other layers, depending upon modulator configuration, may suitably be used.

FIG. **18***a* is an illustration of a modulator being formed without the rapidly-etchable layer **42**. The etch must proceed in a substantially lateral direction to remove the LOCOS oxide **40** from underneath the optical window portion of the membrane, since there are no holes in the optical window. As previously noted, the optical window may be as large as about 150 microns in diameter, so the modulator must remain in the etch for the time it takes to etch half of this diameter, since this region is being etched all around its

perimeter. By placing a rapidly-etchable layer, such as the layer **42**, beneath the membrane **15** and on top of the LOCOS oxide **40**, a lateral conduit **43** is formed as the rapidly-etchable layer **42** is etched away. Thus, as shown in FIG. **18***b*, the etch can flow over the surface of the LOCOS oxide **40** and thus etch the LOCOS oxide in a substantially vertical direction. The gap, which is equivalent to the thickness of the LOCOS oxide **40** and the lateral conduit **43**, will typically be much smaller than the diameter of the modulator cavity. For example, in one embodiment of a modulator, the gap **20** is preferably about one-quarter of the operating wavelength, or about 3300 angstroms. In another, the gap is about 1.1 micron. Thus, a vertically proceeding etch will remove the LOCOS oxide **40** in substantially less time than a laterally proceeding etch, resulting in less damage to permanent features of the modulator, such as the conductive layer **30** and the unprotected optical window. As the LOCOS oxide **40** is removed, the gap **20** is formed, as shown in FIG. **19**.

The shape of the membrane **15** as it rises over the upturned edge of the layer **12** nearest the modulator cavity **21** imparts a "springiness" to the membrane **15**. The shape of this region of the membrane **15** may be adjusted to impart more or less of such springiness to the membrane by adjusting the encroachment of the LOCOS oxide **40** under the layer **12**. The encroachment of the LOCOS oxide **40** under the layer **12** can be controlled by variations in the LOCOS process that are known to those skilled in the art.

It should be understood that the embodiments and variations shown and described herein are illustrative of the principles of this invention and that various modifications may occur to, and be implemented by, those skilled in the art without departing from the scope and spirit of the invention. For example, modulators according to the present invention can be formed without the cavity defining layer **12***a*. Embodiments of two such modulators are shown in FIGS. **20** and **21**. In the embodiment shown in FIG. **20**, a well is formed using milling or etching techniques, filled with an erodible material such as silicon dioxide or aluminum, a rapidly-etchable layer is deposited on the erodible material and patterned, and then a membrane layer is deposited on the rapidly-etchable layer and patterned. The underlying layers are removed via the previously described steps. In the embodiment of FIG. **21**, an "island" of erodible material is deposited on a substrate and patterned, a rapidly-etchable layer is deposited on the erodible material and then patterned, and then a membrane layer is deposited and patterned. The underlying layers are removed as previously described.

The aformentioned embodiments of a method according to the present invention achieve precise control of the size, i.e., the width or diameter, of the modulator cavity. In other embodiments, however, the present method can be used for forming modulators wherein such precise control over the size of the modulator cavity is not desired. The steps of one such embodiment are illustrated in FIGS. **22–26**.

As shown in FIG. **22**, an oxide layer **41** is deposited or grown on a substrate **10**. In turn, a rapidly-etchable layer **42***a* is deposited or grown on the oxide layer **41**. Note that in this embodiment, the oxide layer **41** is not a LOCOS oxide. Furthermore, in the previously described embodiments, the rapidly-etchable layer **42***a* was described to be a material that etches very rapidly compared to the LOCOS oxide **40**. In the present embodiment, the material forming the rapidly-etchable layer **42***a* is one that it is attacked by an etch that will not attack the membrane **15** or oxide layer **41**. Suitable materials include, without limitation, amorphous silicon and polycrystalline silicon.

The rapidly-etchable layer **42***a* is patterned as desired as shown in FIG. **23**. The shape and lateral dimension of the patterned layer **42** will approximate the size of the resulting modulator cavity. As illustrated in FIG. **24**, a membrane-forming layer **15***a* is deposited on the rapidly-etchable layer **42** and patterned. Again, it is not necessary to remove or pattern the membrane-forming layer **15***a* in the field. It is important, however, that holes **14** are patterned in the membrane if such holes are the way in which etch is delivered to the underlying layers. If required, a layer **30***a* of conductive material is deposited on the membrane **15** and patterned as previously described.

The nascent modulator is then placed in an etch suitable for etching the rapidly-etchable layer **42**, which is preferably amorphous silicon or polycrystalline silicon in the present embodiment. Suitable etches include ethylene diamine pyrocatechol, or potassium hydroxide, or tetramethylhydrazine or a mixture of nitric acid, hydrofluoric acid and water. In appropriate concentrations known to those skilled in the art, such etches will attack the layer **42** yet leave the membrane **15** and underlying oxide **41** substantially unetched. As the rapidly-etchable layer **42** is removed, a lateral conduit **43** is formed as shown in FIG. **25**. The device is then placed in a second etch suitable for removing the oxide layer **41**, such as the previously described HF-based etches. The gap **20** is formed as the oxide layer **41** is removed as shown in FIG. **26**.

In the embodiment described in FIGS. **7–19**, the silicon surrounding the LOCOS oxide **40** functioned as an "etch stop". In the present embodiment, in the absence of such an etch stop, the membrane **15** will be somewhat "undercut" as the etch proceeds isotropically in a lateral direction under the membrane **15**.

It will be appreciated that a glass such as those previously described is suitable for use as the rapidly-etchable layer **42***a* in the present embodiment. If so, the second etch step to remove the oxide layer **41** is not required, since the etch used to remove the glass will remove the oxide layer. Likewise, the embodiment illustrated in FIGS. **7–19** may use amorphous silicon or polycrystalline silicon for the rapidly-etchable layer. If so, a second etch to remove the LOCOS oxide **40** will be required.

The present invention may be modified in other ways, as well, a few of which are described below. In one modification, forming a lateral conduit utilizing a rapidly-etchable layer of material is applicable to fabricating other modulators or devices other than modulators wherein there is limited acess to a region that must be etched, especially if other features of such devices are vulnerable to attack while the region is being etched. For example, FIGS. **27–30** illustrate steps in a method according to the present invention for forming a structure other than a modulator. FIG. **27** shows two device layers **80** and **85**, and a rapidly-etchable layer of material that has been patterned into four discrete regions **42**. It will be appreciated that more or less device layers and more or less regions **42** of rapidly-etchable material can be utilized depending upon the nature of the structure being formed. A further layer **90***a* is deposited or grown on the regions **42**, as illustrated in FIG. **28**. FIG. **29** shows the layer **90***a* patterned into the layer **90**. Such patterning includes, as a minimum, the formation of holes **95**, if the holes are the means for delivering an etch to remove the regions **42**. FIG. **29** further illustrates that lateral conduits **43** have been formed by etching away the regions **42**. In FIG. **30**, a portion of the device layer **85** beneath each lateral conduit **43** is removed by delivering an etch to the lateral conduits **43**. Thus, a series of gaps **100** are formed in the structure. As previously described, the layer **85** may be etched using the same etch that was used to etch the regions **42**, depending upon the material used for the rapidly-etchable layer.

In other modifications, the methods described herein are used for forming membranes having a shape other than the preferred circular shape, or materials other than those described herein may be used for fabricating the modulator.

We claim:

1. A method for forming a micromechanical modulator comprising the steps of:

(a) forming a composition for creating a gap between a substrate and a membrane;

(b) forming a membrane over the composition; and

(c) creating the gap by removing the composition by:

forming a lateral conduit by removing a first portion of said composition, and

removing a second portion of the composition utilizing the lateral conduit for access, wherein, the first portion is comprised of a first material that is physically adapted to be removed substantially more quickly than a second material comprising the second portion.

2. The method of claim 1 wherein step (a) further comprises the steps of:

(i) defining a modulator cavity; and

(ii) forming the means for creating a gap between the substrate and the membrane within the modulator cavity.

3. The method of claim 1 wherein step (b) further comprises the step of forming holes in the membrane.

4. The method of claim 1 wherein the physical adaptation of the first portion is that it comprises a rapidly-etchable material disposed on the second portion of the composition, wherein the rapidly-etchable materials is etchable at a much quicker rate than the second material comprising the second portion of the composition.

5. The method of claim 4 wherein step (c) further comprises providing an etch that rapidly removes the rapidly-etchable material.

6. The method of claim 5 wherein the etch also removes the second material.

7. The method of claim 5 wherein step (b) further comprises the step of forming holes in the membrane and step (c) further comprises providing the etch through the holes in the membrane.

8. A method for making a micromechanical modulator comprising the steps of:

(a) depositing a cavity-defining layer on a suitably-prepared substrate;

(b) patterning the cavity-defining layer into a desired shape that defines a region that will become a modulator cavity and further removes the cavity-defining layer from the substrate in the region;

(c) oxidizing the substrate in the region;

(d) depositing a rapidly-etchable layer on the oxidized substrate of step (c);

(e) patterning the rapidly-etchable layer;

(f) depositing a membrane-forming layer on the patterned rapidly-etchable layer;

(g) patterning the membrane-forming layer into a membrane, wherein holes are formed in the membrane; and

(h) removing the rapidly-etchable layer and the oxidized substrate.

9. A composition for forming a micromechanical modulator comprising:

a substrate;

a membrane supported above a portion of the substrate;

first and second layers comprising respective first and second materials, which layers are removed to form a gap between the membrane and the portion of the substrate, and further wherein the first layer is proximal to the membrane and the first material is etchable by a first etchant at a substantially faster rate than the second material.

10. The composition of claim 9, wherein the second material is an oxide formed within the portion of the substrate.

11. The composition of claim 9 wherein, the first layer is removed by the first etchant, it forms a lateral conduit by which one of either the first etchant or a second etchant is delivered to the second layer.

12. The composition of claim 11 wherein the first material is selected from the group consisting of phosphoro-silicate glass, boron-phosphoro-silicate glass, phosphoro-tetraorthosilicate, boron-phosphoro-tetraorthosilicate, plasma-enhanced chemical vapor deposition silicon nitride or silicon oxide, and spin-on-glass.

13. The composition of claim 11 wherein the first material is amorphous silicon or polycrystalline silicon.

14. The composition of claim 11 wherein the substrate is silicon and the membrane is silicon nitride.

15. A method for forming a feature in a structure wherein there is limited access to a region of a first layer, comprising a first material that must be etched to form the feature, comprising the steps of:

(a) forming a rapidly-etchable layer on the first layer, the rapidly-etchable layer comprising a second material that is etched rapidly via a first etch relative to the first material;

(b) forming a second layer on the rapidly-etchable layer;

(c) delivering the first etch to the rapidly-etchable layer, thereby removing it and forming a conduit; and

(d) delivering to the first layer, via the conduit, one of either the first etch, or a second etch if the first layer is not etchable by the first etch, to remove the region and form the feature.

16. The method of claim 15 wherein step (a) further comprises patterning the rapidly-etchable layer into a size and shape suitable for forming the feature.

17. The method of claim 15 wherein step (b) further comprises forming holes in the second layer by which etch is delivered to the rapidly-etchable layer.

18. The method of claim 15 wherein the step of forming a rapidly-etchable layer comprises forming a layer of material selected from the group consisting of phosphoro-silicate glass, boron-phosphoro-silicate glass, phosphoro-tetraorthosilicate, boron-phosphoro-tetraorthosilicate, plasma-enhanced chemical vapor deposition silicon nitride or silicon nitride, and spin-on-glass.

19. The method of claim 15 wherein the step of forming a rapidly-etchable layer comprises forming a layer of material selected from the group consisting of amorphous silicon or polycrystalline silicon.

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