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

(10) **Patent No.: US 6,663,788 B2**
(45) **Date of Patent: *Dec. 16, 2003**

(54) **METHOD FOR MANUFACTURING A MECHANICAL CONFORMAL GRATING DEVICE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 225 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/867,927**

(22) Filed: **May 30, 2001**

(65) **Prior Publication Data**

US 2001/0024325 A1 Sep. 27, 2001

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/491,354, filed on Jan. 26, 2000, now Pat. No. 6,307,663.

(51) **Int. Cl.**[7] **C23F 1/00**; H01B 13/00; B29D 11/00

(52) **U.S. Cl.** **216/24**; 216/13; 216/2

(58) **Field of Search** 216/2, 13, 24; 437/927; 359/291–295, 213, 224, 226

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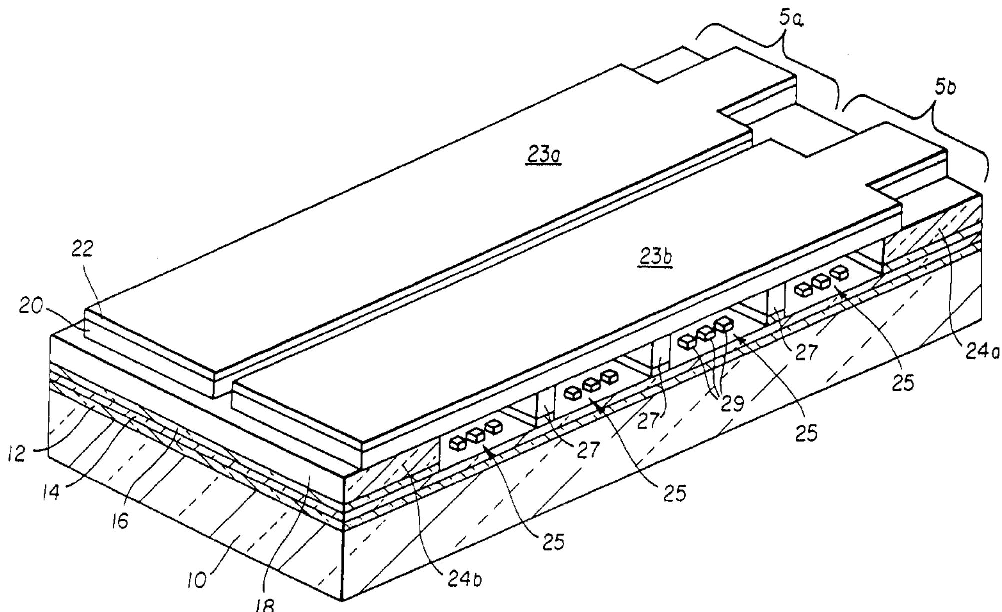
(57) **ABSTRACT**

A method of manufacturing a conformal grating device, that includes the steps of: forming a spacer layer on a substrate; removing portions of the spacer layer to define an active region with at least two channels and at least one intermediate support; forming a sacrificial layer in the active region; forming conductive reflective ribbon elements over the active region; and removing the sacrificial layer from the active region.

29 Claims, 13 Drawing Sheets



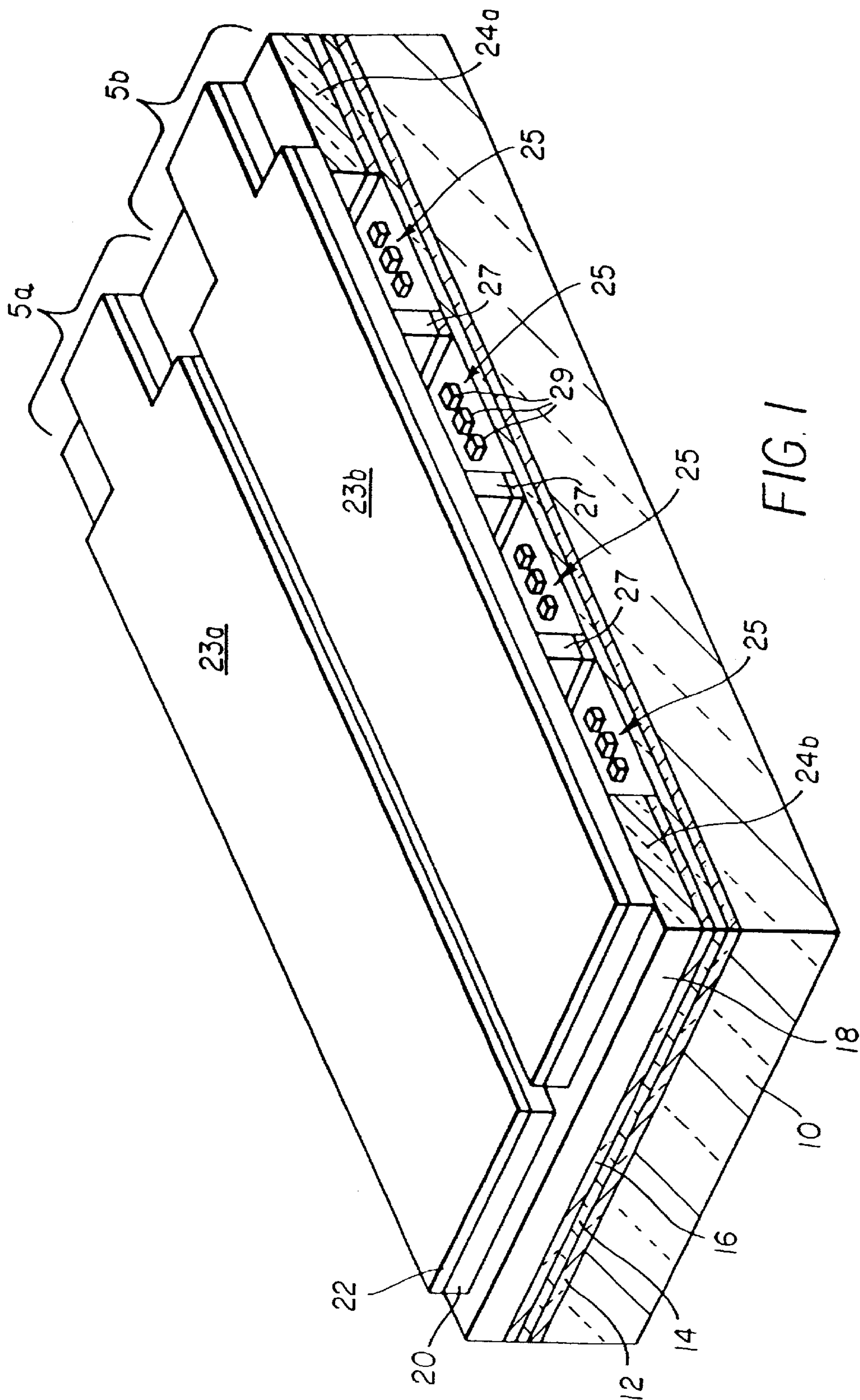


FIG. 1

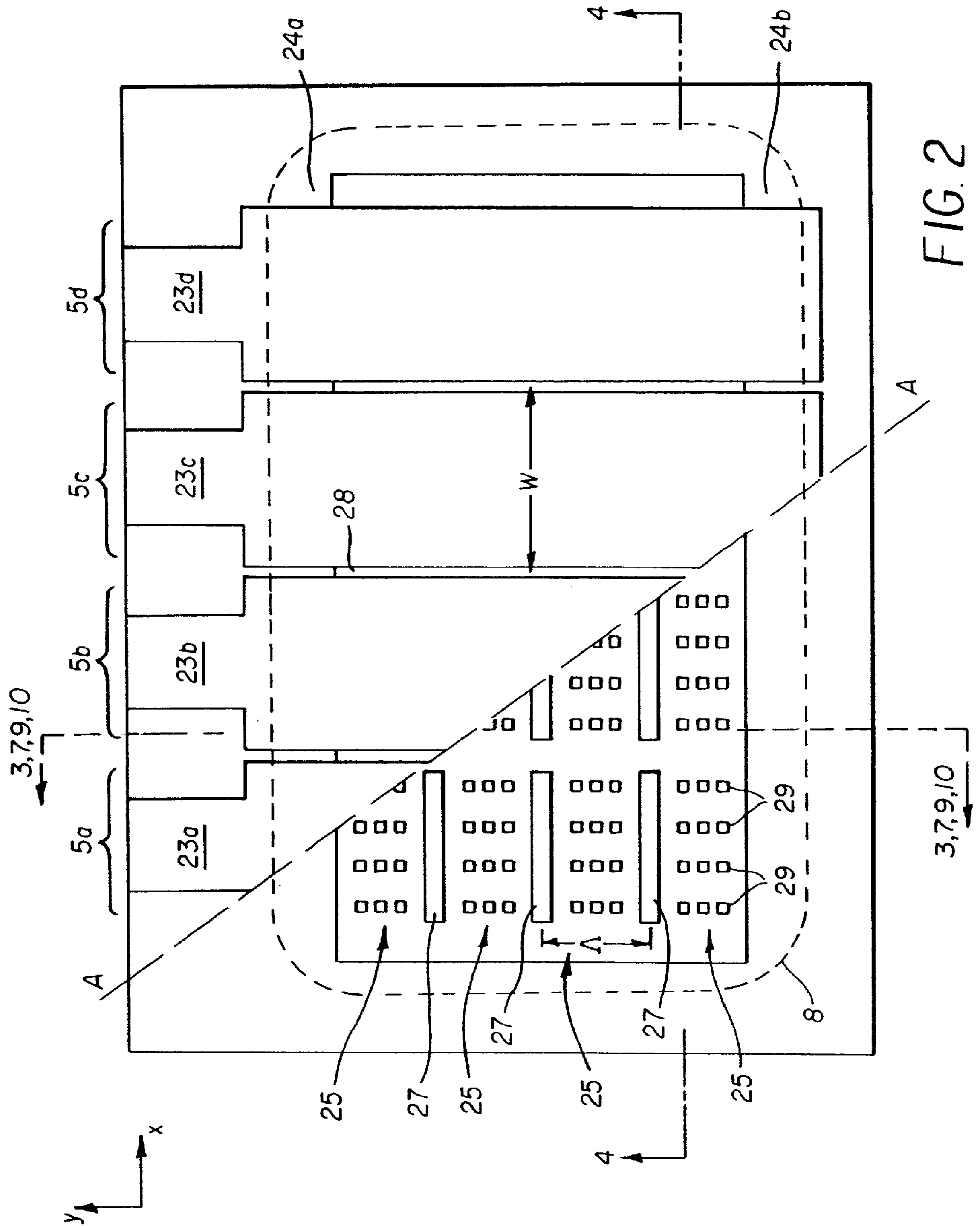


FIG. 2

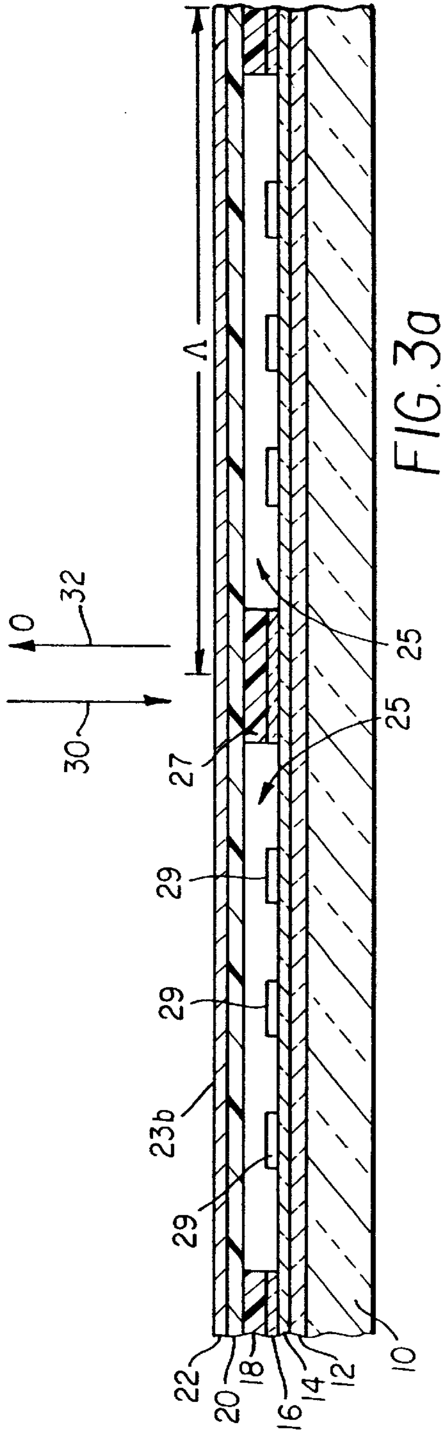


FIG. 3a

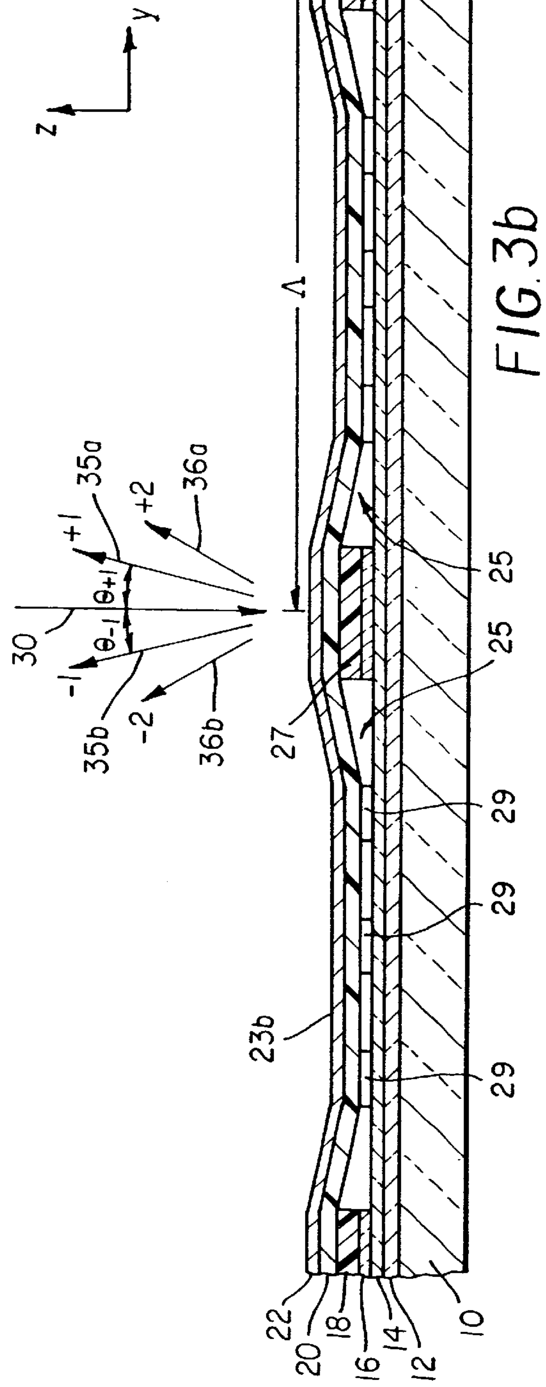


FIG. 3b

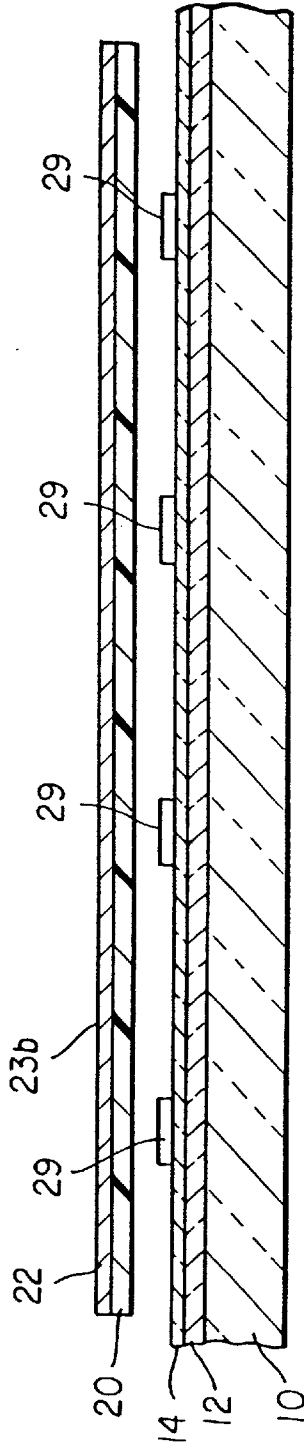


FIG. 4a

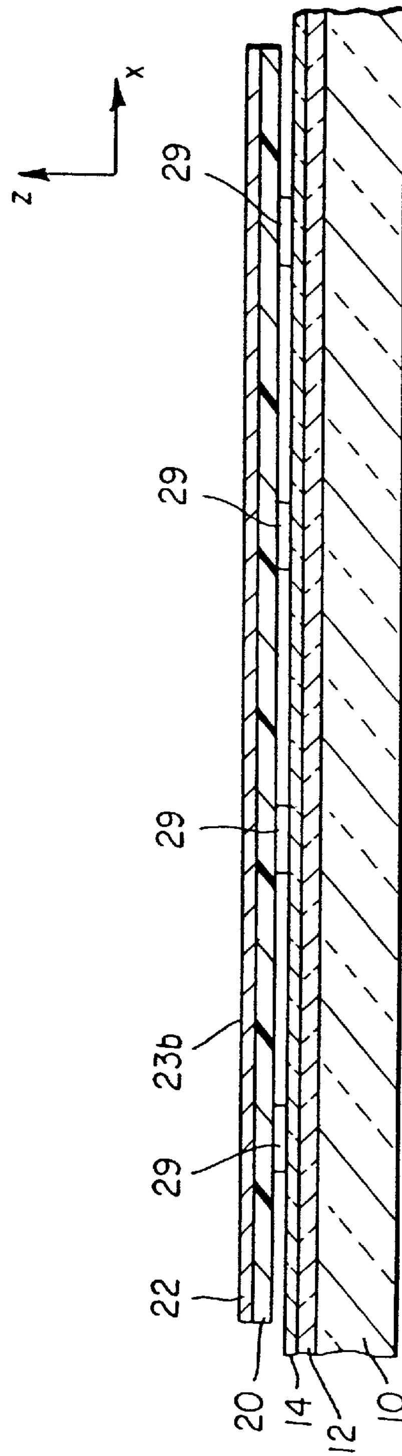


FIG. 4b

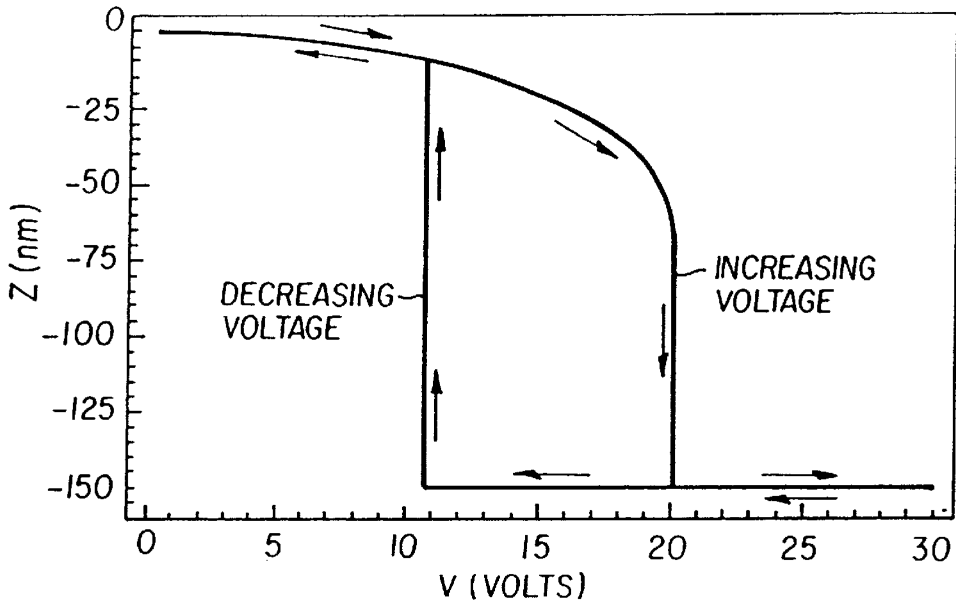


FIG. 5

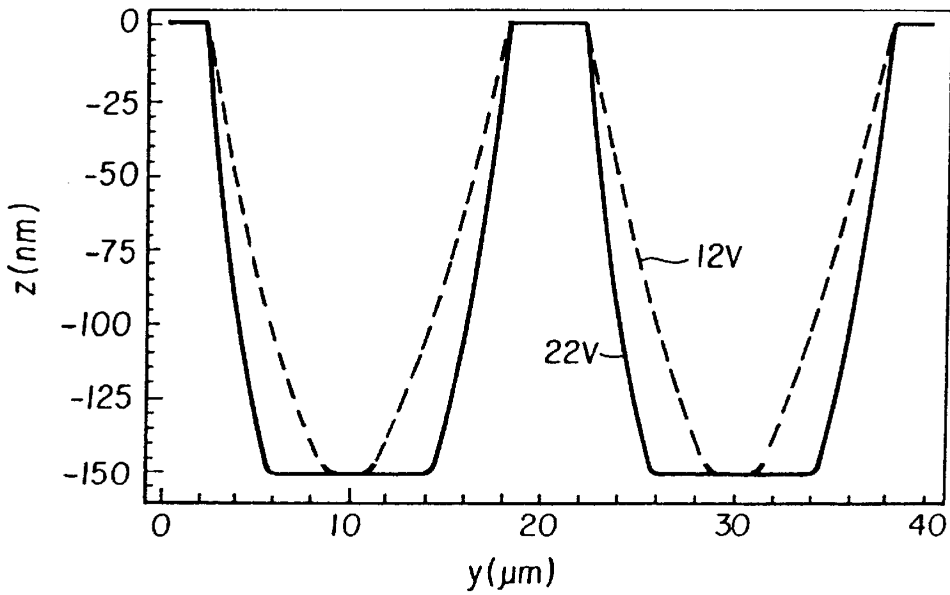


FIG. 6

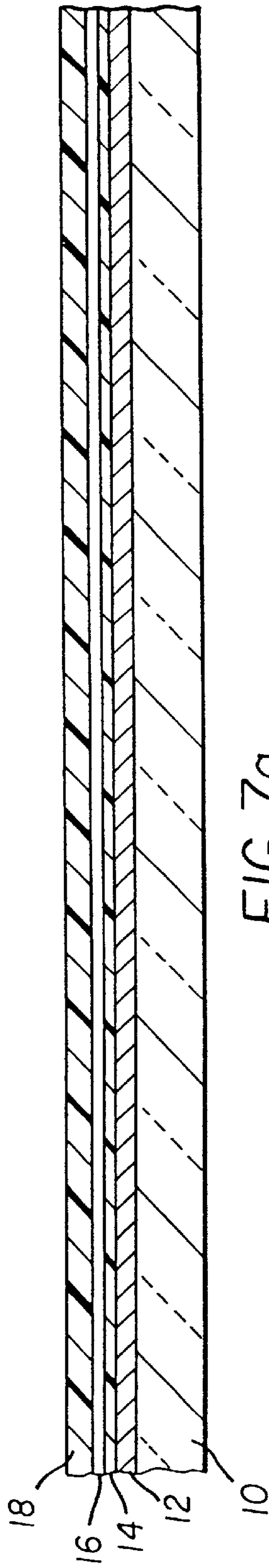


FIG. 7a
18
16
14
12
10

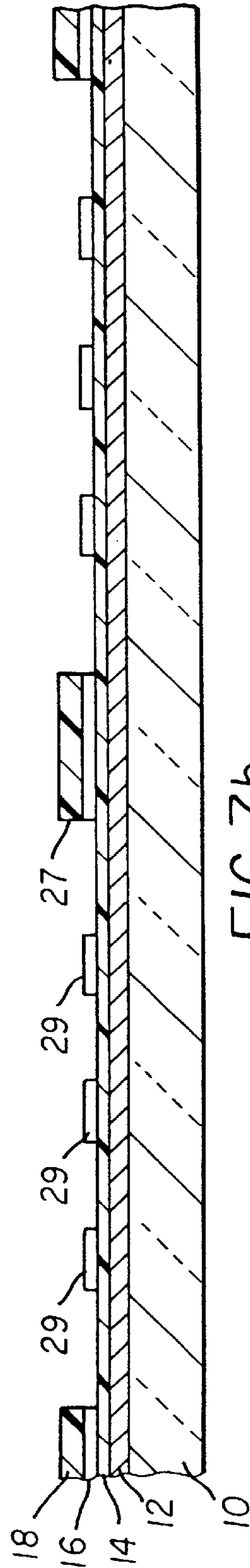


FIG. 7b
27
29
29
29
18
16
14
12
10

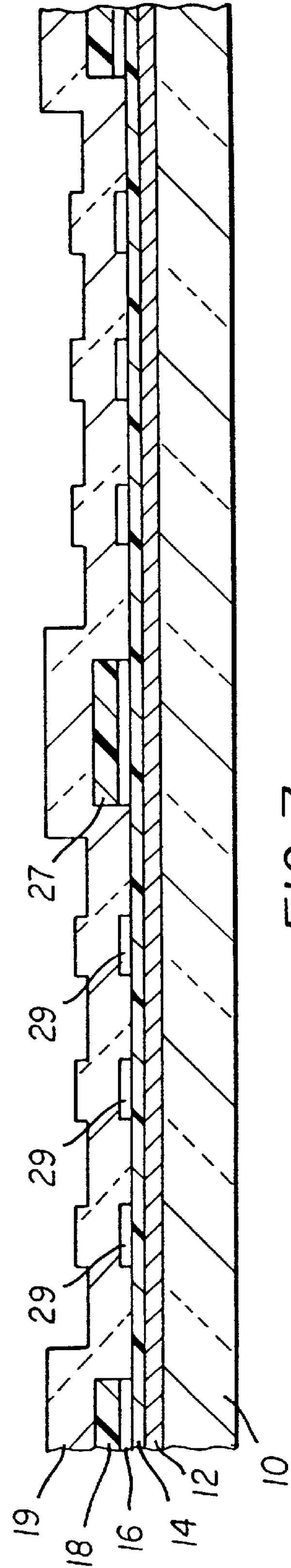


FIG. 7c
27
29
29
29
19
18
16
14
12
10

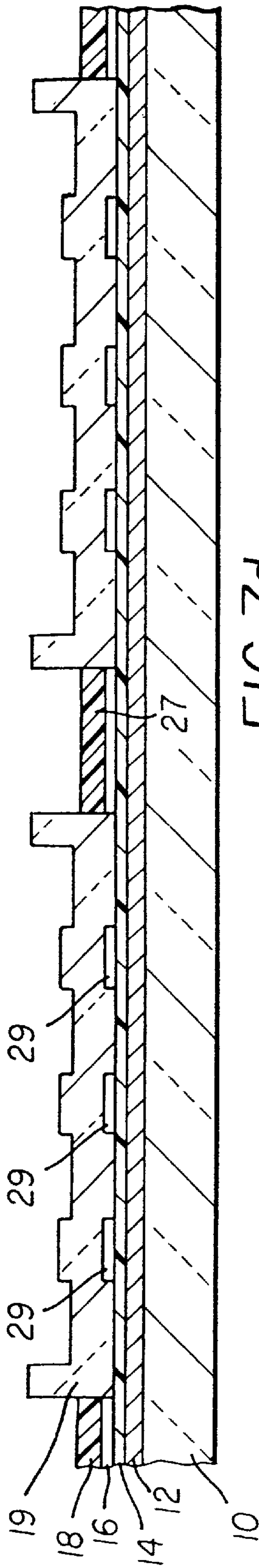


FIG. 7d

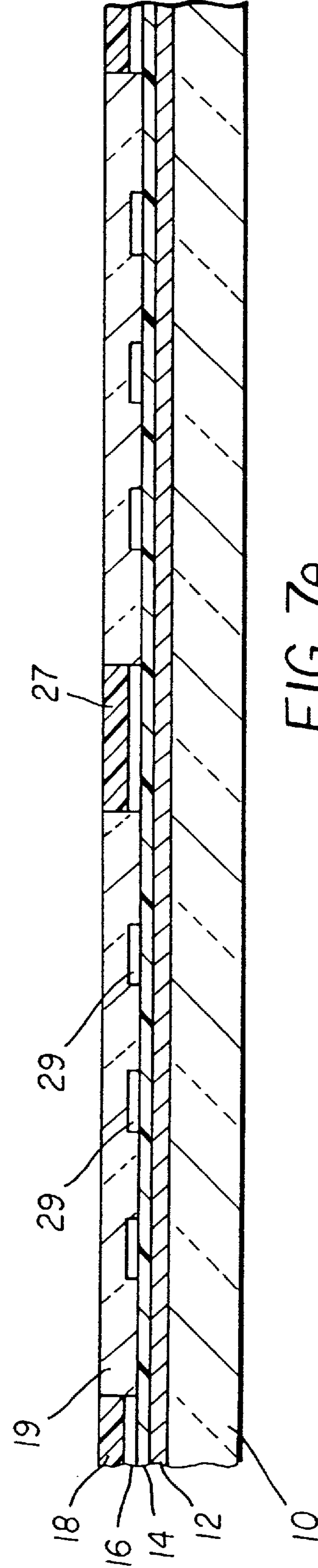


FIG. 7e

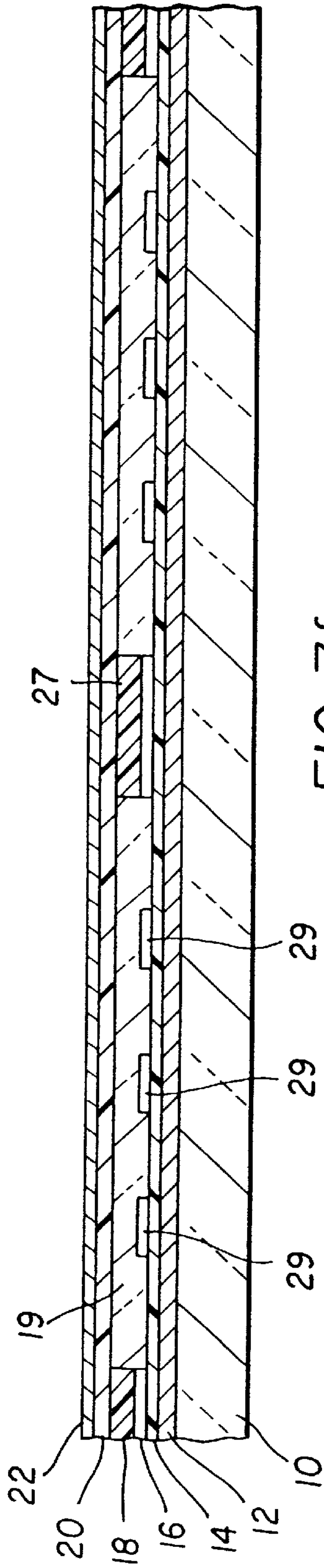


FIG. 7f

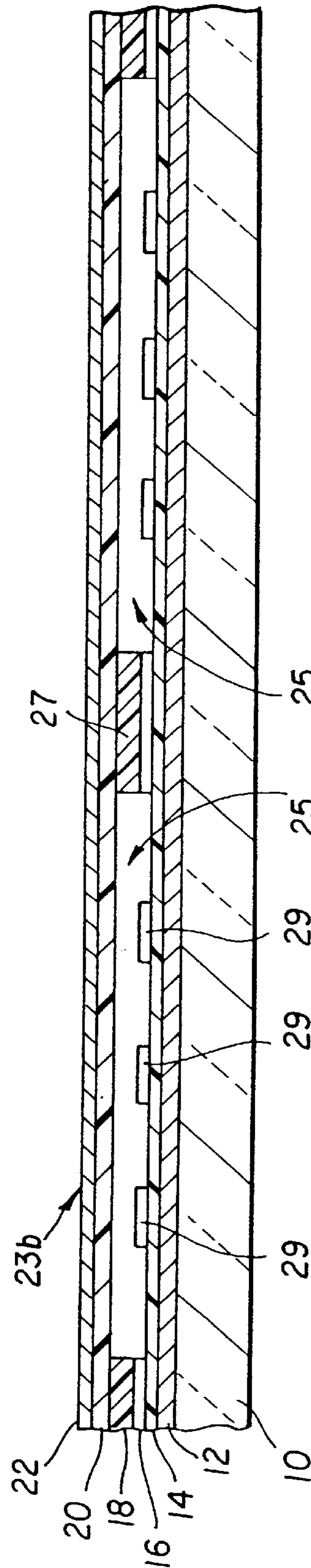


FIG. 7g

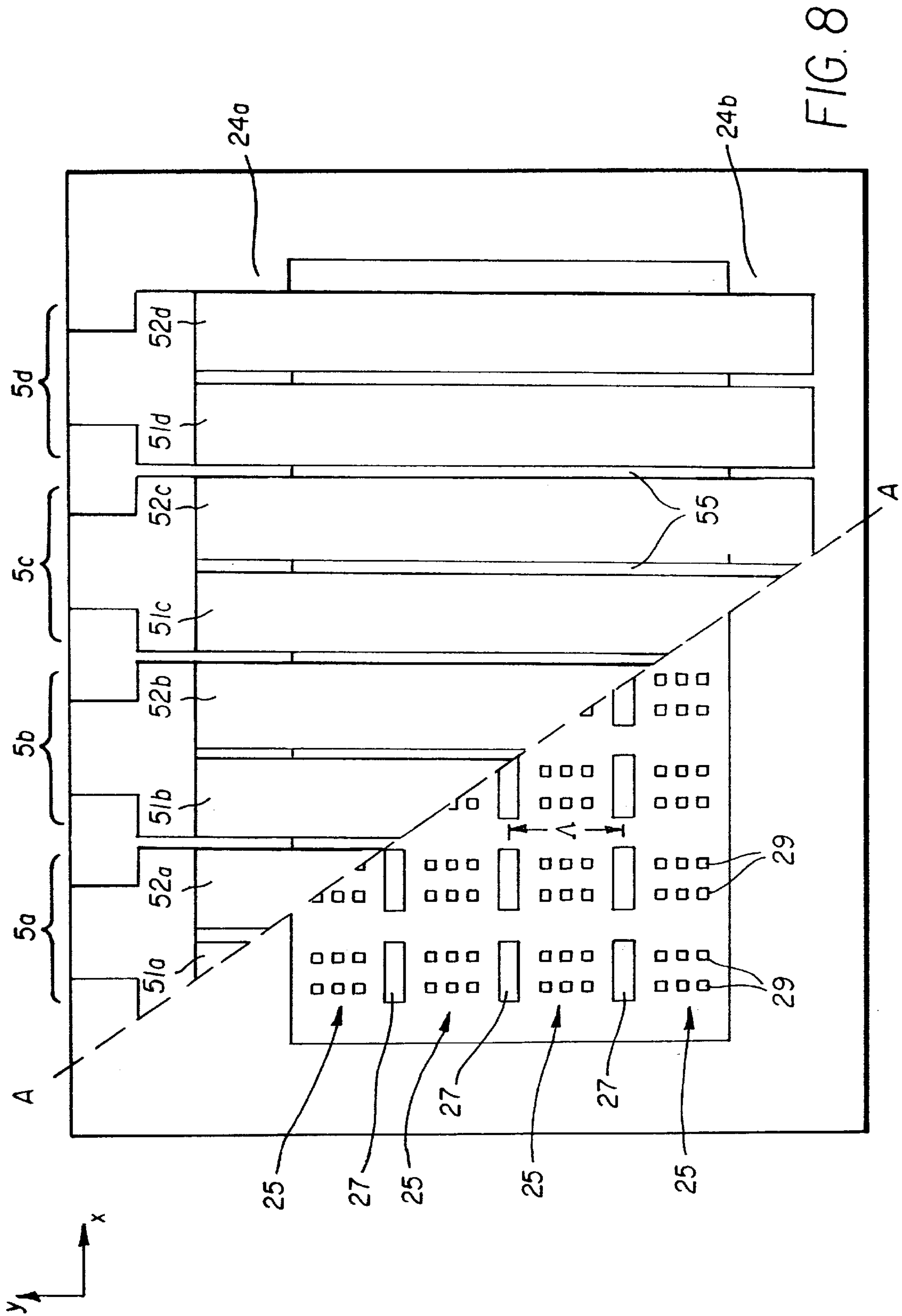


FIG. 8
24a
24b
5a
5b
5c
5d
51a
52a
51b
52b
51c
52c
51d
52d
55
A
A
25
27
29
Λ
x
y

FIG. 9a

FIG. 9b

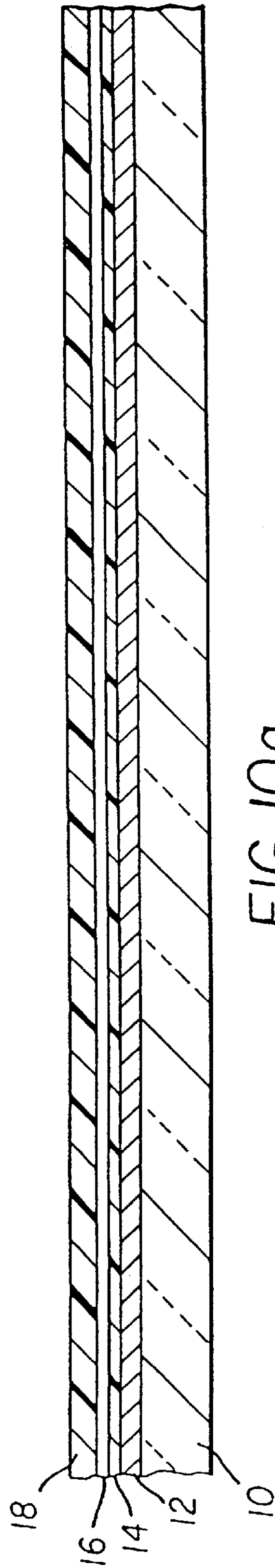


FIG. 10a

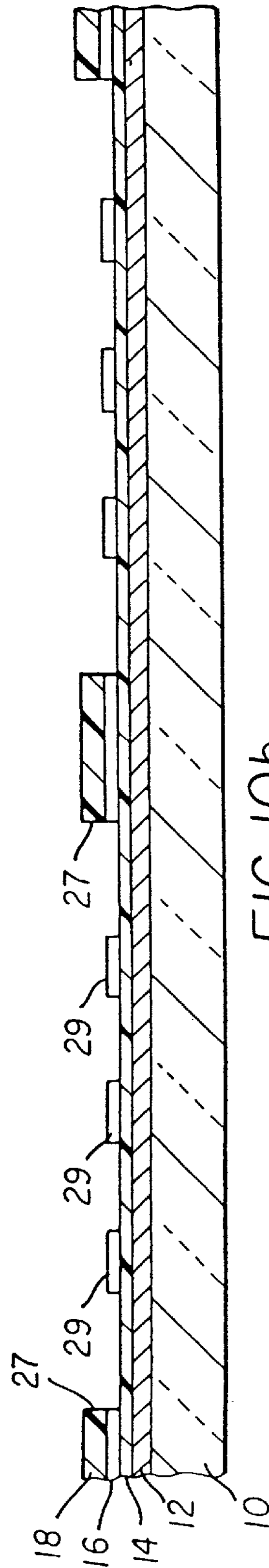


FIG. 10b

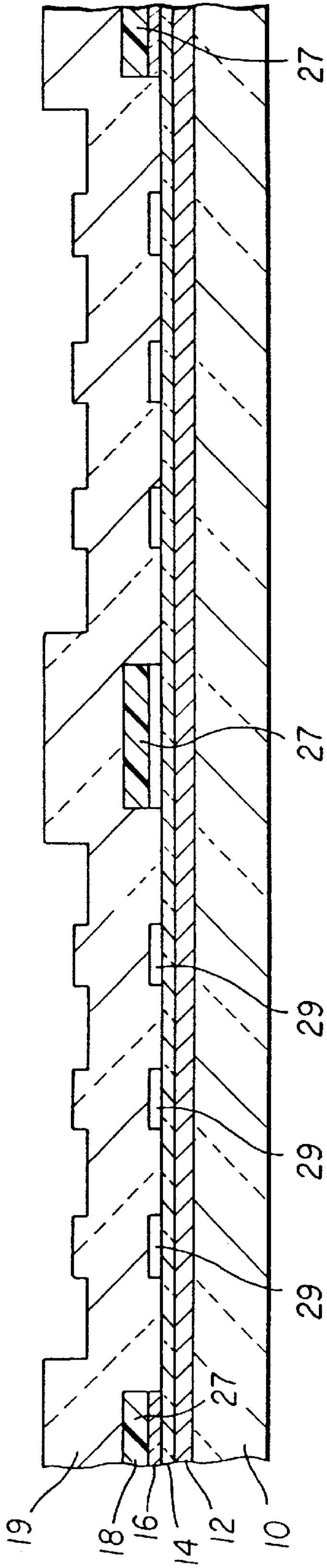


FIG. 10c

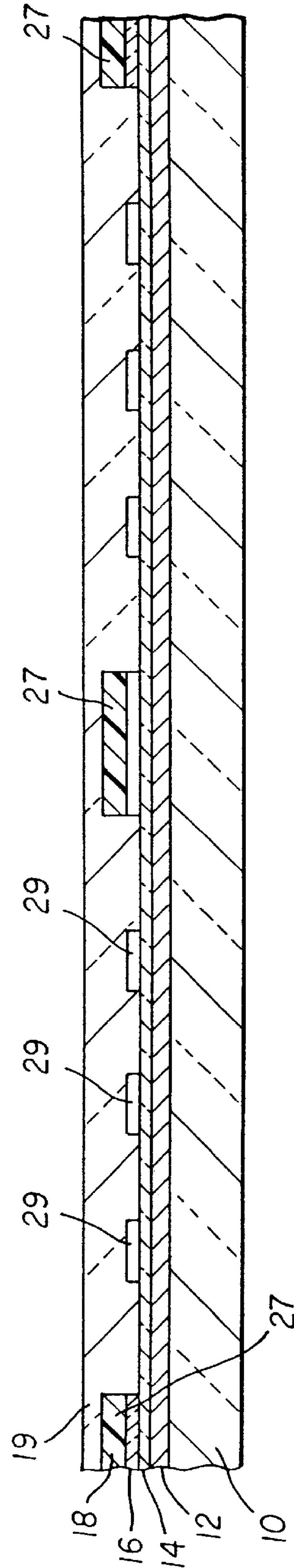


FIG. 10d

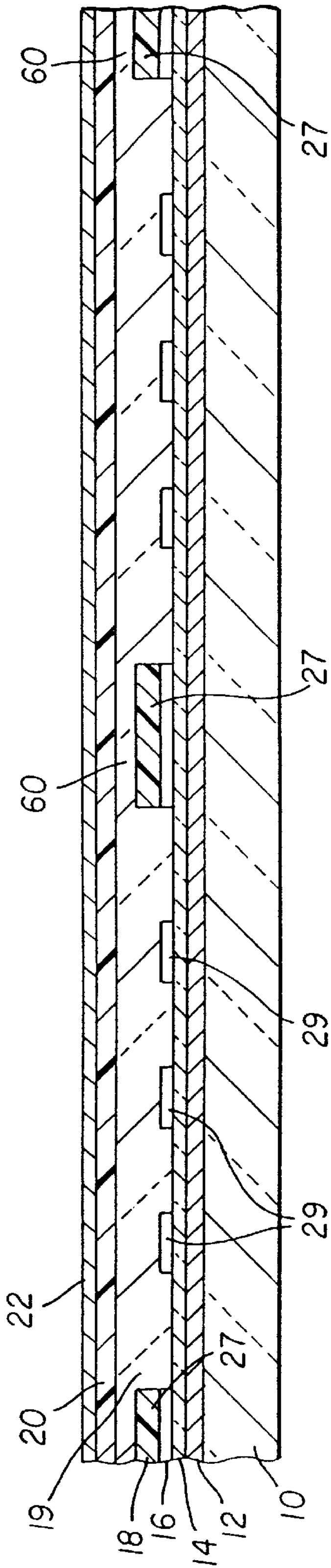


FIG. 10e

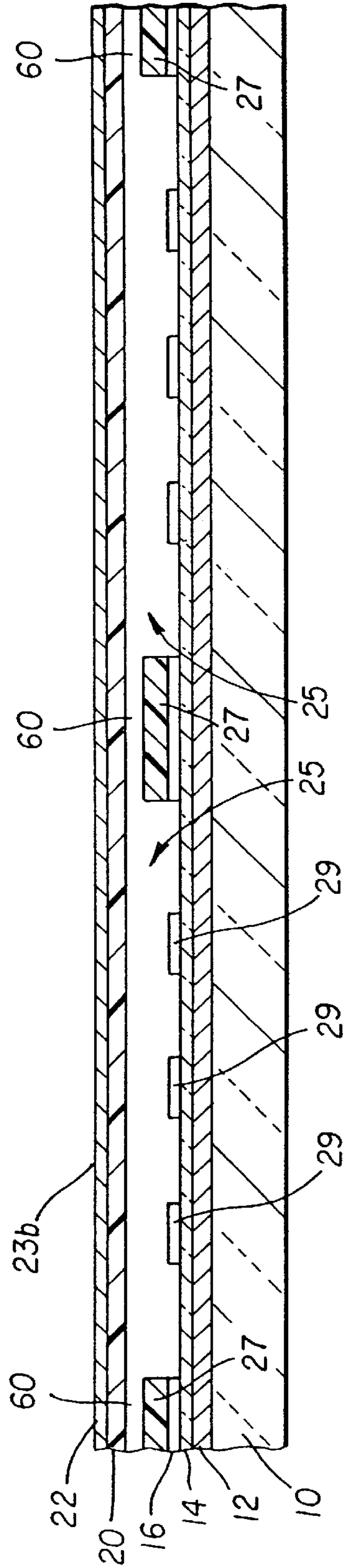


FIG. 10f

METHOD FOR MANUFACTURING A MECHANICAL CONFORMAL GRATING DEVICE

CROSS REFERENCE TO RELATED APPLICATION

This is a continuation-in-part Ser. No. 09/491,354, filed on Jan. 26, 2000 of U.S. Pat. No. 6,307,663, issued Oct. 23, 2001, entitled Spatial Light Modulator with Conformal Grating Elements, by Kowarz.

FIELD OF THE INVENTION

This invention relates to the fabrication of a micromechanical device for spatially and temporally modulating an incident beam of light by diffraction. More particularly, this invention discloses a method for manufacturing an electromechanical device with a conformal grating structure.

BACKGROUND OF THE INVENTION

Electromechanical spatial light modulators with a variety of designs have been used in applications such as display, optical processing, printing, optical data storage and spectroscopy. These modulators produce spatial variations in the phase and/or amplitude of an incident light beam using arrays of individually addressable devices.

One class of electromechanical spatial light modulators has devices with a periodic sequence of reflective elements that form electromechanical phase gratings. In such devices, the incident light beam is selectively reflected or diffracted into a number of discrete orders. Depending on the application, one or more of these diffracted orders may be collected and used by the optical system. Electromechanical phase gratings can be formed in metallized elastomer gels; see U.S. Pat. No. 4,626,920, issued Dec. 2, 1986 to Glenn, and U.S. Pat. No. 4,857,978, issued Aug. 15, 1989 to Goldburt et al. The electrodes below the elastomer are patterned so that the application of a voltage deforms the elastomer producing a nearly sinusoidal phase grating. These types of devices have been successfully used in color projection displays.

An electromechanical phase grating with a much faster response time can be made of suspended micromechanical ribbon elements, as described in U.S. Pat. No. 5,311,360, issued May 10, 1994, to Bloom et al. This device, also known as a grating light valve (GLV), can be fabricated with CMOS-like processes on silicon. Improvements in the device were later described by Bloom et al. that included: 1) patterned raised areas beneath the ribbons to minimize contact area to obviate stiction between the ribbons and the substrate, and 2) an alternative device design in which the spacing between ribbons was decreased and alternate ribbons were actuated to produce good contrast. See U.S. Pat. No. 5,459,610, issued Oct. 17, 1995. Bloom et al. also presented a method for fabricating the device; see U.S. Pat. No. 5,677,783, issued Oct. 14, 1997. Additional improvements in the design and fabrication of the GLV were described in U.S. Pat. No. 5,841,579, issued Nov. 24, 1998 to Bloom et al., and in U.S. Pat. No. 5,661,592, issued Aug. 26, 1997 to Bornstein et al.

Previously mentioned linear GLV arrays have a diffraction direction that is not perpendicular to the array direction, and thus increases the complexity of the optical system required for separating the diffracted orders. Furthermore, the active region of the array is relatively narrow, hence requiring good alignment of line illumination over the entire

length of the array, typically to within 10–30 microns over a few centimeters of length. The line illumination then also needs to be very straight over the entire linear array.

There is a need, therefore, for a linear array of grating devices that has a large active region with the diffraction direction perpendicular to the array direction. Furthermore, the device must be able to diffract light efficiently at high speed into discrete orders and the device fabrication must be compatible with CMOS-like processes.

SUMMARY OF THE INVENTION

The need is met according to the present invention by providing a method of manufacturing a conformal grating device, that includes the steps of: forming a spacer layer on a substrate; removing portions of the spacer layer to define an active region with at least two channels and at least one intermediate support; forming a sacrificial layer in the active region; forming conductive reflective ribbon elements over the active region; and removing the sacrificial layer from the active region.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective, partially cut-away view of a spatial light modulator with electromechanical conformal grating devices, showing two devices in a linear array;

FIG. **2** is a top view of a spatial light modulator with electromechanical conformal grating devices, showing four individually operable devices in a linear array;

FIGS. **3***a* and **3***b* are cross-sectional views through line **3,7,9,10—3,7,9,10** in FIG. **2**, showing the operation of an electromechanical conformal grating device in an unactuated state and an actuated state, respectively;

FIGS. **4***a* and **4***b* are cross-sectional views through line **4—4** in FIG. **2** showing the device in an unactuated state and an actuated state, respectively;

FIG. **5** is a plot showing ribbon element position as a function of applied voltage;

FIG. **6** is a diagram showing the device profile in response to two different actuation voltages;

FIG. **7***a* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating the layer structure prior to any patterning;

FIG. **7***b* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating patterning of the active region to form channels and intermediate supports;

FIG. **7***c* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating deposition of a sacrificial layer;

FIG. **7***d* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating patterning of the sacrificial layer;

FIG. **7***e* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating planarizing of the sacrificial layer;

FIG. **7***f* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating deposition of a ribbon layer and a reflective and conductive layer;

FIG. **7***g* is a cross-sectional view through line **3,7,9,10—3,7,9,10** in FIG. **2** illustrating removal of the sacrificial layer after patterning elongated ribbon elements;

FIG. **8** is a top view of an alternate embodiment of the spatial light modulator;

FIG. **9***a* is a cross sectional view of an alternative embodiment of the conformal grating device in an unactuated state; and

FIG. 9b is a cross sectional view of an alternative embodiment of the conformal grating device in an actuated state.

FIGS. 10a–10f illustrate the fabrication steps used to make an alternative embodiment of the conformal grating device.

DETAILED DESCRIPTION OF THE INVENTION

The conformal grating devices of the preferred embodiment of the present invention are illustrated in FIGS. 1–2, 3a–3b, and 4a–4b. FIG. 1 shows the structure of two side-by-side conformal grating devices 5a and 5b in an unactuated state. In this embodiment, the devices can be operated by the application of an electrostatic force. A substrate 10 made of glass, metal, plastic, or semiconductor materials, is covered by a bottom conductive layer 12. The grating devices 5a and 5b are formed on top of the bottom conductive layer 12 and the substrate 10. The bottom conductive layer 12 acts as an electrode to actuate the devices. The bottom conductive layer 12 can be made of materials such as aluminum, titanium, gold, silver, tungsten, doped silicon, or indium tin oxide. A dielectric protective layer 14 covers the bottom conductive layer 12. Above the protective layer 14 a standoff layer 16 is formed which is followed by a spacer layer 18. On top of the spacer layer 18, a ribbon layer 20 is formed which is covered by a reflective layer 22. In the present embodiment, the reflective layer 22 is also a conductor in order to provide electrodes for the actuation of the conformal grating devices 5a and 5b. The reflective and conductive layer 22 is patterned to provide electrodes to the two conformal grating devices 5a and 5b. The ribbon layer 20 preferably comprises a material with a sufficient tensile stress to provide a large restoring force. Examples of ribbon materials are silicon nitride, titanium aluminide, and titanium oxide. The thickness and tensile stress of the ribbon layer 20 are chosen to optimize performance by influencing the electrostatic force for actuation and the restoring force. These forces affect the voltage requirement, speed, and resonance frequency of the conformal grating devices 5a and 5b.

Each of the two devices 5a and 5b has an associated elongated ribbon element 23a and 23b, respectively, patterned from the reflective and conductive layer 22 and the ribbon layer 20, and herein referred to as conductive reflective ribbon elements. The elongated-conductive reflective ribbon elements 23a and 23b are supported by end supports 24a and 24b formed from the spacer layer 18 and by one or more intermediate supports 27. In FIG. 1, three intermediate supports 27 are shown formed from the spacer layer 18. These intermediate supports 27 are uniformly separated in order to form four equal-width channels 25. The conductive reflective ribbon elements 23a and 23b are secured to the end supports 24a and 24b and to the intermediate supports 27. The end supports 24a and 24b are not defined other than at their edges facing the channel 25. A plurality of square standoffs 29 is patterned at the bottom of the channels 25 from the standoff layer 16. These standoffs 29 reduce the possibility of the conductive reflective ribbon elements 23a, 23b sticking when actuated. The standoffs 29 may also be patterned in shapes other than square, for example, rectangular or round.

A top view of a four-device linear array of conformal grating devices 5a, 5b, 5c and 5d is shown in FIG. 2. The conductive reflective ribbon elements 23a, 23b, 23c, and 23d are depicted partially removed over the portion of the diagram below the line A—A in order to show the underlying structure. For best optical performance and maximum contrast, the intermediate supports 27 must be completely hidden below the conductive reflective ribbon elements 23a, 23b, 23c and 23d. Therefore, when viewed from the top, the intermediate supports 27 must not be visible in the gaps 28 between the conformal grating devices 5a–5d. Here each of the conformal grating devices has three intermediate supports 27 with four equal-width channels 25. The active region 8 is the portion of the device where the electromechanical actuation takes place and contains the channels 25, the intermediate supports 27, and the end supports 24a and 24b. The active region 8 is completely covered by the ribbon layer 20 in the form of the elongated-conductive reflective ribbon elements 23a, 23b, 23c, and 23d.

The center-to-center separation Λ of the intermediate supports 27 defines the period of the conformal grating devices in the actuated state. The conductive reflective ribbon elements 23a–23d are mechanically and electrically isolated from one another, allowing independent operation of the four conformal grating devices 5a–5d. The bottom conductive layer 12 of FIG. 1 can be common to all of the devices.

FIG. 3a is a side view, through line 3,7,9,10—3,7,9,10 of FIG. 2, of two channels 25 of the conformal grating device 5b in the unactuated state. FIG. 3b shows the same view of the actuated state. For operation of the device, an attractive electrostatic force is produced by applying a voltage difference between the bottom conductive layer 12 and the reflective and conductive layer 22 of the conductive reflective ribbon element 23b. In the unactuated state (see FIG. 3a), with no voltage difference, the ribbon element 23b is suspended flat between the end supports 24a, 24b. In this state, an incident light beam 30 is primarily reflected 32 into the mirror direction. To obtain the actuated state, a voltage is applied to the conformal grating device 5b, which deforms the conductive reflective ribbon element 23b and produces a partially conformal grating with period Λ. FIG. 3b shows the device in the fully actuated state with the conductive reflective ribbon element 23b in contact with the standoffs 29. The height difference between the bottom of element 23b and the top of the standoffs 29 is chosen to be approximately ¼ of the wavelength λ of the incident light. The optimum height depends on the specific shape of the actuated device. In the actuated state, the incident light beam 30 is primarily diffracted into the +1st order 35a and −1st order 35b, with additional light diffracted into the +2nd order 36a and −2nd order 36b. A small amount of light is diffracted into even higher orders and some is reflected. For light incident perpendicular to the surface of the device, the angle θm between the incident beam and the mth order diffracted beam is given by

$$\sin \theta m = m\lambda/\Lambda,$$

where m is an integer. One or more of the diffracted orders can be collected and used by the optical system, depending on the application. When the applied voltage is removed, the forces due to the tensile stress and bending restores the ribbon element 23b to its original unactuated state.

FIGS. 4a and 4b show a rotated side view through line 4—4 of FIG. 2 of the conformal grating device 5b in the unactuated and actuated states, respectively. The conductive reflective ribbon element 23b is suspended by the end support 24b and the adjacent intermediate support 27 (not shown in this perspective). The application of a voltage actuates the device as illustrated in FIG. 4b.

To understand the electromechanical and optical operation of the conformal grating device in more detail, it is

helpful to examine the expected performance of a realistic design with the following materials and parameters:

Substrate material: silicon

Bottom conductive layer: doped silicon

Protective layer: silicon dioxide, thickness=50 nm

Spacer layer: silicon dioxide, thickness=150 nm

Ribbon layer: silicon nitride, thickness=100 nm, tensile stress=600 Mpa

Reflective and conductive layer: aluminum, thickness=50 nm

Grating period Λ=20 μm

Suspended length of conductive reflective ribbon element=16 μm

Width of conductive reflective ribbon element w=30 μm

Width of intermediate supports=4 μm

This type of design allows for fabrication with CMOS methods and integration with CMOS circuitry. The resonant frequency of the ribbon elements in this particular design is approximately 11 MHz. Most practical designs have resonant frequencies between 2 MHz and 15 MHz. Because of this high resonance, the switching time of the device can be very short.

FIGS. **5** and **6** show the modeled electromechanical operation of this particular device. FIG. **5** is a plot of the position of the conductive reflective ribbon element at the center of a channel as a function of applied voltage, illustrating the associated hysteresis. As the voltage is increased from 0 V, the center displacement increases in approximately a quadratic manner until the pull-down voltage of 20.1 V is reached. At this voltage, the electrostatic force overcomes the tensile restoring force and the ribbon slams into the substrate. Further increasing the applied voltage changes the shape of the deformed ribbon, but cannot change the center position. With the ribbon in contact with the substrate, the voltage can be reduced below the pull-down value while maintaining contact, until release at 10.8 V. This hysteresis can be exploited to improve the optical performance of the device. It can also be used as a switch in certain applications.

FIG. **6** demonstrates how the grating profile may be modified by adjusting the applied voltage. The profile of two periods of the actuated device is shown at 12 V (dotted line) and at 22 V (solid line), with the ribbon and substrate in contact. To obtain this 12 V profile, contact must first be established by applying a value larger than the pull-down voltage of 20.1 V. Because 12 V is only slightly larger that the release voltage, only a small portion of the ribbon touches the substrate. This change in shape with voltage has an important impact on the diffraction efficiency of the device.

The fabrication sequence for making a conformal grating device is illustrated in FIGS. *7a*–*7g*. Referring now to FIG. *7a*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, illustrated is the built-up layer of one embodiment of the invention with standoffs **29** formed at the bottom of the channels **25**. The device is built upon a substrate **10**, covered by the bottom conductive layer **12**, and a dielectric protective layer **14** on top of the bottom conductive layer **12**. As mentioned above, the substrate **10** can be glass, plastic, metal, or a semiconductor material. In one embodiment, the substrate **10** is silicon and the dielectric protective layer **14** is a thermal oxide. An epitaxial layer, doping by diffusion, or ion implantation can form the bottom conductive layer **12**. To form the standoffs **29** and channels **25**, a standoff layer **16** is deposited followed by a spacer layer **18**. The spacer layer **18** is selected from the group consisting of silicon oxide, silicon nitride polysilicon, and polyimide. In a preferred embodiment the standoff layer **16** is silicon nitride deposited by chemical vapor deposition. The top surface of the standoff layer **16** will be used to define an actuation height resulting from operation. In another embodiment, the spacer layer **18** is silicon oxide deposited by chemical vapor deposition. The total height of the actuation of the elongated-conductive reflective ribbon elements **23***a*–**23***d* is defined by the thickness of the spacer layer **18**.

Referring now to FIG. **7***b*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, etching of the channels **25** to form the intermediate supports **27** is illustrated. The patterning of the spacer layer **18** is carried out using standard photolithographic processing and etching methods to define the active region **8** where the channels **25** and intermediate supports **27** are located. The etching of the oxide spacer layer uses chemistry designed to stop on the silicon nitride standoff layer **16**. The standoff layer **16** is then patterned using photolithographic processing and etching methods to produce the standoffs **29**, as illustrated in FIG. **7***b*. The standoffs **29** act as mechanical stops for the actuation of the conformal grating device. The actuated elongated-conductive reflective ribbon elements **23***a*–**23***d* come into contact with the surface standoffs **29**.

Referring now to FIG. **7***c*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, the deposition of a sacrificial layer **19** is illustrated. To allow additional layers atop the existing structure, as shown in FIG. **7***c*, a conformal sacrificial layer **19** is deposited to a thickness greater than the sum of the thickness of the standoff layer **16** and the spacer layer **18**. The material for the sacrificial layer **19** is different from the spacer layer **18** and is selected from the group consisting of silicon oxide, silicon nitride, polysilicon, doped-polysilicon, silicon-germanium alloys, and polyimide. In one embodiment, the sacrificial layer **19** is polysilicon deposited by chemical vapor deposition.

Referring now to FIG. **7***d*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, the patterning of the sacrificial layer **19** is illustrated. The patterning of the sacrificial layer **19** is carried out using standard photolithographic processing and a mask which is the reverse of the mask used to etch the spacer layer **18** defining the active region **8** where the channels **25** and intermediate supports **27** are located. The mask can be biased to account for misalignment. The sacrificial layer **19** is then completely removed from the intermediate supports **27** and the areas outside of the active region **8**. The removal of the sacrificial layer **19** outside of the active region **8** improves the uniformity of the planarization step described below. The removal of the sacrificial layer **19** may be done prior to providing the ribbon layer **20**. This removal process ensures good mechanical attachment of the elongated-conductive reflective ribbon elements **23***a*–**23***d* to the intermediate supports **27** and the end supports **24***a* and **25***b* (not shown in FIG. **7***d*).

Referring now to FIG. **7***e*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, the planarization of the sacrificial layer **19** to a level substantially near the top surface of the intermediate supports **27** is illustrated. Chemical mechanical polishing methods are used to achieve the polished structure. The polished surface of sacrificial layer **19** filling the channels **25** is preferably polished to be optically coplanar with the top surface of the intermediate supports **27**. As is well known in the practice of optical engineering, this requires a surface planarity of less than about 200 Angstrom units at visible wavelengths.

Referring now to FIG. **7***f*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, deposition

of the ribbon layer **20** and of the reflective and conductive layer **22** to illustrate. The ribbon layer **20** is provided on top of the optically-coplanar sacrificial layer **19** and intermediate supports **27**, thereby also covering the entire active region **8** of the device. Silicon nitride is a well-suited material for the ribbon layer **20** and can be patterned to provide the needed mechanical structure. Its material properties are well suited for the application because of the intrinsic tensile stress easily controlled by the deposition process. In a preferred alternative embodiment titanium aluminide is used as the ribbon layer **20** material. Its material properties are well suited for the application because its intrinsic tensile stress is easily controlled by sputter deposition and annealing. Titanium aluminide is also electrically conducting. The reflective and conductive layer **22** deposited atop the ribbon layer **20** needs to have good electric conducting properties. The light reflecting properties of the reflective and conductive layer **22** improve the efficiency of diffraction so as to maximize the diffracted light and minimize loss of light by absorption. The material for the reflective and conductive layer **22** is selected from the group consisting of aluminum, titanium, gold, silver, tungsten, silicon alloys, and indium tin oxide.

Electrical contact to the bottom conductive layer can be made from the back side through the substrate **10** if the substrate is electrically conductive. Alternatively electrical contact can be made on the front side by photolithographically patterning areas outside the active region (not shown) and etching through the spacer layer **18**, standoff layer **16** and dielectric protective layer **14**.

The elongated-conductive reflective ribbon elements **23***a*–**23***d* are now patterned from the ribbon layer **20** and the reflective and conductive layer **22** using photolithographic processing and etching. This etching process defines the top-view geometry of the elongated-conductive reflective ribbon elements **23***a*–**23***d* shown in FIGS. **1** and **2**.

Referring now to FIG. **7***g*, which is a cross-sectional view along line **3,7,9,10—3,7,9,10** indicated in FIG. **2**, the removal of the sacrificial layer **19** from within the active region **8** to form channels **25** and intermediate supports **27** is illustrated. In one embodiment, the sacrificial layer **19** is polysilicon which can be selectively removed by dry etching methods using xenon difluoride to yield the cross-sectional view illustrated in FIG. **7***g*. The gas has access to the sacrificial layer **19** through the gaps **28** between the elongated-conductive reflective ribbon elements **23***a*–**23***d*. The removal of the sacrificial layer **19** is the final step needed to produce operational conformal grating devices **5***a*–**5***d*. The devices can now be actuated to operate as described earlier. After removal of the sacrificial layer **19**, the elongated-conductive reflective ribbon elements **23***a*–**23***d* remain optically coplanar providing the ribbon layer **20** is deposited with uniform thickness and uniform tensile stress.

An alternate embodiment of conformal grating devices is shown in FIG. **8**, which depicts a top view of a four-device linear array similar to FIG. **2**. Each of the conformal grating devices **5***a*, **5***b*, **5***c* and **5***d* now has an associated pair of subdivided elongated-conductive reflective ribbon elements (**51***a*, **52***a*), (**51***b*, **52***b*), (**51***c*, **52***c*) and (**51***d*, **52***d*), respectively. This subdivision of each device permits fabrication of wider devices without significantly impacting optical performance. The preferred method of fabrication is to etch a sacrificial layer from the channel, thus releasing the ribbon elements. The subdivided gaps **55** between the elements allow the etchant to access this sacrificial layer. Increasing the number of subdivided gaps **55** can therefore improve the etching process. In practice, it may be necessary to further subdivide the conformal grating devices into more than two. The conductive reflective ribbon elements are depicted partially removed over the portion of the diagram below the line A—A in order to show the underlying structure. For best optical performance and maximum contrast, the intermediate supports **27** must be completely hidden below the conductive reflective ribbon elements **51***a*, **52***a*, **51***b*, **52***b*, **51***c*, **52***c*, **51***d* and **52***d*. Therefore, when viewed from the top, the intermediate supports **27** must not penetrate into the subdivided gaps **55**. The ribbon elements within a single conformal grating device are mechanically isolated, but electrically coupled. They therefore operate in unison when a voltage is applied.

The conformal grating devices described in the above embodiments have intermediate supports attached to the conductive reflective ribbon elements. To obtain very high contrast, these supports must be completely hidden when the devices are not actuated and the ribbon elements must be completely flat. However, in practice, the fabrication causes some nonuniformity in the profile of the ribbon element just above the intermediate supports. The nonuniformity produces a weak grating reducing the contrast of the device. FIGS. **9***a* and **9***b* show an alternate embodiment that reduces this problem. The side view is the same as in FIGS. **3***a* and **3***b*. FIG. **9***a* depicts the two channels **25** between the three intermediate supports **27** of the device in the unactuated state. FIG. **9***b* shows the same view of the actuated state. In the unactuated state, with no voltage applied to the device, the ribbon element **23***b* is suspended flat above the intermediate supports **27** by the two end supports **24***a* and **24***b* (see FIG. **2**), leaving a small intermediate support gap **60** between the top of the intermediate supports **27** and the bottom of the ribbon element **23***b*. When a voltage is applied to actuate the device, the bottom of the ribbon element **23***b* makes contact with the top of the intermediate supports and a partially conforming grating is created. FIG. **9***b* shows the device in the fully actuated state with the conductive reflective ribbon element **23***b* also touching the standoffs **29**.

FIGS. **10***a*–**10***f* illustrate the fabrication sequence for making the conformal grating device with elongated-conductive reflective ribbon elements suspended above intermediate supports. These figures show the same view of the device as FIGS. **9***a* and **9***b*. The first few steps are the same as the process of FIGS. **7***a* and **7***b*. Referring to FIG. **10***a*, the device is built upon a substrate **10**, covered by the bottom conductive layer **12**, and a dielectric protective layer **14** on top of the bottom conductive layer **12**. To form the standoffs **29** and channels **25**, a standoff layer **16** is deposited followed by a spacer layer **18**.

FIG. **10***b* illustrates etching of the channels **25** to form the intermediate supports **27**. The patterning of the spacer layer **18** is carried out using standard photolithographic processing and etching methods to define the active region **8** where the channels **25** and intermediate supports **27** are located. The standoff layer **16** is then patterned using photolithographic processing and etching methods to produce the standoffs **29**, as illustrated in FIG. **10***b*.

In order to generate an intermediate support gap **60** with a desired height, the end supports **24***a* and **24***b* can be fabricated to be higher than the intermediate supports **27** (not shown in FIG. **10***b*). This step can be performed by depositing and patterning a support layer made, for example, of silicon nitride to increase the height of the end supports **24***a* and **24***b* relative to the intermediate supports.

FIG. **10***c* illustrates deposition of a conformal sacrificial layer **19** on top of the structure from FIG. **10***b*. In order to

ensure that the planarization step (FIG. **10***d*) leaves some sacrificial layer on top of the intermediate supports **27**, the thickness of the sacrificial layer must be substantially greater that the sum of the thickness of the standoff layer **16** and the thickness of the spacer layer **18**.

FIG. **10***d* illustrates planarization of the sacrificial layer **19** to a level above the top surface of the intermediate supports **27**. The sacrificial layer **19** needs to be substantially flat after planarization with some sacrificial material left above the intermediate supports **27** to prevent attachment of the elongated-conductive reflective ribbon element **23***b* to the intermediate supports **27**. Furthermore, in practice to improve the uniformity of planarization and ensure good attachment of the elongated-conductive reflective ribbon element **23***b* to the end supports **24***a* and **24***b*, it is preferable to pattern and remove the sacrificial layer **19** outside of the active region **8** (not shown in FIG. **10***d*).

FIG. **10***e* illustrates deposition of the ribbon layer **20** and of the reflective and conductive layer **22**. The ribbon layer **20** does not make contact with the top surface of the intermediate supports **27** because of the sacrificial material present in the intermediate support gap **60**. The elongated-conductive reflective ribbon elements **23***a*–**23***d* are now patterned from the ribbon layer **20** and the reflective and conductive layer **22** using photolithographic processing and etching. This etching process defines the top-view geometry of the elongated-conductive reflective ribbon elements **23***a*–**23***d* shown in FIG. **2**.

FIG. **10***f* illustrates removal of the sacrificial layer **19** from within the active region **8** to reveal channels **25** and intermediate supports **27**. This step also removes the sacrificial layer **19** from the intermediate support gap **60**, thereby suspending the elongated-conductive reflective ribbon element **27** above the top surface of the intermediate supports **27**. The elongated-conductive reflective ribbon element **23***b* is held in tension above the intermediate supports **27** by the two end supports **24***a* and **24***b* (not shown in FIG. **10***f*). The removal of the sacrificial layer **19** is the final step needed to produce operational devices.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

5*a* conformal grating device
5*b* conformal grating device
5*c* conformal grating device
5*d* conformal grating device
8 active region
10 substrate
12 bottom conductive layer
14 protective layer
16 standoff layer
18 spacer layer
19 sacrificial layer
20 ribbon layer
22 reflective and conductive layer
23*a* elongated-conductive reflective ribbon element
23*b* elongated-conductive reflective ribbon element
23*c* elongated-conductive reflective ribbon element
23*d* elongated-conductive reflective ribbon element
24*a* end support
24*b* end support
25 channel
27 intermediate support
28 gap
29 standoff
30 incident light beam
32 reflected light beam
35*a* $+1^{st}$ order beam
35*b* -1st order beam
36*a* $+2^{nd}$ order beam
36*b* -2nd order beam
51*a* subdivided elongated-conductive reflective ribbon element
51*b* elongated-conductive reflective ribbon element
51*c* subdivided elongated-conductive reflective ribbon element
51*d* subdivided elongated-conductive reflective ribbon element
52*a* subdivided elongated-conductive reflective ribbon element
52*b* subdivided elongated-conductive reflective ribbon element
52*c* subdivided elongated-conductive reflective ribbon element
52*d* subdivided elongated-conductive reflective ribbon element
55 subdivided gap
60 intermediate support gap

What is claimed is:

1. A method of manufacturing a conformal grating device, comprising the steps of:

a) forming a spacer layer on a substrate;

b) removing portions of the spacer layer to define an active region with at least two channels and at least one intermediate support, wherein the at least two channels and the at least one intermediate support define a grating period of the conformal grating device;

c) forming a sacrificial layer in the active region;

d) forming conductive reflective ribbon elements over the active region; and

e) removing the sacrificial layer from the active region.

2. The method claimed in claim **1**, wherein the sacrificial layer is formed by the steps of:

c1) depositing the sacrificial layer over the substrate;

c2) removing the sacrificial layer from the a top surface of the intermediate supports and areas outside of the active regions; and

c3) planarizing the sacrificial layer to be substantially optically coplanar with the spacer layer and the top surface of the intermediate support.

3. The method claimed in claim **2**, wherein the removal of the sacrificial layer from the active region leaves the conductive reflective ribbon elements attached to the top surface of the intermediate supports.

4. The method claimed in claim **2**, wherein the planarizing step is performed by chemical mechanical polishing.

5. The method claimed in claim **1**, further comprising the steps of:

forming a standoff layer on the substrate prior to forming the spacer layer; and patterning the standoff layer in the active region to define a plurality of standoffs between the intermediate supports.

6. The method claimed in claim **5**, wherein the removal of the sacrificial layer from the active region leaves the conductive reflective ribbon elements suspended above the intermediate supports.

7. The method claimed in claim **1**, wherein the conductive reflective ribbons elements are formed by the steps of:

d1) forming a ribbon layer over the substrate;

d2) forming a reflective conductive layer on the ribbon layer; and

d3) patterning the reflective conductive layer and the ribbon layer to form conductive reflective ribbon elements over the active regions.

8. The method claimed in claim **5**, wherein the step of forming a sacrificial layer in the active region leaves a portion of the sacrificial layer on a top surface of the intermediate support, and wherein the thickness of the sacrificial layer is substantially greater than a sum of the thickness of the spacer layer and the standoff layer.

9. The method claimed in claim **1**, further comprising the step of forming an electrically conductive layer on the substrate prior to forming the spacer layer, and providing a contact to the electrically conductive layer.

10. The method claimed in claim **1**, wherein the step of removing the sacrificial layer is performed by dry etching.

11. The method claimed in claim **1**, wherein the intermediate support is fabricated to be completely hidden below the elongated conductive reflective ribbon elements.

12. The method claimed in claim **1**, wherein the elongated conductive reflective ribbon elements are further subdivided.

13. The method claimed in claim **1**, wherein the step of providing the bottom electrically conductive layer comprises the step of utilizing ion implantation.

14. The method claimed in claim **1**, wherein the step of providing the bottom electrically conductive layer comprises the step of depositing a thin conductive film over the substrate.

15. The method claimed in claim **1**, wherein the conductive reflective ribbon layer elements are tensile.

16. The method claimed in claim **1**, wherein the sacrificial layer is deposited to be at least as thick as the spacer layer.

17. A method of manufacturing a conformal grating device, comprising the steps of:

a) forming a conductive layer on a substrate;

b) forming a standoff layer on the conductive layer;

c) forming a spacer layer on the standoff layer;

d) removing portions of the spacer layer to define an active region with at least two channels, leaving other portions of the spacer layer to define intermediate supports in the active region, wherein the at least two channels and the intermediate supports define a grating period of the conformal grating device;

e) patterning the standoff layer in the active region to form a plurality of standoffs;

f) depositing a sacrificial layer over the substrate;

g) removing the sacrificial layer from the a top surface of the intermediate supports and areas outside of the active region;

h) planarizing the sacrificial layer to a level substantially optically coplanar with the top surface of the intermediate supports;

i) forming a ribbon layer over the substrate;

j) forming a reflective conductive layer on the ribbon layer;

k) patterning the reflective conductive layer and the ribbon layer to form conductive reflective ribbon elements over the active region; and

l) removing the sacrificial layer from the active region.

18. The method claimed in claim **17**, wherein the sacrificial layer is completely removed from the top surface of the intermediate supports and the removal of the sacrificial layer from the active region leaves the conductive reflective ribbon elements attached to the top surface of the intermediate supports.

19. The method of claim **17**, wherein the substrate is selected from the group consisting of: glass, plastic, metal, and semiconductor material.

20. The method of claim **17**, wherein the substrate is a semiconductor and the conductive layer is formed by doping the semiconductor substrate.

21. The method of claim **17**, wherein the conductive layer is formed by depositing a thin conductive film over the substrate.

22. The method claimed in claim **17**, wherein the spacer layer is selected from the group consisting of: silicon oxide, silicon nitride, and polyimide.

23. The method claimed in claim **17**, wherein the sacrificial layer is selected from the group consisting of: silicon oxide, silicon nitride, polysilicon, doped-polysilicon, silicon-germanium alloys and polyimide.

24. The method claimed in claim **17**, wherein the reflective conductive layer is selected from the group consisting of: aluminum, titanium, gold, silver, tungsten, silicon alloys and indium tin oxide.

25. The method claimed in claim **17**, wherein the conductive layer is selected from the group consisting of: aluminum, titanium, gold, silver, tungsten, silicon alloys and indium tin oxide.

26. The method claimed in claim **17**, wherein the ribbon layer is selected from the group consisting of: silicon nitride, titanium aluminide, and titanium oxide.

27. A method of manufacturing a conformal grating device, comprising the steps of:

a) forming a conductive layer on a substrate;

b) forming a standoff layer on the conductive layer;

c) forming a spacer layer on the standoff layer;

d) removing portions of the spacer layer to define an active region with at least two channels, leaving other portions of the spacer layer to define intermediate supports in the active region, wherein the at least two channels and the intermediate supports define a grating period of the conformal grating device;

e) patterning the standoff layer in the channels to form a plurality of standoffs;

f) depositing a sacrificial layer over the substrate;

g) planarizing the sacrificial layer to a level above the a top surface of the intermediate supports;

h) forming a ribbon layer over the substrate;

i) forming a reflective conductive layer on the ribbon layer;

j) patterning the reflective conductive layer and the ribbon layer to form conductive reflective ribbon elements over the active region; and

k) removing the sacrificial layer from the active region.

28. The method claimed in claim **27**, wherein the planarizing step includes partial removal of the sacrificial layer from the top surface of the intermediate supports.

29. The method claimed in claim **27**, wherein the step of removing the sacrificial layer from the active region leaves the conductive reflective ribbon elements suspended above the intermediate supports.

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