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(54) **HYBRID ELECTROSTATIC ACTUATOR**

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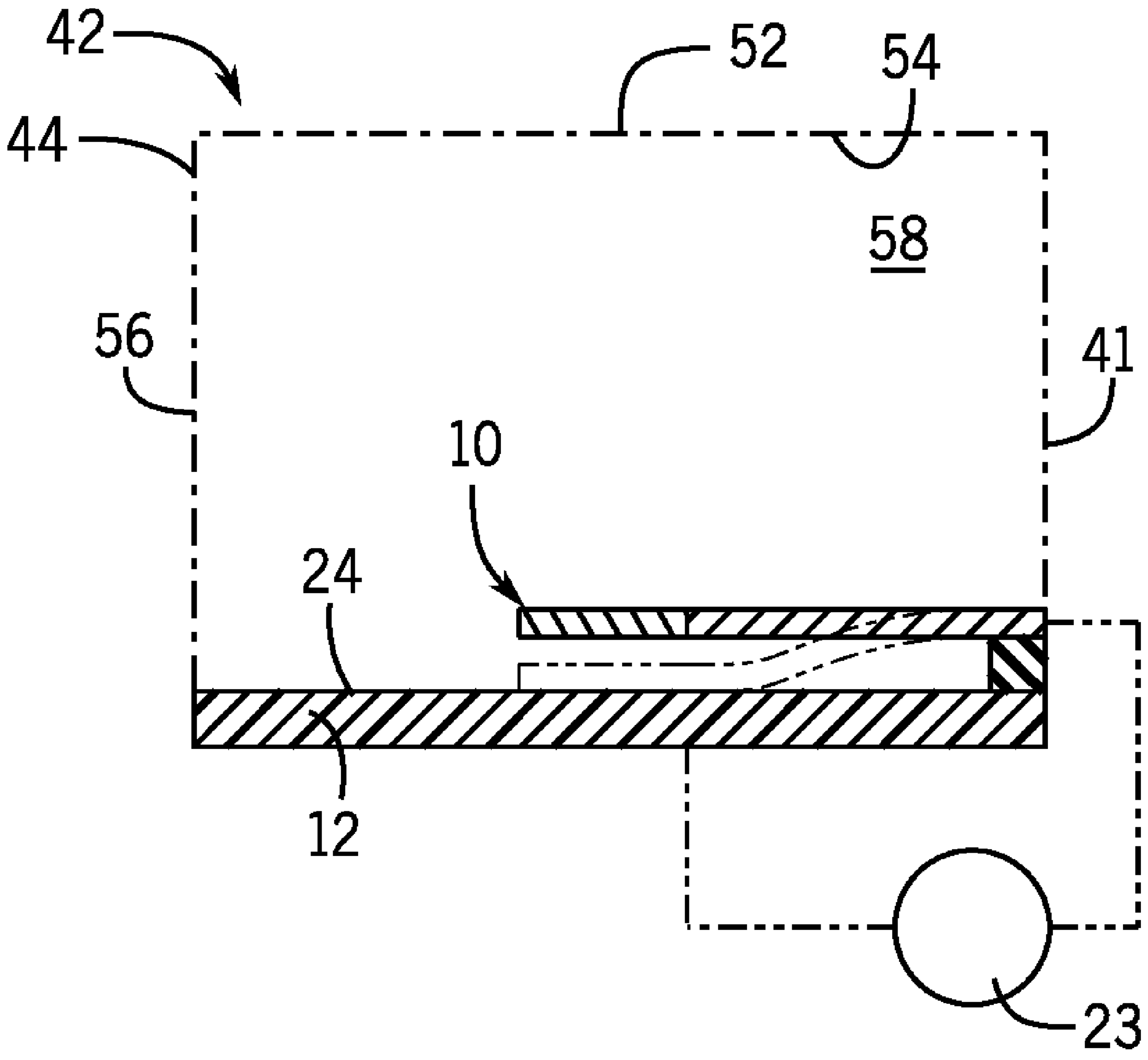
G02B 5/24	(2006.01)

(52) **U.S. Cl.**
CPC ***H02N 1/002*** (2013.01); ***G02B 5/24*** (2013.01); ***G02B 3/14*** (2013.01)

(57) **ABSTRACT**

A hybrid electrostatic actuator for use in conjunction with microfluidic devices, microlenses, optical irises and flat panel displays is provided. The hybrid electrostatic actuator includes a substrate having an upper surface and an electrical conductor supported in spaced relation to the substrate. A fluid is received between the substrate and the electrical conductor. An electrostatic generator is configured to selectively apply a variable electrostatic force on the electrical conductor. The application of the variable electrostatic force on the electrical conductor displaces the fluid from between the substrate and the electrical conductor.



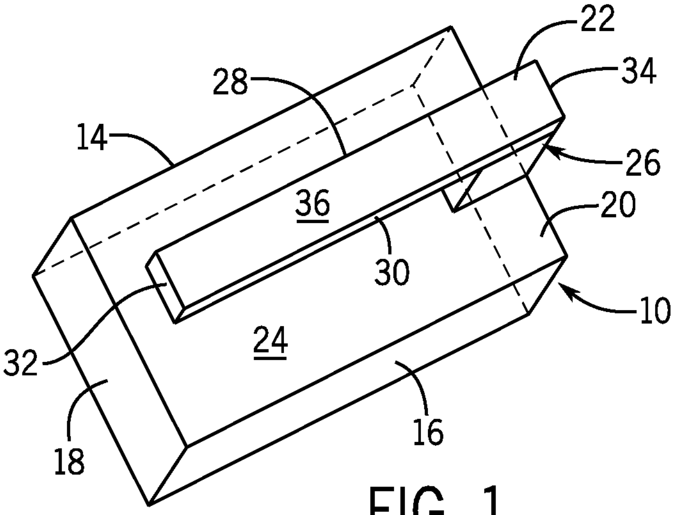


FIG. 1

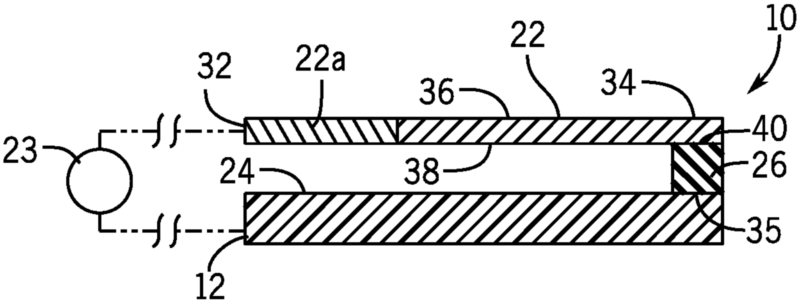


FIG. 2A

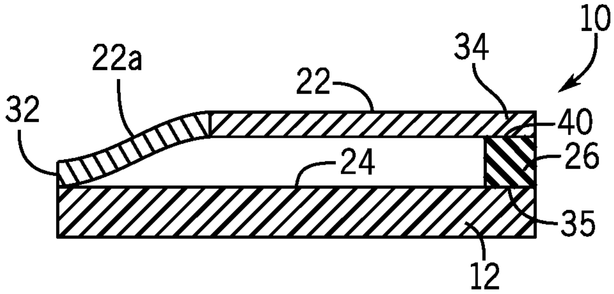


FIG. 2B

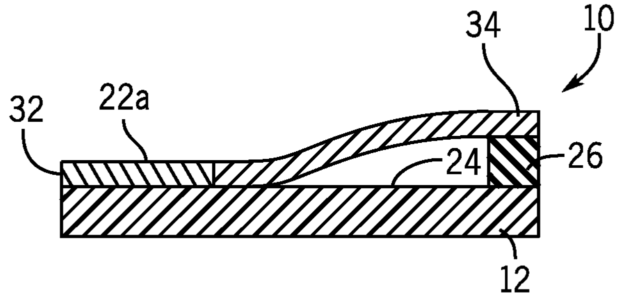


FIG. 2C

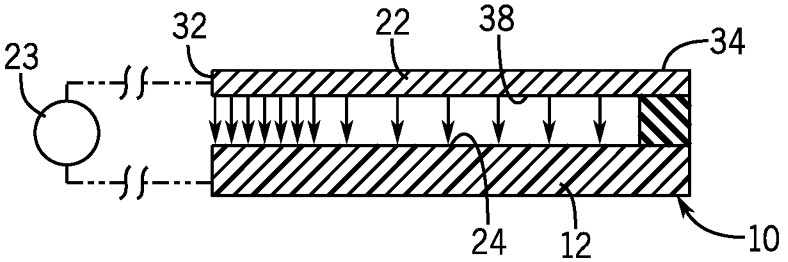


FIG. 3A

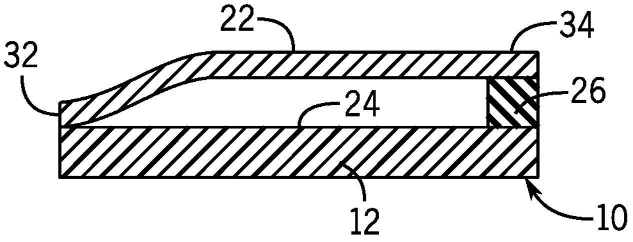


FIG. 3B

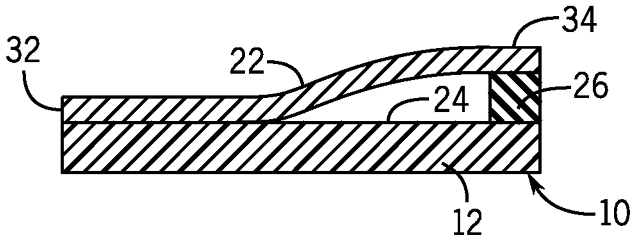


FIG. 3C

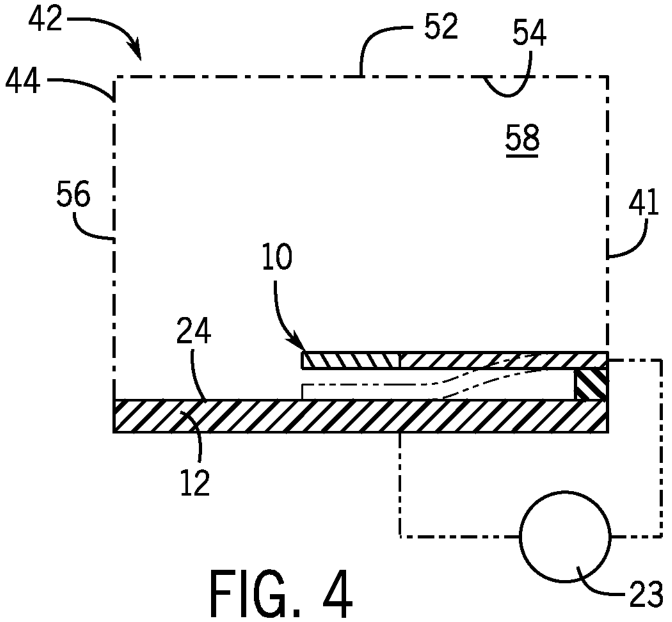


FIG. 4

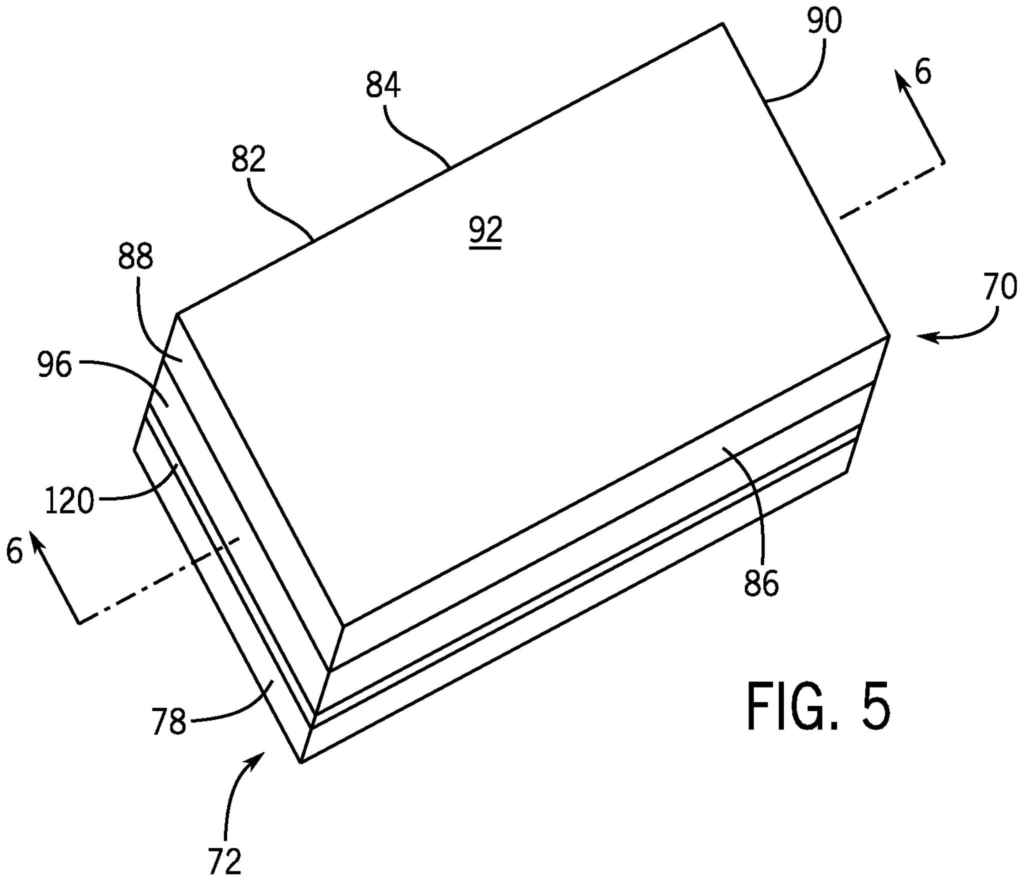


FIG. 5

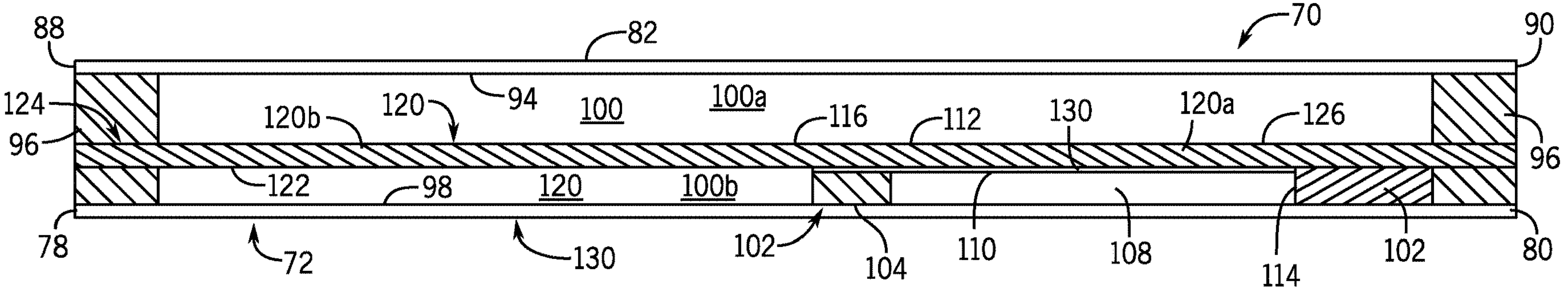

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FIG. 6

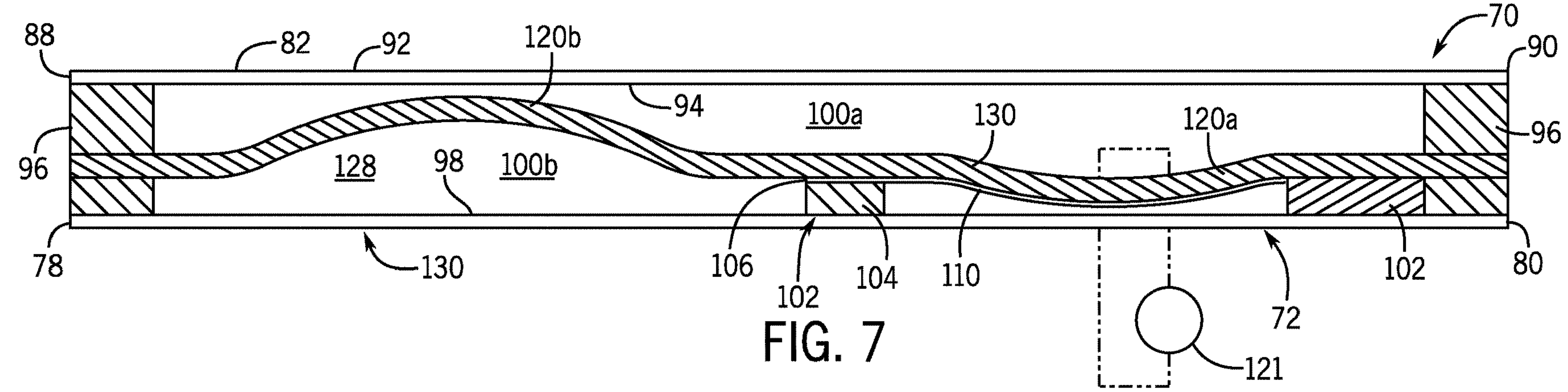
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FIG. 7

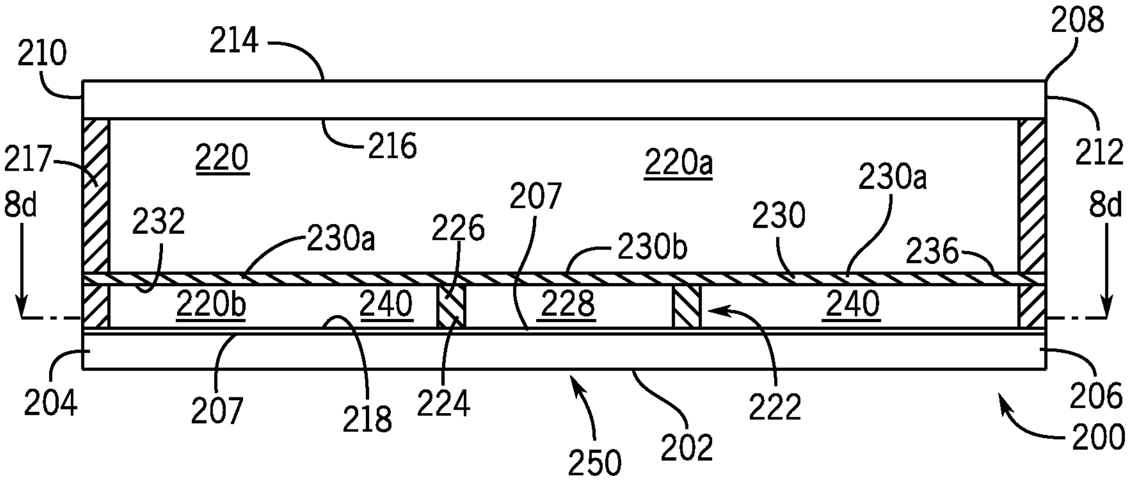

FIG. 8A

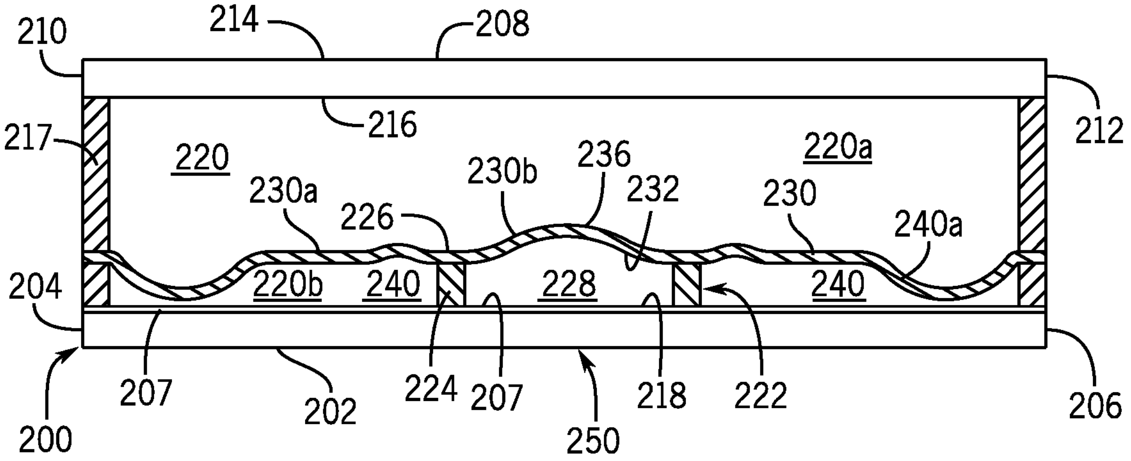

FIG. 8B

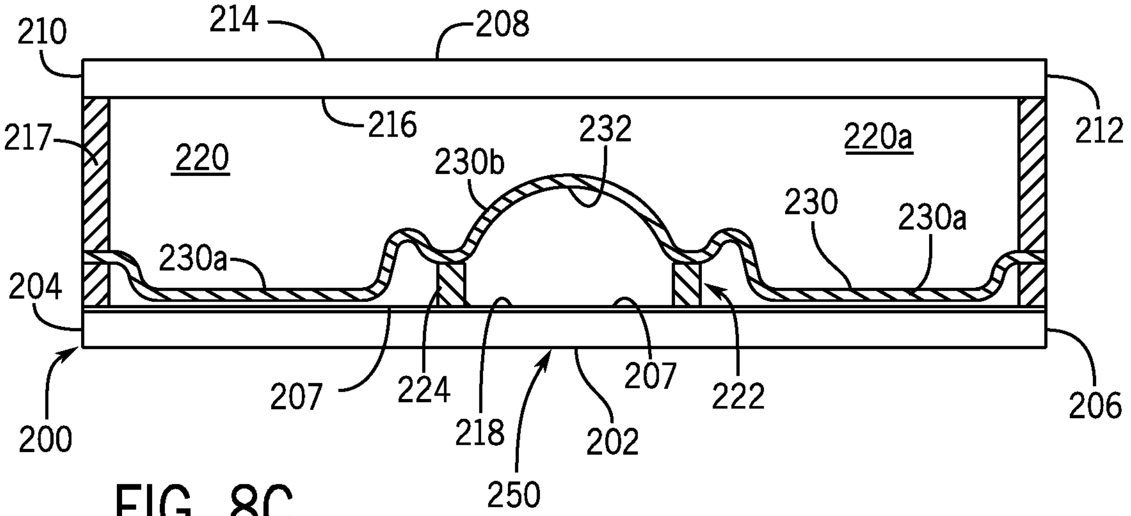

FIG. 8C

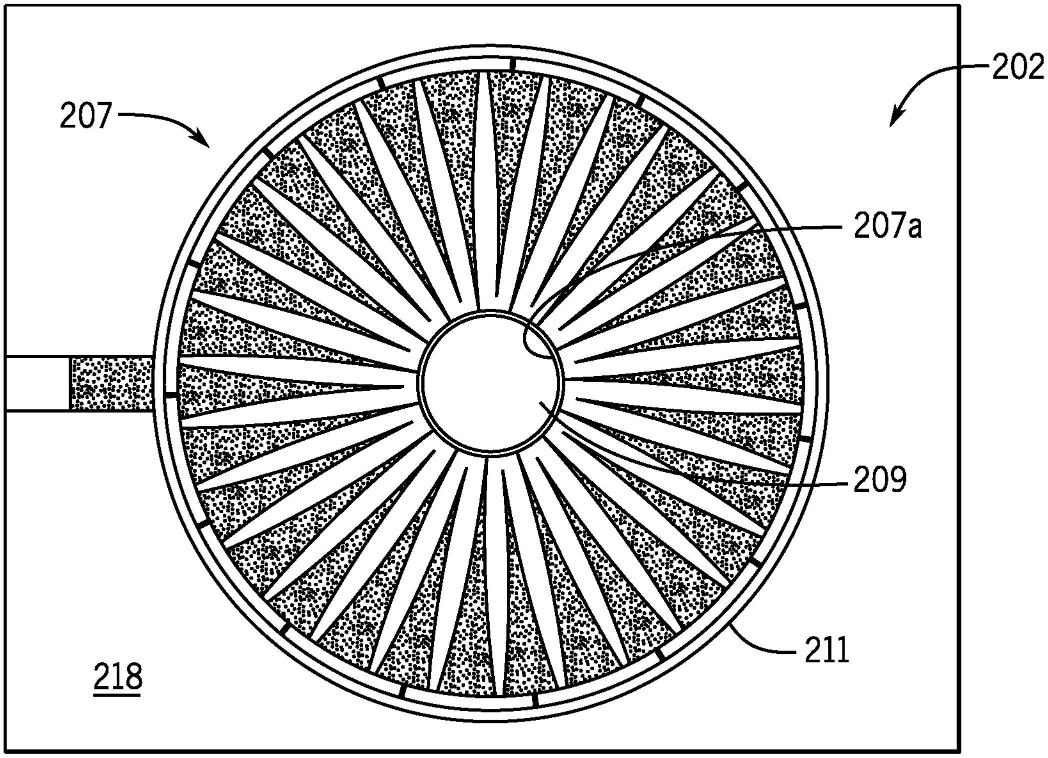

FIG. 8D

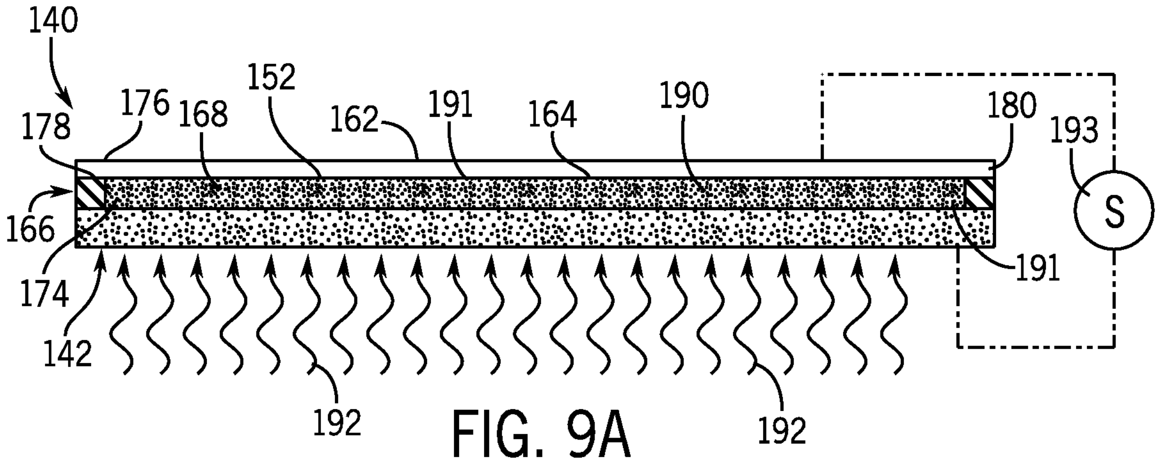

FIG. 9A

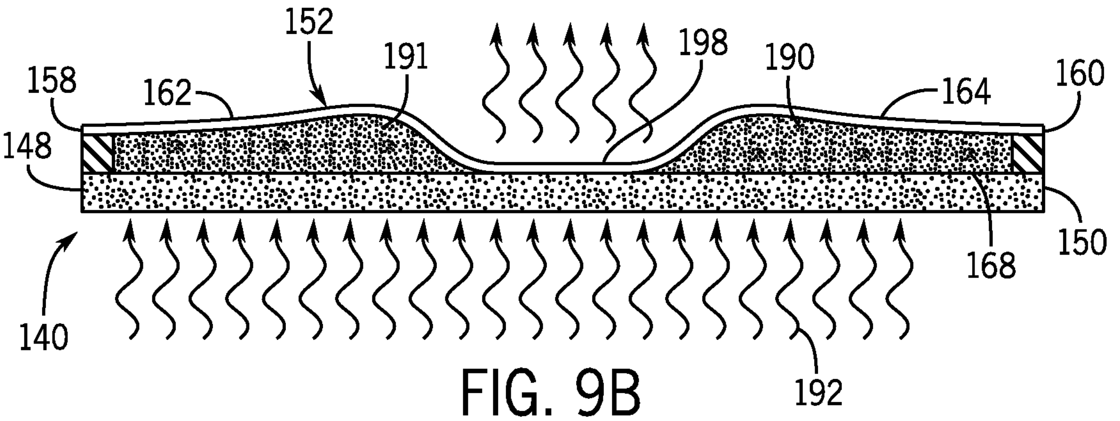

FIG. 9B

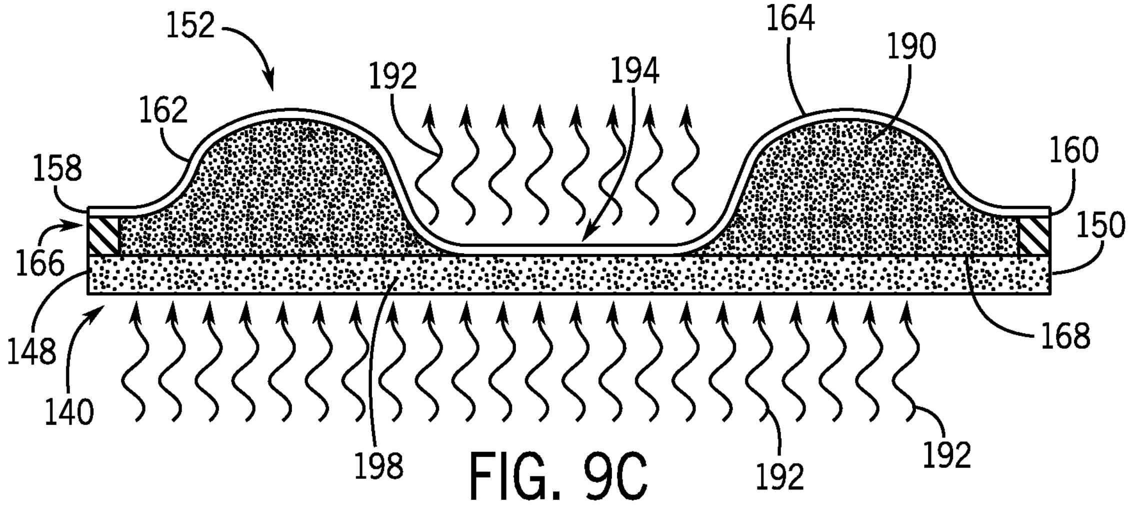

FIG. 9C

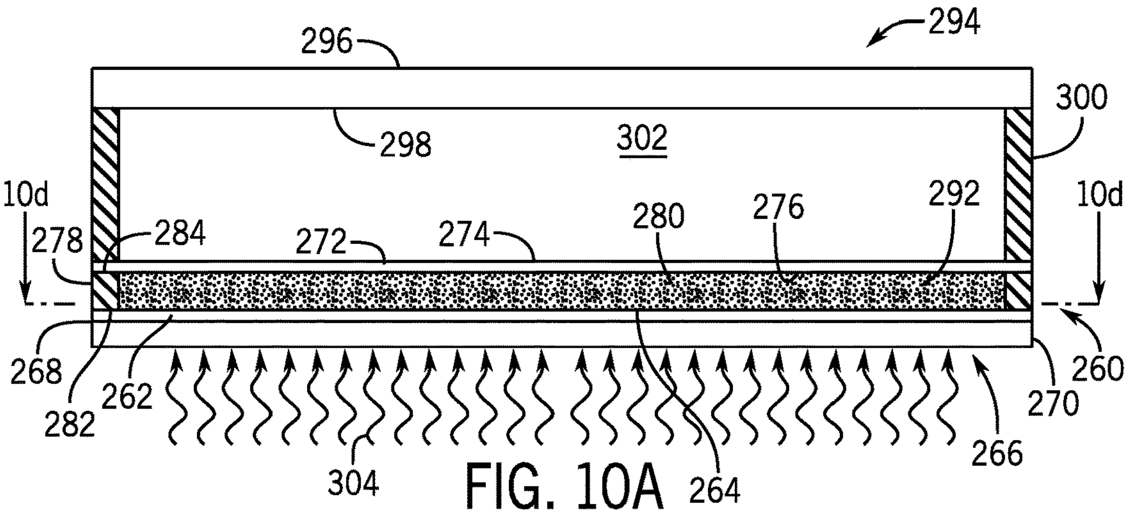

FIG. 10A

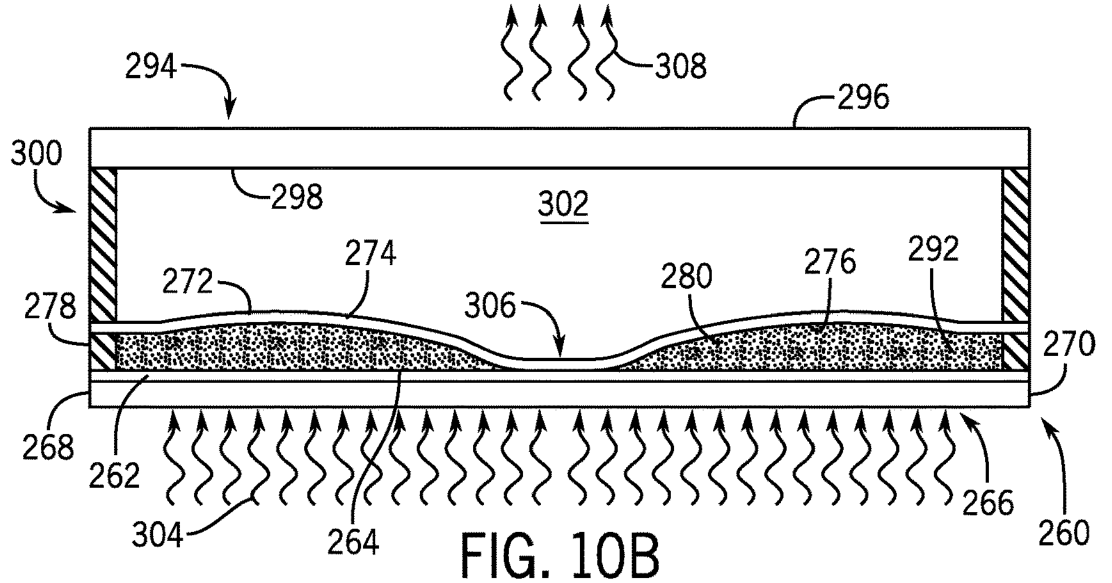

FIG. 10B

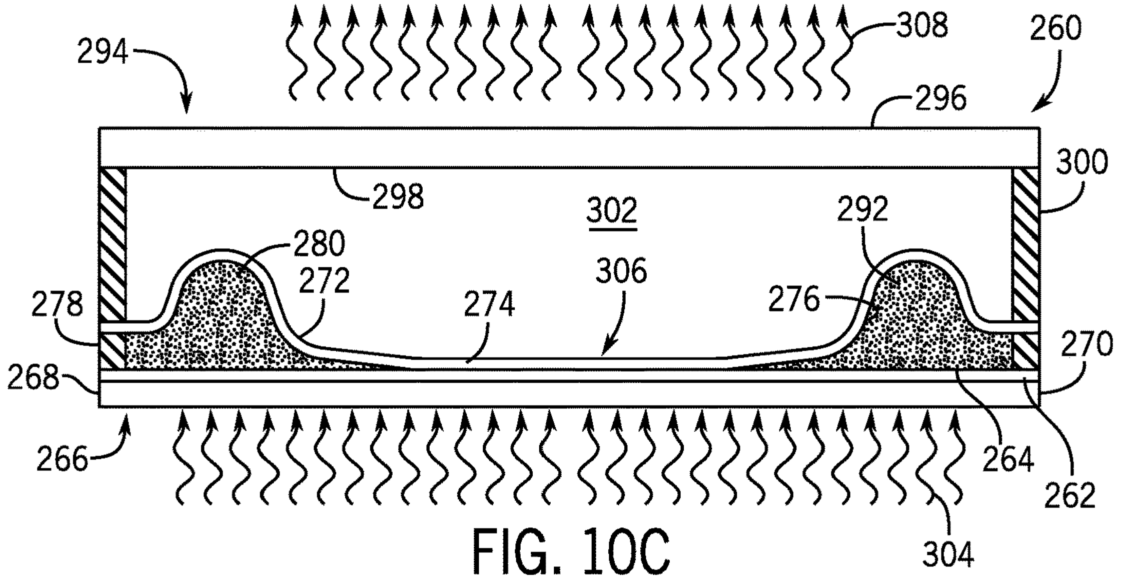

FIG. 10C

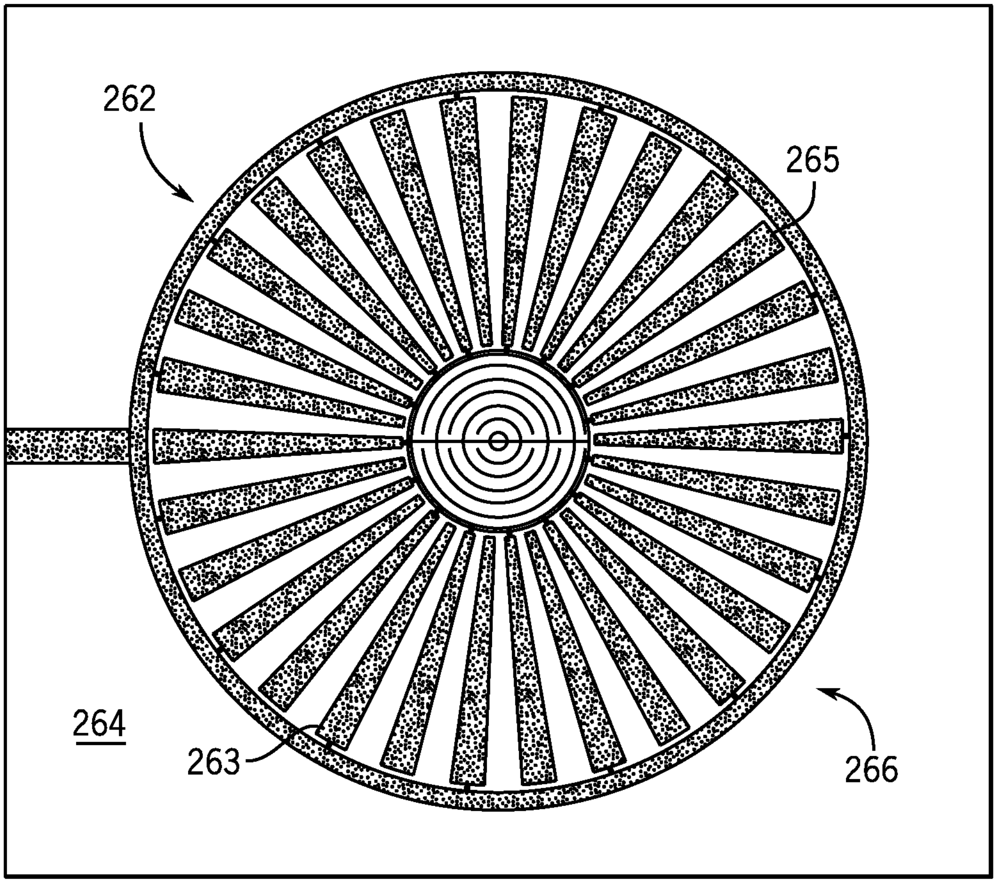

FIG. 10D

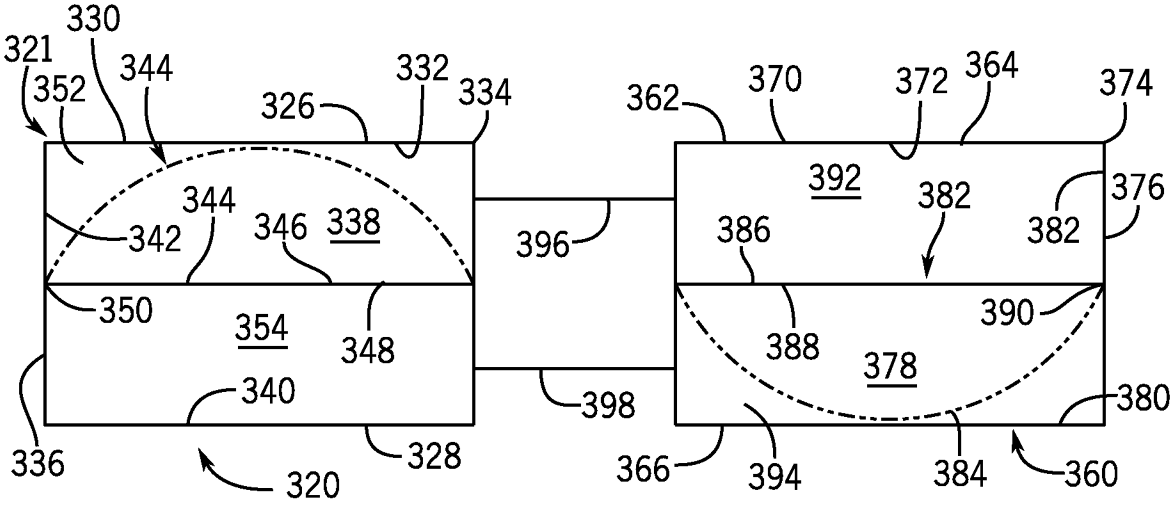

FIG. 11

HYBRID ELECTROSTATIC ACTUATOR

REFERENCE TO GOVERNMENT GRANT

[0001] This invention was made with government support under CNS1329481 awarded by the National Science Foundation and EB019460 awarded by the National Institutes of Health. The government has certain rights in the invention.

FIELD OF THE INVENTION

[0002] This invention relates generally to microfluidic devices, and in particular, to to hybrid electrostatic actuators for use in conjunction with microfluidic devices, microlenses, optical irises and flat panel displays.

BACKGROUND AND SUMMARY OF THE INVENTION

[0003] Micro-Electro-Mechanical System (MEMS) actuators are devices that convert electrical energy to mechanical motion. These actuators are used in a variety of optical, RF, and industrial applications, including as a focusing mechanism for a microlens. For example, in a liquid tunable microlens with a deformable membrane, a relatively large amount of liquid must be displaced into a lens chamber such that the reactive force of the deformable membrane exerts a relatively high pressure in the lens chamber. To drive a liquid tunable microlens, a parallel plate capacitive actuator may be used. A parallel plate capacitive actuator includes a single moving plate and a fixed plate (usually fixed to a substrate). When a voltage is applied to the capacitor, the moving plate is attracted to the fixed plate thereby displacing any liquid received therebetween. This "pull-in" of the moving plate happens as a result of an imbalance between the spring force of the actuator and the electrostatic force applied onto plates.

[0004] It is well known that in a simple parallel plate capacitive actuator, pull-in instabilities occur the voltage applied is above a certain threshold. This phenomenon, is inherent in the nature of the device, usually limits the practical displacement of liquid to 10% of the gap between the moving and fixed plates. Ideally, if one can manipulate these forces in a controlled way, it becomes possible to create a stable actuator that provides a large displacement and force.

[0005] Alternatively, it has been contemplated to utilize zipping actuators to generate a sufficiently large displacement and force in optofluidic devices. Zipping actuators utilize a bendable plate positioned opposite the fixed electrode. When electrified, one end of the bendable plate is pulled-in to the fixed electrode thereby creating a high force at the other end of the bendable plate. In prior art designs, however, the initial gap between electrodes is non-uniform, thereby making it impractical for mass production.

[0006] In view of the foregoing, there exists an ongoing need for a hybrid electrostatic actuator which is simple to manufacture like a parallel plate capacitive actuator, but that can provide both high pressure and large liquid displacement like a zipping actuator.

[0007] Therefore, it is a primary object and feature of a present invention to provide a hybrid electrostatic actuator that may be used in conjunction with microfluidic devices, microlenses, optical irises and flat panel displays.

[0008] It is a further object and feature of the present invention to provide a hybrid electrostatic actuator that can provide both high pressure and large liquid displacement.

[0009] It is still a further object and feature of the present invention to provide a hybrid electrostatic actuator that simple and inexpensive to fabricate.

[0010] In accordance with present invention, a hybrid electrostatic actuator is provided. The hybrid electrostatic actuator includes a substrate having an upper surface and an electrical conductor supported in spaced relation to the substrate. A fluid is received between the substrate and the electrical conductor. An electrostatic generator is configured to selectively apply a variable electrostatic force on the electrical conductor. The application of the variable electrostatic force on the electrostatic conductor displaces the fluid from between the substrate and the electrical conductor.

[0011] The electrical conductor may be an electrode having first and second ends and extending along an axis. The electrode has a length. An anchor interconnects the electrical conductor and substrate. The anchor supports the second end of electrode. Application of the variable electrostatic force to the electrode causes the first end of the electrode to pull-in towards the substrate. The electrode is configured to urge the fluid from the between the substrate and the electrode as the electrode is pulled in towards the substrate. The electrode may have a variable stiffness along the length thereof or the electrode may have a consistent stiffness along the length thereof.

[0012] The actuator may also include an enclosure defining a chamber for receiving the electrical conductor and fluid therein. The chamber may be connectable to a downstream device such that fluid displaced in respond to the application of the variable electrostatic force to the electrical conductor is urged into the downstream device. Alternatively, the enclosure may be defined by a compliant membrane such that fluid displaced in respond to the application of the variable electrostatic force to the electrical conductor deforms the compliant membrane.

[0013] In accordance with a further aspect of the present invention, a liquid tunable microlens assembly is provided. The liquid tunable microlens assembly includes an enclosure defined by first and second spaced transparent panels defining a cavity therebetween. A compliant membrane is received within the cavity and is deformable in response to an electrostatic force. The membrane divides the cavity into first and second fluid chambers and defines a microlens. A first fluid is received in the first fluid chamber and has a first refractive index. A second fluid is received in the second fluid chamber and has a second refractive index. The second refractive index is different from the first refractive index. An electrostatic generator is configured to generate a variable electrostatic force. The variable electrostatic force deforms the membrane and varies a focal length of the microlens in response to the magnitude of the variable electrostatic force.

[0014] The first transparent panel and the compliant membrane may electrically conductive. The electrostatic generator includes a voltage source operatively connected between the first transparent panel and the compliant membrane to generate a selected voltage thereacross. The application of the selected voltage between the first transparent panel and the compliant membrane generates the variable electrostatic force. The variable electrostatic force causes a first portion of compliant membrane to pull-in towards the first transparent panel and a second portion of the compliant membrane to deform so as to vary the focal length of the microlens.

[0015] The microlens assembly may also include a resilient support and an anchor. The resilient support is engageable with the compliant membrane. The resilient support is configured to resist deformation of the first portion of the compliant membrane in response to the variable electrostatic force. The anchor may interconnect the first and. second transparent panels and partially defining the cavity within the enclosure.

[0016] Alternatively, the electrostatic generator may include an electrode disposed in alignment with a first portion of the compliant member. The first fluid may be conductive such that the application of a selected voltage by the electrostatic generator between the electrode and the first fluid generates the variable electrostatic force. The variable electrostatic force causes the first portion of compliant membrane pull-in towards the electrode and the second portion of the compliant membrane deforms to vary the focal length of the microlens. The electrode may have a radially changing areal density.

[0017] In accordance with a still further aspect of the present invention, a light valve is provided. The light valve includes a transparent panel and a compliant membrane interconnected to the transparent panel and defining a cavity. The compliant membrane is deformable in response to an electrostatic force. A light absorbing dielectric fluid is received in the cavity. An electrostatic generator is configured to generate a variable electrostatic force on a portion of the compliant membrane. The variable electrostatic force displacing the light absorbing dielectric fluid from between the portion of the compliant membrane and the transparent panel.

[0018] The portion of the compliant membrane has a dimension. The dimension of the portion of the compliant membrane varies in response to a magnitude of the variable electrostatic force. The electrostatic generator may include a transparent electrode extending along the transparent panel. Alternatively, the transparent panel and the compliant membrane may be electrically conductive. The electrostatic generator includes a voltage source operatively connected between the transparent panel and the compliant membrane to generate a selected voltage thereacross. The application of the selected voltage between the transparent panel and the compliant membrane generates the variable electrostatic force. The variable electrostatic force causes a first portion of compliant membrane to pull-in towards the transparent panel and a second portion of the compliant membrane to deform.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The drawings furnished herewith illustrate a preferred methodology of the present invention in which the above advantages and features are clearly disclosed as well as others which will be readily understood from the following description of the illustrated embodiment.

[0020] In the drawings:

[0021] FIG. **1** is an isometric view of a hybrid actuator in accordance with the present invention;

[0022] FIG. **2***a* is a schematic, side elevational view of the hybrid actuator of the present invention in an initial, non-actuated configuration;

[0023] FIG. **2***b* is a schematic, side elevational view of the hybrid actuator of the present invention after initial actuation;

[0024] FIG. **2***c* is a schematic, side elevational view of the hybrid actuator of the present invention fully actuated;

[0025] FIG. **3***a* is a schematic, side elevational view of an alternate embodiment of the hybrid actuator of FIG. **1** in an intermediate actuation;

[0026] FIG. **3***b* is a schematic, side elevational view of the alternate embodiment of the hybrid actuator of the present invention after initial actuation;

[0027] FIG. **3***c* is a schematic, side elevational view of the alternate embodiment of the hybrid actuator of the present invention fully actuated;

[0028] FIG. **4** is a schematic view of the hybrid actuator of the present invention;

[0029] FIG. **5** is an isometric view of a liquid tunable microlens assembly incorporating a hybrid actuator in accordance with the present invention;

[0030] FIG. **6** is a cross-sectional view of the liquid tunable microlens assembly taken along line **6**-**6** of FIG. **5**;

[0031] FIG. **7** is a cross-sectional view of the liquid tunable microlens assembly of FIG. **6** showing actuation of the hybrid actuator incorporated therein;

[0032] FIG. **8***a* is a cross-sectional view of an alternate embodiment of a liquid tunable microlens assembly incorporating a hybrid actuator in accordance with the present invention;

[0033] FIG. **8***b* is a cross-sectional view of the liquid tunable microlens assembly of FIG. **8***a* showing initial actuation of the hybrid actuator incorporated therein;

[0034] FIG. **8***c* is a cross-sectional view of the liquid tunable microlens assembly of FIG. **8***a* showing full actuation of the hybrid actuator incorporated therein;

[0035] FIG. **8***d* is a cross-sectional view of the liquid tunable microlens assembly taken along line **8***d*-**8***d* of FIG. **8***a;*

[0036] FIG. **9***a* is a cross-sectional view of a light valve incorporating a hybrid actuator in accordance with the present invention;

[0037] FIG. **9***b* is a cross-sectional view of the light valve of FIG. **9***a* showing initial actuation of the hybrid actuator incorporated therein;

[0038] FIG. **9***c* is a cross-sectional view of the liquid tunable microlens assembly of FIG. **9***a* showing full actuation of the hybrid actuator incorporated therein;

[0039] FIG. **10***a* is a cross-sectional view of an alternate embodiment of a light valve incorporating a hybrid actuator in accordance with the present invention;

[0040] FIG. **10***b* is a cross-sectional view of the light valve of FIG. **10***a* showing initial actuation of the hybrid actuator incorporated therein;

[0041] FIG. **10***c* is a cross-sectional view of the light valve of FIG. **10***a* showing full actuation of the hybrid actuator incorporated therein;

[0042] FIG. **10***d* is a cross-sectional view of the light valve taken along line **10***d*-**10***d* of FIG. **10***a;* and

[0043] FIG. **11** is a schematic view of the hybrid actuator of the present invention incorporated into a first type of actuator operatively connected to a corresponding downstream device.

DETAILED DESCRIPTION OF THE DRAWINGS

[0044] Referring to FIG. **1**, a hybrid actuator in accordance with the present invention is generally designated by reference numeral **10**. Hybrid actuator **10** includes substrate **12** and is defined by first and second sides **14** and **16**, respectively, and first and second ends **18** and **20**, respectively. However, it can be appreciated that substrate **12** may have other configurations without deviating from the scope of the present invention.

[0045] Hybrid actuator **10** further includes electrode **22** supported above upper surface **24** of substrate **12** by anchor **26**. By way of example, electrode **22** may be defined by first and second sides **28** and **30**, respectively, and first and second ends **32** and **34**, respectively. However, it can be appreciated that electrode **22** may have other configurations without deviating from the scope of the present invention. As best seen in FIGS. **2***a*-**2***c* and **3***a*-**3***c,* electrode **22** includes upper surface **36** and lower surface **38** bonded to upper surface **40** of anchor **26** adjacent to second end **34** of electrode **22**. Lower surface **35** of anchor **26** is bonded to upper surface **24** of substrate **12** such that electrode **22** is cantilevered over upper surface **24** of substrate **12**.

[0046] It is contemplated for electrode **22** to fabricated from a homogeneous material, an alloy or be engineered to provide a varying stiffness as a function of location. For example, as best seen in FIGS. **2***a*-**2***c,* electrode **22** may be fabricated from two different materials with dissimilar young modulus or with layers of different materials having different thicknesses (not shown), or a combination of both.

[0047] Referring to FIG. **4**, hybrid actuator **10** may be received within an enclosure. Enclosure **41** includes cover **42** corresponding in size and shape to substrate **12**. More specifically, cover **42** includes upper surface **52** and lower surface **54**. The outer periphery **44** of cover **42** is sealably connected to substrate **12** by, for example, seal **56** so as to define a fluid chamber **58** between lower surface **54** of cover **42**, upper surface **24** of substrate, and seal **56**.

[0048] In operation, a fluid is provided in fluid chamber **58** of hybrid actuator **10**. A voltage is applied between electrode **22** and substrate **12** by source **23** such that an electrostatic force is induced on electrode **22**. In the event that electrode **22** is fabricated with varying stiffness as a function of location, the portion **22***a* of electrode **22** that is more compliant will tend to deform initially in response to the electrostatic force, FIG. **2***b*. After the electrostatic force exceeds a threshold, a pull-in of first end **32** of electrode **22** toward upper surface **24** of substrate **12** results. Thereafter, as the voltage is increased, electrode **22** behaves like a zipper, resulting in the electrostatic force causing a pull-in of electrode **22** toward upper surface **24** of substrate **12** from first end **32** to second end **34** thereof, FIG. **2***c*. It can be understood that movement of electrode **22** and/or the fluid urged from between electrode **22** and substrate **12** during the pull-in of electrode **22** may be used to actuate a desired downstream operation.

[0049] Referring to FIGS. **3***a*-**3***c,* in the event that electrode **22** is fabricated with a relatively consistent stiffness as a function of location, it is contemplated for the electrostatic force exerted on electrode **22** to be non-uniform. In other words, electrostatic forces of different intensities may be applied at a given time to various portions of electrode **22**. As a result, a pull-in will occur first at those portions of electrode **22** upon which the electrostatic forces with the greatest intensities are applied, FIG. **3***a*. For example, by increasing the electrostatic forces on electrode **22** from first end **32** to second end **34** thereof, electrode **22** will behave like a zipping actuator, thereby resulting in the pull-in of electrode **22** toward upper surface **24** of substrate **12** from first end **32** to second end **34** thereof, FIGS. **3***b*-**3***c*. The electrostatic force may varied by providing different voltages between electrode **22** and substrate **12** or by designing a certain electrode pattern on substrate **12** to create a force that varies as a function of location, hereinafter described. It can be understood that operation of hybrid actuator **10** may be utilized to actuate a downstream device (not shown) in a conventional manner.

[0050] Referring to FIG. **5**, a variation of hybrid actuator **10** may be incorporated into various devices such as a liquid tunable microlens assembly, generally designated by the reference numeral **70**. Microlens assembly **70** includes transparent substrate **72** and is defined by parallel, first and second sides interconnected by first and second ends **78** and **80**, respectively. As described, microlens assembly **70** has a generally rectangular, box-like configuration. However, it can be appreciated that microlens assembly **70** may have other configurations without deviating from the scope of the present invention.

[0051] Microlens assembly **70** further includes a transparent cover **82** corresponding in size and shape to substrate **72**. More specifically, cover **82** is defined by first and second sides **84** and **86** interconnected by first and second ends **88** and **90**, respectively. Referring to FIGS. **6**-**7**, cover **82** further includes upper surface **92** and lower surface **94**. Seal **96** is positioned adjacent the outer peripheries of substrate **72** and cover **82** and sealably bonds lower surface **94** of cover **82** to upper surface **98** of substrate **72** so as to define fluid chamber **100** between lower surface **94** of cover **82**, upper surface **98** of substrate **72** and seal **96**.

[0052] Microlens assembly **70** further includes anchor **102** received within fluid chamber **100**. Anchor **102** has a lower surface **104** bonded to upper surface **98** of substrate **72** and an upper surface **106**. By way of example, anchor **102** has a generally ring-like structure having a circular configuration defining actuation chamber **108**, however, other configurations are possible without deviating from the scope of the present invention. Elastic membrane **110** is supported above upper surface **98** of substrate **72** by anchor **102**. By way of example, lower surface **112** of elastic membrane **110** adjacent second end **116** thereof may be interconnected to anchor **102** such that first end **114** of elastic membrane **110** is cantilevered over actuation chamber **108**.

[0053] A hyperelastic membrane **120** is positioned within the interior of fluid chamber **100**. Membrane **120** is defined by a first portion **120***a* which is electrically conductive and a non-conductive second portion **120***b*. By way of example, first portion **120***a* may include a thin, conductive film deposited thereon or therein to render first portion **120***a* electrically conductive. Membrane **120** includes a lower surface **122** bonded to upper surface **130** of elastic membrane **110** adjacent to first portion **120***a,* and an outer periphery **124** bonded to seal **96**. Membrane **120** divides fluid chamber **100** into: 1) first fluid portion **100***a* defined by upper surface **126** of membrane **120** and lower surface **94** of cover **82** and being adapted for receiving a first fluid having a first refractive index and being an insulator therein; and 2) second fluid portion **100***b* defined by lower surface **122** of membrane **120** and upper surface **98** of substrate **72** and being adapted for receiving a second fluid having a second refractive index, different from the first refractive index, therein. Second fluid portion **100***b* of fluid chamber **100** includes actuation chamber **108** in communication with first portion **120***a* of membrane **120** and a lens portion **128** between seal **96** and anchor **102** in communication with second portion **120***b* of membrane **120**. Actuation chamber **108** is in fluid communication with lens portion **128** of second fluid portion **100***b* of fluid chamber **100**. First fluid in first fluid portion **100***a*, second fluid in lens portion **128** of second fluid portion **100***b* of fluid chamber **100**, second portion **120***b* of membrane **120** define microlens **130** having a focal length.

[0054] In operation, elastic membrane **110** urges first portion **120***a* of membrane **120** towards an initial configuration, FIG. **6**, wherein membrane **120** is generally planar and microlens **130** has an initial focal length. A voltage is applied by source **121** between substrate **72** and first portion **120***a* of membrane **120**, as heretofore described, so as generate an electrostatic force on first portion **120***a* of membrane **120**. Once the electrostatic force exceeds a threshold, a pull-in of the center of first portion **120***a* of membrane **120** toward upper surface **98** of substrate **72** results, FIG. **7**. Thereafter, by varying the electrostatic force between substrate **72** and first portion **120***a* of membrane **120**, e.g., by providing different voltages between substrate **72** and first portion **120***a* of membrane **120** or by designing a certain electrode pattern on substrate **12** to create a force that varies as a function of location, as hereinafter described, first portion **120***a* of membrane **120** behaves like a zipper, such that electrostatic force on first portion **120***a* of membrane **120** causes a pull-in of elastic membrane **110** toward upper surface **98** of substrate **72** radially outward from the center thereof toward anchor **102**.

[0055] As first portion **120***a* of membrane **120** is pulled towards upper surface **98** of substrate **72**, first portion **120***a* of membrane **120** urges the second fluid from actuation chamber **108** to lens portion **128** which, in turn, urges second portion **120***b* of membrane **120** toward lower surface **94** of cover **82**. It can be understood that the change of shape of second portion **120***b* of membrane **120** changes the focal length of microlens **130**. It is noted that by varying the electrostatic force on first portion **120***a* of membrane **120**, the size of the first portion **120***a* of membrane **120** pulled towards upper surface **98** of substrate **72** may be controlled. In such manner, the focal length of microlens **130** may be adjusted to a desired focal length.

[0056] Referring to FIGS. **8***a*-**8***d*, an alternate embodiment of a liquid tunable microlens assembly is generally designated by the reference numeral **200**. Microlens assembly **200** includes transparent substrate **202** having opposite first and second ends **204** and **206**, respectively, and an electrode **207** extending along upper surface **218** thereof. It is contemplated for microlens assembly **200** to have a generally square, box-like configuration. However, it can be appreciated that microlens assembly **200** may have other configurations without deviating from the scope of the present invention.

[0057] Referring to FIG. **8***d*, it is contemplated for electrode **207** to be a planar electrode having an inner edge **207***a* defining an opening **209** axially aligned with lens chamber **228**, hereinafter described. Electrode **207** further includes a plurality of electrically connected electrode sections **211** arranged in a circular pattern on upper surface **218** of substrate **202** and extending radially outward from inner edge **207***a*. It is intended for the areal density of electrode **207** to increase radially from inner edge **207***a* thereof, for reasons hereinafter described.

[0058] Microlens assembly **200** further includes a transparent cover **208** corresponding in size and shape to substrate **202**, including first and second ends **210** and **212**, respectively. Cover **208** further includes upper surface **214** and lower surface **216**. Seal **217** is positioned adjacent the outer peripheries of substrate **202** and cover **208** and interconnects/sealably bonds lower surface **216** of cover **208** to upper surface **218** of substrate **202**, so as to define fluid chamber **220** between lower surface **216** of cover **208**, upper surface **218** of substrate **202** and seal **217**.

[0059] Microlens assembly **200** further includes anchor **222** received within fluid chamber **220**. Anchor **222** has a lower surface **224** bonded to upper surface **218** of substrate **202** and an upper surface **226**. By way of example, anchor **222** has a generally ring-like structure having a circular configuration defining lens chamber **228**, however, other configurations are possible without deviating from the scope of the present invention. It is intended for anchor **222** to be porous to allow for the fluid to pass between lens chamber **228** and generally ring-shaped actuation chamber **240**, for reasons hereinafter described.

[0060] Hyperelastic membrane **230** is positioned within the interior of fluid chamber **220**. More specifically, membrane **230** includes a lower surface **232** bonded to upper surface **226** of anchor **222** and an outer periphery **235** interconnected/bonded to seal **217**. Membrane **230** divides fluid chamber **220** into: 1) first fluid portion **220***a* defined by upper surface **236** of membrane **230** and lower surface **216** of cover **208** and being adapted for receiving a first conductive fluid, e.g., salinized water, having a first refractive index therein; and 2) second fluid portion **220***b* defined by lower surface **232** of membrane **230** and upper surface **218** of substrate **202** and being adapted for receiving a second insulative fluid, e.g., transparent oil, having a second refractive index, different from the first refractive index, therein.

[0061] Second fluid portion **220***b* of fluid chamber **220** includes: 1) a generally ring-shaped actuation chamber **240** extending between seal **217** and outer surface **242** of anchor **222** and communicating with a first portion **230***a* of membrane **230**; and 2) lens chamber **228** defined within anchor **222** and communicating with a circular central, second portion **230***b* of membrane **230**. Actuation chambers **240** is in fluid communication with lens chamber **228** of second fluid portion **220***b* of fluid chamber **220**. First fluid in first fluid portion **220***a*, second fluid in lens chamber **228** of second fluid portion **220***b* of fluid chamber **220**, and second portion **230***b* of membrane **230** define microlens **250** having a focal length.

[0062] In operation, a voltage is applied by source (not shown) between electrode **207** and the first fluid, e.g., salinized water, in first fluid portion **220***a* so as generate an electrostatic force on first portion **230***a* of membrane **230** therebetween. Due to the increase in areal density of electrode **207** as electrode **207** extends radially outward from inner edge **207***a* thereof, the capacitance between electrode **207** and the first fluid increases as electrode **207** extends radially outward from inner edge **207***a* thereof. The increased capacitance between of electrode **207** and the first fluid as electrode **207** extends radially outward from inner edge **207***a* causes a greater electrostatic force on membrane **230** adjacent seal **217**. Once the electrostatic force exceeds a threshold, a pull-in of first portions **230***a* of membrane **230** adjacent seal **217** toward upper surface **218** of substrate **202** results, FIG. **9***b*. Thereafter, an increase in the voltage between electrode **207** and the first fluid will increase the electrostatic force between of electrode **207** and the first fluid as electrode **207** will increase the electrostatic force on membrane **230** causing first portion **230***a* of membrane **120** to behave like zippers. In other words, the electrostatic force on first portion **230***a* of membrane **230** causes a pull-in of first portion **230***a* of membrane **230** toward upper surface **218** of substrate **202** radially inward toward anchor **222** at the center of microlens assembly **200**, FIG. **9***c*.

[0063] As first portion **230***a* of membrane **230** is pulled toward upper surface **218** of substrate **202**, first portion **230***a* of membrane **230** urges the second fluid from first actuation chamber **240** into lens chamber **228** through porous anchor **222**, which, in turn, urges second portion **230***b* of membrane **230** toward lower surface **216** of cover **208**. It can be understood that the change of shape of second portion **230***b* of membrane **230** changes the focal length of microlens **250**. As such, by varying the magnitude and/or location of the voltage applied between electrode **207** and the first fluid, e.g., sanitized water, in first fluid portion **220***a,* the electrostatic forces on first portion **230***a* of membrane **230** may be varied, thereby controlling the amount of first portion **230***a* of membrane **230** that is pulled towards upper surface **218** of substrate **202**. In such manner, the focal length of microlens **250** may be adjusted to a desired focal length.

[0064] It is further contemplated to incorporate the structure of a hybrid actuator of the present invention into a light valve, generally designated by the reference numeral **140**, FIGS. **9***a*-**9***c*. Light valve **140** includes electrically conductive, transparent substrate **142** defined by first and second sides interconnected by first and second ends **148** and **150**, respectively. As described, light valve **140** has a generally rectangular, box-like configuration. However, it can be appreciated that light valve **140** may have other configurations without deviating from the scope of the present invention.

[0065] Light valve **140** further includes a transparent, compliant conductive membrane **152** corresponding in size and shape to substrate **142**. More specifically, membrane **152** is defined by first and second sides **154** and **156**, respectively, and first and second ends **158** and **160**, respectively. Membrane **152** further includes upper surface **162** and lower surface **164**. Anchor **166** is positioned adjacent the outer peripheries of substrate **142** and membrane **152** and bonds lower surface **164** of membrane **152** to upper surface **168** of substrate **142** so as to define fluid chamber **190** between lower surface **164** of membrane **152**, upper surface **162** of substrate **142** and anchor **166**. Fluid chamber **190** is adapted by receiving a light absorbing dielectric ink **191**, for reasons hereinafter described.

[0066] Anchor **166** is defined by lower surface **174** bonded to upper surface **168** of substrate **142** and upper surface **176** bonded to lower surface **164** of membrane **152**. By way of example, anchor **102** has a generally ring-like structure having rectangular configuration defined by first and second parallel end legs **178** and **180**, respectively, interconnected by first and second parallel side legs **182** and **184**, respectively, perpendicular thereto. It is noted that other configurations are possible without deviating from the scope of the present invention.

[0067] In operation, light rays **192** may be directed toward substrate **142** of light valve **140**. It can be understood that light absorbing dielectric ink **191** in fluid chamber **190** of light valve **140** blocks all light rays **192** incident on substrate **142** from passing therethrough, FIG. **9***a*. Thereafter, a voltage may be provided by a source (not shown) across membrane **152** and substrate **142** at a desired location such that the electrostatic force exerted on membrane **152** causes the pull-in of membrane **152** toward upper surface **168** of substrate **142** at the desired location, FIG. **9***b*. It is intended for the increase of the electrostatic field on membrane **152** at the desired location initiates the collapse of membrane **152** from the desired location, leading to a zipping actuation. More specifically, such that electrostatic force on membrane **152** at the desired location causes a pull-in of membrane **152** toward upper surface **168** of substrate **142** radially outward from the desired location thereof toward anchor **166**. As membrane **152** collapses onto upper surface **168** of substrate **142**, membrane **152** urges the light absorbing dielectric ink from the central portion of fluid chamber **190** toward anchor **166**. With membrane **152** collapsed onto upper surface **168** of substrate **142**, FIG. **9***c*, transparent area **194** is provided in light valve **140**. As such, a portion **196** of light rays **192** incident on central portion **198** of substrate **142** are allowed to pass through transparent area **194**. By varying the voltage provided across membrane **152** and substrate **142**, it can be appreciated that transparent area **194** may be varied to a desired dimension. Hence, as described, it can be appreciated that light valve **140** may act as a tunable optical valve.

[0068] Referring to FIGS. **10***a*-**10***c,* an alternate arrangement of a light valve incorporating a hybrid actuator is generally designated by the reference numeral **260**. Light valve **260** includes transparent electrode **262** extending along upper surface **264** of transparent substrate **266** between first and second ends **268** and **270**, respectively, thereof. More specifically, referring to FIG. **10***d*, it is contemplated for electrode **262** to be a planar electrode having a central portion **263** axially aligned with central portion **310** of substrate **266**, hereinafter described. Electrode **262** further includes a plurality of electrically connected electrode sections **265** arranged in a circular pattern on upper surface **264** of substrate **266** and extending radially outward from central portion **263**. It is intended for the areal density of electrode **262** to decrease radially from central portion **263**, for reasons hereinafter described. As described, light valve **260** has a generally rectangular, box-like configuration. However, it can be appreciated that light valve **260** may have other configurations without deviating from the scope of the present invention.

[0069] Light valve **260** further includes a transparent, compliant membrane **272** corresponding in size and shape to substrate **266**. Membrane **272** further includes upper surface **274** and lower surface **276**. Anchor **278** is positioned adjacent the outer peripheries of substrate **266** and membrane **272** and bonds lower surface **276** of membrane **272** to upper surface **264** of substrate **266** so as to define first fluid chamber **280** between lower surface **276** of membrane **272**, upper surface **264** of substrate **266** and anchor **278**. First fluid chamber **280** is adapted by receiving a light absorbing dielectric ink **292**, for reasons hereinafter described. More specifically, anchor **278** includes lower surface **282** bonded to upper surface **264** of substrate **266** and upper surface **284** bonded to lower surface **276** of membrane **272**. By way of example, anchor **278** has a generally ring-like structure having rectangular configuration, but other configurations are possible without deviating from the scope of the present invention.

[0070] Light valve **260** further includes a transparent cover **294** corresponding in size and shape to substrate **266**. Cover **294** is defined by upper surface **296** and lower surface

298. Seal **300** is positioned adjacent the outer periphery of cover **294** and interconnects/sealably bonds lower surface **298** of cover **294** to upper surface **274** of membrane **272** so as to define second fluid chamber **302** between lower surface **298** of cover **294**, upper surface **274** of membrane **272** and seal **300**. Second fluid chamber **302** is adapted by receiving a transparent conductive fluid, such as salinized water, therein, for reasons hereinafter described.

[0071] In operation, light rays **304** may be directed toward substrate **266** of light valve **260**. It can be understood that light absorbing dielectric ink **292** in first fluid chamber **280** of light valve **260** blocks all light rays **304** incident on substrate **265** from passing therethrough, FIG. **10***a*. Thereafter, a voltage is applied by source (not shown) between electrode **262** and the fluid, e.g., salinized water, in second fluid chamber portion **302** such that an electrostatic force is exerted at a desired location on membrane **272**, e.g., the portion of membrane **272** axially aligned with the center of electrode **262**, causes the pull-in of membrane **272** toward upper surface **264** of substrate **256** at the desired location, FIG. **10***b*. It is intended for the increase of the electrostatic force on membrane **272**, e.g. by increase the voltage across electrode **262** and the fluid in second fluid chamber portion **302**, so as to initiate the collapse of membrane **272** from the desired location radially outward, leading to a zipping actuation. More specifically, electrostatic force on membrane **272** at the desired location causes a pull-in of membrane **272** toward upper surface **264** of substrate **266** radially outward toward anchor **278**. As membrane **272** collapses onto upper surface **264** of substrate **266**, membrane **272** urges the light absorbing dielectric ink from the central portion of first fluid chamber **280** toward anchor **278**. With membrane **272** collapsed onto upper surface **264** of substrate **266**, FIG. **10***c*, transparent area **306** is provided in light valve **260**. As such, a portion **308** of light rays **304** incident on central portion **310** of substrate **266** are allowed to pass through transparent area **306**. By varying the location and/or magnitude of the voltage applied to between electrode **262** and the conductive fluid, e.g., salinized water, in second fluid chamber **302**, and hence, the electrostatic force on membrane **272**, it can be appreciated that transparent area **306** may be varied to a desired dimension. In such manner, it can be appreciated that light valve **260** may be used as a tunable optical valve.

[0072] Referring to FIG. **11**, it can be understood that the various embodiments of the hybrid actuator disclosed herein may be utilized to actuate a downstream device **320**. Device **320** includes enclosure **321** having cover **326** corresponding in size and shape to substrate **328**. Cover **326** includes upper surface **330** and lower surface **332**. The outer periphery **334** of cover **326** sealably connected to substrate **328** by, for example, sidewall **336** so as to define a chamber **338** between lower surface **332** of cover **326**, upper surface **340** of substrate **328**, and inner surface **342** of sidewall **336**.

[0073] Device **320** further includes a compliant membrane **344** corresponding in size and shape to substrate **328**. More specifically, membrane **344** includes upper surface **346**, lower surface **348** and outer periphery **350** sealably connected to inner surface **342** of sidewall **336**. Membrane **344** divides chamber **338** into 1) first fluid portion **352** defined by upper surface **346** of membrane **344** and lower surface **332** of cover **326** and adapted for receiving a first fluid therein; and 2) second fluid portion **354** defined by lower surface **348** of membrane **344** and upper surface **340** of substrate **328** and adapted for receiving a second fluid therein.

[0074] Actuator **360** includes enclosure **362** having cover **364** corresponding in size and shape to conductive substrate **366**. Cover **364** includes upper surface **370** and lower surface **372**. The outer periphery **374** of cover **364** is sealably connected to substrate **366** by, for example, sidewall **376** so as to define a chamber **378** between lower surface **372** of cover **364**, upper surface **380** of substrate **366**, and inner surface **382** of sidewall **376**.

[0075] Actuator **360** further includes an electrically conductive, compliant membrane **384** corresponding in size and shape to substrate **366**. More specifically, membrane **384** includes upper surface **386**, lower surface **388** and outer periphery **390** sealably connected to inner surface **382** of sidewall **366**. Membrane **384** divides chamber **378** into 1) first fluid portion **392** defined by upper surface **386** of membrane **384** and lower surface **372** of cover **364** and adapted for receiving a first fluid therein; and 2) second fluid portion **394** defined by lower surface **388** of membrane **384** and upper surface **380** of substrate **366** and adapted for receiving a second fluid therein. First fluid portion **392** of chamber **378** of actuator **360** is fluidically connected to first fluid portion **352** of chamber **338** of device **320** by line **396**. Similarly, second fluid portion **394** of chamber **378** of actuator **360** is fluidically connected to second fluid portion **354** of chamber **338** of device **320** by line **398**.

[0076] In operation, a voltage may be provided by a source (not shown) across membrane **384** and substrate **366** of actuator **360** at a desired location such that the electrostatic force exerted on membrane **384** causes the central portion of membrane **384** toward upper surface **380** of substrate **366** (shown in phantom in FIG. **11**). It is intended for the increase of the electrostatic field on membrane **384** at the desired location initiates the collapse of membrane **384** radially outward from the central portion thereof, leading to a zipping actuation. As membrane **384** of actuator **360** collapses onto upper surface **380** of substrate **366**, membrane **384** urges second fluid from second fluid portion **394** of chamber **378** of actuator **360** into second fluid portion **354** of chamber **338** of device **320** through line **398**.

[0077] As second fluid flows into second fluid portion **354** of chamber **338** of device **320**, it can be appreciated that the second fluid will exert a force on membrane **344** of device **320**, thereby causing membrane **344** to deform (shown in phantom in FIG. **11**). It can be understood that the force associated with the deformation of membrane **344** may be used by device **320** to actuate a desired operation. As the second fluid in second fluid portion **354** of chamber **338** of device **320** causes membrane **344** to deform, membrane **344** urges the first fluid in first fluid portion **352** of chamber **338** of device **320** into first fluid portion **392** of chamber **378** of actuator **360** through line **396**, thereby reducing the fluidic pressure in first fluid portion **352** of chamber **338** of device **320**.

[0078] Upon termination of the voltage provided by the source (not shown) across membrane **384** and substrate **366** of actuator **360**, membrane **384** of actuator **360** returns to its initial configuration thereby urging the first fluid from first fluid portion **392** of chamber **378** of actuator **360** into first fluid portion **352** of chamber **338** of device **320** through line **396**. Similarly, with the fluidic pressure in second fluid portion **394** of chamber **378** of actuator **360** reduced, membrane **344** of device **320** returns to its initial configuration thereby urging the second fluid from second fluid portion **352** of chamber **338** of device **320** into second fluid portion **394** of chamber **378** of actuator **360** through line **398**, such that device **320** and actuator **360** return to their initial configuration.

[0079] It is noted that any and all of the various actuators described above may be incorporated into the liquid tunable microlens and/or the light valves described herein. By way of example, it is contemplated replace the conductive substrates with a standard planar electrode or an electrode with a varying areal density deposited on the upper surface of a substrate in the various embodiments heretofore described. Further, it can be appreciated that a conductive fluid may be utilized instead of conductive first portion **120***a* of membrane **120** in microlens assembly **70**. Likewise, a partially conductive membrane may replace the conductive fluid in first fluid portion **220***a* of fluid chamber **220** in microlens assembly **200** and a partially conductive membrane may replace the conductive fluid in second fluid chamber **302** in light valve **360**. Hence, it can be understood that other variations are possible without deviating from the scope of the present invention.

[0080] Various modes of carrying out the invention are contemplated as being within the scope of the following claims particularly pointing out and distinctly claiming the subject matter that is regarded as the invention.

We claim:

1. A hybrid electrostatic actuator, comprising:

a substrate having an upper surface;

an electrical conductor supported in spaced relation to the substrate;

a fluid received between the substrate and the electrical conductor; and

an electrostatic generator configured to selectively apply a variable electrostatic force on the electrical conductor;

wherein application of the variable electrostatic force on the electrical conductor displaces the fluid from between the substrate and the electrical conductor.

2. The actuator of claim **1** wherein the electrical conductor is an electrode having first and second ends and extending along an axis, the electrode having a length.

3. The actuator of claim **2** further comprising an anchor interconnecting the electrical conductor and substrate, the anchor supporting the second end of electrode.

4. The actuator of claim **3** wherein application of the variable electrostatic force to the electrode causes the first end of the electrode to pull-in towards the substrate.

5. The actuator of claim **3** wherein the electrode is configured to urge the fluid from the between the substrate and the electrode as the electrode is pulled in towards the substrate.

6. The actuator of claim **2** wherein the electrode having a variable stiffness along the length thereof.

7. The actuator of claim **2** wherein the electrode has a consistent stiffness along the length thereof.

8. The actuator of claim **1** further comprising an enclosure defining a chamber for receiving the electrical conductor and fluid therein, the chamber being connectable to a downstream device such that fluid displaced in respond to the application of the variable electrostatic force to the electrical conductor is urged into the downstream device.

9. The actuator of claim **1** further comprising an enclosure defining a chamber for receiving the electrical conductor and fluid therein, the enclosure including a compliant membrane, wherein fluid displaced in respond to the application of the variable electrostatic force to the electrical conductor deforms the compliant membrane.

10. A liquid tunable microlens assembly, comprising:

an enclosure defined by first and second spaced transparent panels defining a cavity therebetween;

a compliant membrane received within the cavity and being deformable in response to an electrostatic force, the membrane dividing the cavity into first and second fluid chambers and defining a microlens;

a first fluid received in the first fluid chamber and having a first refractive index;

a second fluid received in the second fluid chamber and having a second refractive index, the second refractive index being different from the first refractive index; and

an electrostatic generator configured to generate a variable electrostatic force, the variable electrostatic force deforming the membrane and varying a focal length of the microlens in response to the magnitude of the variable electrostatic force.

11. The microlens assembly of claim **10** wherein:

the first transparent panel and the compliant membrane are electrically conductive;

the electrostatic generator includes a voltage source operatively connected between the first transparent panel and the compliant membrane to generate a selected voltage thereacross; and

the application of the selected voltage between the first transparent panel and the compliant membrane generates the variable electrostatic force, the variable electrostatic force causing a first portion of compliant membrane to pull-in towards the first transparent panel and a second portion of the compliant membrane to deform so as to vary the focal length of the microlens.

12. The microlens assembly of claim **11** further comprising a resilient support engageable with the compliant membrane, the resilient support configured to resist deformation of the first portion of the compliant membrane in response to the variable electrostatic force.

13. The microlens assembly of claim **10** wherein:

the electrostatic generator includes an electrode disposed in alignment with a first portion of the compliant member;

the first fluid is conductive; and

the application of a selected voltage by the electrostatic generator between the electrode and the first fluid generates the variable electrostatic force, the variable electrostatic force causes the first portion of compliant membrane pull-in towards the electrode and the second portion of the compliant membrane deforms to vary the focal length of the microlens.

14. The microlens assembly of claim **13** wherein the electrode has radially changing areal density.

15. The microlens assembly of claim **10** further comprising an anchor interconnecting the first and second transparent panels and partially defining the cavity within the enclosure.

16. A light valve, comprising:

a transparent panel;

a compliant membrane interconnected to the transparent panel and defining a cavity, the compliant membrane being deformable in response to an electrostatic force;

a light absorbing dielectric fluid received in the cavity; and

an electrostatic generator configured to generate a variable electrostatic force on a portion of the compliant membrane, the variable electrostatic force displacing the light absorbing dielectric fluid from between the portion of the compliant membrane and the transparent panel.

17. The light valve of claim **16** wherein the portion of the compliant membrane has a dimension, the dimension of the portion of the compliant membrane varying in response to a magnitude of the variable electrostatic force.

18. The light valve of claim **16** wherein the electrostatic generator includes an electrode extending along the transparent panel, the electrode being transparent.

19. The light valve of claim **16** further wherein the transparent panel is electrically conductive.

20. The light valve of claim **15** wherein:

the transparent panel and the compliant membrane are electrically conductive;

the electrostatic generator includes a voltage source operatively connected between the transparent panel and the compliant membrane to generate a selected voltage thereacross; and

the application of the selected voltage between the transparent panel and the compliant membrane generates the variable electrostatic force, the variable electrostatic force causing a first portion of compliant membrane to pull-in towards the transparent panel and a second portion of the compliant membrane to deform.

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