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Microelectromechanical actuator on insulating substrate

Abstract

The present disclosure relates to an apparatus, system, and method for a microelectromechanical (MEM) device formed on a transparent, insulating substrate. The MEM device may take the form of an electrostatic comb actuator. The fabrication process employs three-dimensional structuring of the substrate to form the actuator combs, biasing elements, and linkages. The combs and other elements of the actuator may be rendered electrically conducting by a conformal conductive coating. The conductive coating may be segmented into a plurality of electrodes without the use of standard lithography techniques. A linear-rotational actuator is provided, which may comprise two perpendicularly-arranged, linear actuators that utilize moveable linkage beams in two orthogonal dimensions. A linear or torsional ratcheting actuator is also provided by using comb actuators in conjunction with a ratcheting wheel or cog. Furthermore, several methods for electrically connecting non-contiguous or enclosed elements are provided.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATION (1) This application is a divisional of, claims priority to and the benefit of, co-pending U.S. Non-Provisional patent application Ser. No. 17/503,470, filed Oct. 18, 2023, entitled “Microelectromechanical Actuator On Insulating Substrate”, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD
(1) The present disclosure generally relates to an apparatus, system, and methods of fabrication for a microelectromechanical actuator and, in particular, to a microelectromechanical actuator fabricated on an insulating substrate.
BACKGROUND
(2) Many advances have been made in the design and fabrication of micro-electro-mechanical systems (MEMS). Microelectromechanical (MEM) devices commonly use electrostatic comb actuators to generate linear or circular motion. However, two main problems exist with present electrostatic comb actuators. First, comb actuators are generally considered to be low power, low output force devices-problems that are at least partially attributable to limitations in conventional manufacturing techniques, such as surface micromachining and silicon-on-insulator (SOI) micromachining. Second, regardless of the manufacturing technique that is employed, conventional comb actuators require a conductive material in order to effect electrostatic action. In surface micromachining, the requisite conductivity is typically supplied by a doped polysilicon layer, which is deposited along with a sacrificial layer on a substrate. Typically, the thickness of the

polysilicon layer ranges from about 1 μm to about 2 μm. Selective etching of the underlying sacrificial layer releases features formed in the polysilicon layer, which form the tines of the combs in the actuator. Since it is the lateral or side-facing electrical fields that provide the bulk of the attractive or repellent forces between electrodes, the intertine gap aspect ratio determines the amount of force that can be generated per electrode pair. Surface micromachined tines forming the combs may be about 2 μm high and spaced at least 2 μm apart for an aspect ratio (height/width) of 1:1. In this scenario, the limitation is the thickness of the polysilicon layer that can be deposited. Two factors dictate this limitation: (1) the film stress, which increases with height/thickness, and (2) the cost associated with long deposition times. While surface micromachining does have the advantage of cost, it is difficult to integrate with, for example, microfluidic channels, pumps, valves, etc.

(3) Silicon-on-insulator (SOI)-wafer-based surface micromachining, on the other hand, represents a manufacturing technique capable of achieving higher aspect ratios, albeit at the expense of additional complexity and cost. SOI micromachining begins with a doped silicon-on-insulator (SOI) substrate wherein a full-thickness, doped, single-crystal silicon wafer is wafer bonded to a silicon handle wafer at high temperature. A thin layer of silicon is sliced from the doped substrate using either proton or oxygen ion bombardment (typically up to 5 μm thick). It is then attached to an oxide-coated, silicon handle wafer via wafer bonding. At this point, etching of the sacrificial oxide layer would release all elements fabricated in the doped silicon layer. Therefore, additional steps are necessary to form anchors to the substrate. First, it is necessary to open vias in the doped silicon and underlying oxide layers where anchors are desired. Then, silicon epitaxy is used to form the MEM device layer, which is anchored to the substrate through the vias in the oxide layer. Since it is single crystal, the epitaxial silicon is stress-free and may be grown to any desired thickness, typically >10 μm. The epitaxial, single-crystal silicon layer is then patterned to form the actuator features. Selective etching of the underlying oxide layer releases the features and ultimately forms the tines of the comb drive. Aspect ratios of 4:1 or 5:1 can be generated in this manner. This geometry comes with considerable additional complexity and cost and is therefore not widely adopted. Another approach combines surface micromachining with backside bulk micromachining to produce comb actuators with aspect ratios of approximately 8:1. This approach is mainly directed toward 2D scanning mirrors and would be challenging to integrate with, for example, microfluidic channels, pumps, valves, etc.

(4) Surface, SOI and bulk micromachining produce structures that are 2.5D; that is, they are more complex than two-dimensional structures, but are not quite three-dimensional structures. As mentioned, these techniques produce electrostatic comb actuators capable of providing limited drive forces of about 10 to 30 microNewtons (UN); to achieve this level of output force, the comb actuator requires a relatively high operating voltage, up to 100 Volts or more. The relatively low drive force of conventional comb actuators limits their usefulness as power sources for many types of MEM devices. Furthermore, the 2.5D nature of the fabrication process limits (1) the types of devices that can be made and (2) their integration with microfluidics.

(5) Despite strong incentives across a variety of industries, there remains a long-felt need for true three-dimensional MEMS technology, capable of achieving high aspect ratios, high output forces, and comparatively low operating voltages, as well as the ability to manufacture a variety of three-dimensional shapes, suitable for a variety of applications. It would also be beneficial to have MEM devices that can be integrated with microfluidics or photonics, and that can be fabricated on insulating and/or transparent substrates. Other desirable features and characteristics will become apparent from the subsequent detailed description, the drawings, and the appended claims, when considered in view of this background.

SUMMARY

(6) The present invention provides for embodiments and methods of fabrication of true three-dimensional MEM devices that comprise features disposed on an insulating substrate, wherein said

features may be configured to perform a variety of functions. Among the functions contemplated herein, a MEM device may comprise features appropriate for applications including, but not limited to, drug discovery, DNA sequencing, electrophoresis, sensing, defense, bio-medical, manufacturing, consumer products, aviation, automotive, integrated circuits (e.g., micro-cooling), inspection, and safety systems. Furthermore, among the functions contemplated herein, a MEM device may comprise an electrostatic comb actuator. Representative substrates may include glass and sapphire.

(7) In one aspect of an exemplary embodiment of the present invention, femtosecond-pulsed lasers provide a fabrication technique that allows for true three-dimensional structures to be fabricated by processing a transparent, insulating substrate. One advantage of employing this method is that no sacrificial layers are needed. Another advantage is that high aspect ratios may be obtained. Another advantage is that true three-dimensional structures can be realized. Yet another advantage is that microfluidic channels and devices may be integrated on the same chip with the same process.

(8) In a further embodiment in accordance with the above, two-photon polymerization provides a fabrication technique that allows for true three-dimensional structures to be fabricated with insulating polymer material and integrated with true three-dimensional structures fabricated by femtosecond laser structuring on an insulating substrate.

(9) In a further embodiment in accordance with the above, surface micromachining provides a fabrication technique that allows for 2.5D actuators to be integrated with true three-dimensional structures fabricated by femtosecond laser structuring on an insulating substrate.

(10) In a further embodiment in accordance with the above, any fabrication technique suited to provide for true three-dimensional structures to be fabricated on, or by processing, an insulating substrate, falls within the purview of this disclosure.

(11) In another aspect of an exemplary embodiment in accordance with any of the above, magnetron sputter deposition provides a fabrication technique for depositing one or more conductive layers on an insulating substrate.

(12) In a further embodiment in accordance with any of the above, evaporation with planetary rotation of the substrate provides a fabrication technique for depositing one or more conductive layers on an insulating substrate. As used here, “planetary rotation” refers to a process wherein the normal axis of the wafer is tilted with respect to the source, as the Earth's axis is tilted with respect to the sun; as the wafer rotates, the beam of atoms from the source will ‘see’ different sides of a 3D feature and coat them all accordingly.

(13) In a further embodiment in accordance with any of the above, any conformal deposition process may be used for depositing one or more conductive layers on an insulating substrate or three-dimensional structure. Furthermore, at least three methods of segmenting a monolithically deposited conductive layer without the need for liftoff or post-deposition etching are provided to fabricate said separate subcomponents.

(14) In another aspect of an exemplary embodiment in accordance with any of the above, three-dimensional features defining a trench may be used to segment the conformal horizontal and vertical portions of a conductive layer into separate subcomponents.

(15) In a further embodiment in accordance with any of the above, three-dimensional features define a method for inducing segmentation via a suspended element, such as a biasing element, or a spring.

(16) In a further embodiment in accordance with any of the above, three-dimensional features define a method for inducing segmentation via an overhang or an undercut.

(17) In yet a further embodiment in accordance with any of the above, three-dimensional features define a method for inducing segmentation via any 3D shape that obscures the atomic flux of the deposition process, resulting in a deposition-free zone.

(18) In yet a further embodiment in accordance with any of the above, segmentation of a conductive layer is achieved via a temporary, external shadow mask, first applied, and then

removed from the insulating substrate.
(19) In another aspect of an exemplary embodiment in accordance with any of the above, the present invention advantageously provides a common process wherein both MEMS and microfluidics may be fabricated on a single substrate.
(20) In another aspect of an exemplary embodiment in accordance with any of the above, the present invention advantageously provides a common process wherein both MEMS and photonics may be fabricated on a transparent substrate.
(21) In yet another aspect of an exemplary embodiment in accordance with any of the above, a linear actuator MEM device may be fabricated on an insulating substrate.
(22) In a further embodiment in accordance with any of the above, a linear-rotational actuator is provided that may be fabricated on an insulating substrate.
(23) In a further embodiment in accordance with any of the above, a linear ratcheting actuator is provided that can be fabricated on an insulating substrate.
(24) In a further embodiment in accordance with any of the above, a torsional ratcheting actuator is provided that can be fabricated on an insulating substrate.
(25) In a further embodiment in accordance with any of the above, a two-stroke rachet pawl actuator is provided having improved speed and efficiency characteristics.
(26) In yet another aspect of an exemplary embodiment in accordance with any of the above, an apparatus, system, and/or method is provided, which eliminates hysteresis in the motion of an actuator thereby increasing precision in the movement of the actuator.
(27) It is an object of the present disclosure to allow integration of these devices with other technologies that are compatible with insulators and transparent substrates, such as microfluidics, photonics, sensors, etc.

Description

DESCRIPTION OF THE DRAWINGS
(1) Non-limiting and non-exhaustive embodiments of the present invention are described with reference to the following drawings. In the drawings, like numerals describe like components throughout the several views.
(2) For a better understanding of the present invention, reference will be made to the following Detailed Description, which is to be read in association with the accompanying drawings, which are incorporated in and constitute a part of this specification, show certain aspects of the subject matter disclosed herein, and, together with the description, help explain some of the principles associated with the disclosed implementations, wherein:
(3) FIG. **1** illustrates a schematic, perspective view of interdigitated fingers of an electrostatic comb drive, according to an embodiment of the present invention;
(4) FIG. **2**A illustrates a sectional view of an insulating substrate with various femtosecond, laser-irradiated structures in a first fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring, according to an embodiment of the present invention;
(5) FIG. **2**B illustrates a sectional view of an insulating substrate after an etching process in a second fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring, according to an embodiment of the present invention;
(6) FIG. **2**C illustrates a sectional view of an insulating substrate after a conformal conductive layer deposition process in a third fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring, according to an embodiment of the present invention;
(7) FIG. **3**A illustrates a perspective, partial cutaway view of an insulating substrate with various femtosecond laser irradiated structures in a first fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and two-photon polymerization, according to an

embodiment of the present invention;
(8) FIG. **3**B illustrates a perspective, partial cutaway view of an insulating substrate with various wet-etched structures in a second fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and two-photon polymerization, according to an embodiment of the present invention;
(9) FIG. **3**C illustrates a perspective, partial cutaway view of an insulating substrate with various two-photon polymerized structures in a third fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and two-photon polymerization, according to an embodiment of the present invention;
(10) FIG. **4**A illustrates a perspective, partial cutaway view of an insulating substrate with a patterned, sacrificial oxide layer in a second fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and surface micromachining, according to an embodiment of the present invention;
(11) FIG. **4**B illustrates a perspective, partial cutaway view of an insulating substrate with a polysilicon deposition layer in a third fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and surface micromachining, according to an embodiment of the present invention;
(12) FIG. **4**C illustrates a perspective, partial cutaway view of an insulating substrate with a patterned polysilicon layer in a fourth fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and surface micromachining, according to an embodiment of the present invention;
(13) FIG. **4**D illustrates a perspective, partial cutaway view of an insulating substrate with an etched sacrificial oxide layer in a fifth fabrication step for an electrostatic comb actuator produced by femtosecond laser structuring and surface micromachining, according to an embodiment of the present invention;
(14) FIG. **5** illustrates a sectional view of a various structures etched into an insulating substrate for the purpose of segmenting a monolithically deposited conductive layer, including, from left to right, a simple trench, a trench having an overhang profile and/or an undercut profile, and a trench with a suspended element, according to an embodiment of the present invention;
(15) FIG. **6**A illustrates a perspective view of a linear actuator, according to an embodiment of the present invention;
(16) FIG. **6**B illustrates an enlarged view taken from FIG. **6**A, showing the interdigitated electrodes of a linear actuator with segmentation features, according to an embodiment of the present invention;
(17) FIG. **6**C illustrates an enlarged view taken from FIG. **6**A, showing the biasing element and linkage beam intersection with suspended element segmented electrodes, according to an embodiment of the present invention;
(18) FIG. **6**D illustrates an enlarged view taken from FIG. **6**A, showing segmented electrodes via an undercut structure, according to an embodiment of the present invention;
(19) FIG. **7**A illustrates a perspective view of a linear-rotational electrostatic comb actuator on an insulating substrate, according to an embodiment of the present invention;
(20) FIG. **7**B illustrates an enlarged perspective view of electrode segmentation structures on a linkage beam of a linear-rotational electrostatic comb actuator on an insulating substrate, according to an embodiment of the present invention;
(21) FIG. **8**A illustrates a top view of a linkage beam, a rotating joint, and the cogs of a linear-rotational electrostatic comb actuator on an insulating substrate, according to an embodiment of the present invention;
(22) FIG. **8**B illustrates a sectional view taken from FIG. **8**A of a linkage beam, a rotating joint, and the cogs of a linear-rotational electrostatic comb actuator on an insulating substrate, according to an embodiment of the present invention;

(23) FIG. **9**A illustrates a sectional view of an as-fabricated gap between a spindle and a cog and within a rotational joint of a linear-rotational electrostatic comb actuator on an insulating substrate, according to an embodiment of the present invention;
(24) FIG. **9**B illustrates a sectional view of post-fabrication gap removal by downward displacement due to gravity of a cog relative to a spindle and within a rotational joint in a linear-rotational electrostatic comb actuator on an insulating substrate, according to an embodiment of the present invention;
(25) FIG. **10**A illustrates a perspective view of a linear ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(26) FIG. **10**B illustrates an enlarged top view a ratchet wheel, forward driving pawls, and anti-reverse pawls of a linear ratcheting actuator on an insulating substrate, according to an embodiment of the present invention, where solid lines represent a rest position, and where dashed lines represent an actuated position;
(27) FIG. **11** illustrates a top view of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(28) FIG. **12**A illustrates an enlarged perspective view of an isolated trace structure connecting two electrodes of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(29) FIG. **12**B illustrates a sectional view taken from FIG. **12**A, showing the isolated trace of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(30) FIG. **13**A illustrates an enlarged perspective view of a glass bridge connecting two electrodes over a moveable ring of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(31) FIG. **13**B illustrates a sectional view taken from FIG. **13**A, showing the profile of the glass bridge and moveable ring of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(32) FIG. **14**A illustrates an enlarged view of a thin film bridge connecting two electrodes over a moveable ring of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention;
(33) FIG. **14**B illustrates a sectional view taken from FIG. **14**A, showing the profile of the thin film bridge and moveable ring of a torsional ratcheting actuator on an insulating substrate, according to an embodiment of the present invention; and
(34) FIG. **15** illustrates a perspective view of a torsional ratcheting actuator on an insulating substrate having additional electrical connections made using wire bonds, according to an embodiment of the present invention.

DETAILED DESCRIPTION

(35) Non-limiting embodiments of the invention will be described below with reference to the accompanying drawings, wherein like reference numerals represent like elements throughout. While the invention has been described in detail with respect to the preferred embodiments thereof, it will be appreciated that upon reading and understanding of the foregoing, certain variations to the preferred embodiments will become apparent, which variations are nonetheless within the spirit and scope of the invention. The drawings featured in the figures are provided for the purposes of illustrating some embodiments of the invention and are not to be considered as limitation thereto.
(36) The terms “a” or “an”, as used herein, are defined as one or as more than one. The term “plurality”, as used herein, is defined as two or as more than two. The term “another”, as used herein, is defined as at least a second or more. The terms “including” and/or “having”, as used herein, are defined as comprising (i.e., open language). The term “coupled”, as used herein, is defined as connected, although not necessarily directly, and not necessarily mechanically.
(37) Reference throughout this document to “some embodiments”, “one embodiment”, “certain

embodiments", and "an embodiment" or similar terms means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearances of such phrases or in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments without limitation.

(38) The term "or" as used herein is to be interpreted as an inclusive or meaning any one or any combination. Therefore, "A, B or C" means any of the following: "A; B; C; A and B; A and C; B and C; A, B and C". An exception to this definition will occur only when a combination of elements, functions, steps or acts are in some way inherently mutually exclusive.

(39) The drawings featured in the figures are provided for the purposes of illustrating some embodiments of the present invention and are not to be considered as limitation thereto. The term "means" preceding a present participle of an operation indicates a desired function for which there is one or more embodiments, i.e., one or more methods, devices, or apparatuses for achieving the desired function and that one skilled in the art could select from these or their equivalent in view of the disclosure herein and use of the term "means" is not intended to be limiting.

(40) FIG. **1** shows a schematic, exemplary electrostatic comb actuator **10**. The comb actuator **10** comprises a series of interdigitated electrodes **20**, also called tines, which are formed from single crystal silicon or polysilicon and disposed on a substrate. The silicon layer may be doped so that the MEM layers are highly conductive. When a voltage is applied between the electrodes, an electric field **30** is generated, substantially as shown. The electric field **30** produces an attractive force between the electrodes **20** which urges the electrodes to greater meshing or overlap in the lengthwise direction thereof. Typically, one set of electrodes is moveable while the other set remains stationary relative to the substrate. The moveable set of electrodes, then, converts electrical energy into mechanical energy. The force is proportional to the amount of energy stored as capacitance between the tines of the comb. The stored energy is given by

(41) $E=\frac{1}{2}CV^2$, where C is the capacitance and Vis the applied voltage. The capacitance is related to the geometry of the interdigitated electrodes **20** by

(42) $C=\frac{A}{w}$

(43) where A is equal to l×h, the overlapping area between two adjacent electrodes **20**, w is the perpendicular, free-space distance between the electrodes **20**, and e is the permittivity of the free space. Therefore, to increase the force generated per unit-length of a given interdigitated electrode **20** pair, it is necessary to maximize the ratio of h/w, where h is the height of the electrode **20**.

(44) The present disclosure provides several methods for fabricating an actuator, such as an exemplary electrostatic comb actuator **10**. Three fabrication processes are contemplated in this disclosure: femtosecond laser structuring (FLS), FLS with two-photon polymerization (2PP), and FLS with surface micromachining (SMM). All three techniques are capable of producing three-dimensional MEM devices on insulating and transparent substrates. Likewise, all three techniques allow integration of these devices with other technologies fabricated on insulating and transparent substrates, such as microfluidics, photonics, sensors, etc. The first two techniques, FLS and FLS+2PP, require a conductive layer, such as a metal, to be deposited after 3D structure fabrication in order to enable actuation. FLS+SMM, on the other hand, does not require a conductive layer coating because conductivity is provided by the doped polysilicon mechanical layer. Nevertheless, it may be advantageous to include a conductive layer for the purposes of adding structural integrity and/or electrodes to the device. Both FLS and FLS+2PP are capable of producing high aspect ratio interdigitated comb features relative to standard polysilicon MEM devices. Advantageously, with sufficiently high aspect ratios for both the comb features and the conformal coatings, enhanced forces may be generated per pair of electrode tines **20**, as shown in FIG. **1**.

(45) The FLS fabrication process is illustrated in FIGS. **2**A-**2**C. Referring to FIG. **2**A, a substrate **110**, which may be a transparent substrate such as glass or sapphire, may be irradiated with a series

of femtosecond laser pulses focused inside the substrate **110**. The pulses may be used to write volume pixels **112**, or voxels, which may be selectively etchable using wet chemistry. In FIG. **2**B the voxels have been etched away leaving behind one or more trenches, cavities or voids **114**, one or more undercut and/or overhang trenches **116**, and/or one or more recesses **118** having suspended elements, such as a biasing element **130**. Etching may be achieved through a suitable wet chemistry, such as heated potassium hydroxide (KOH) or hydrofluoric acid (HF).

(46) In FIG. **2**C a conductive layer **150** has been disposed on the substrate and on the etched features. The conductive layer may comprise one or more metal layers, one or more conductive semiconductor layers, and/or one or more transparent conductive layers. One or more conductive layers may serve various functions; functions contemplated herein include promoting adhesion to the substrate, acting as a solder barrier, acting as a structural element, forming a wire-bondable surface, and/or acting as an electrode. Example adhesion layer metals may include Titanium and/or Chromium. Example barrier metals may include Nickel and/or Palladium. Example structural layers may include Copper and/or Tungsten. Example bondable metals include Gold and/or Platinum. An example conductive semiconductor layer is doped polysilicon. An example transparent conductive layer is indium tin oxide (ITO). All of these materials may function as an electrode.

(47) The fabrication process for FLS and 2PP is illustrated in FIGS. **3**A-**3**C. Because the materials used in 2PP are incompatible with the FLS wet chemistry, the FLS process must be completed prior to 2PP. In FIG. **3**A the substrate **110** is irradiated **112** to form a suspended or free-floating linkage beam **140** or other passive component to be moved by the actuator. In FIG. **3**B the irradiated features are preferentially etched away to form a trench, cavity or void **114** allowing the linkage beam **140** to move. In FIG. **3**C, 2PP is used to form the comb drive **100** elements on the surface of the substrate **110**. This is accomplished by immersing the substrate in a monomer resin and cross-linking it with a laser beam focused inside the resin which converts the monomer liquid into a polymer solid **40**. As with many other additive manufacturing techniques, the features may be disposed layer-by-layer from the bottom up. Alternatively, the printing beam can be moved in 3 dimensions to form arbitrary shapes, such as wires or waveguides. A layer printed at the surface level forms a bond **42** with the glass substrate **110** and can be used to create anchor points **132** from which cantilevered or suspended elements, such as a biasing element **130**, can be formed. In this example, both anchored and suspended elements are combined to form a comb actuator **100**. Finally, a conductive layer (not shown) is disposed on the substrate and operational elements of the actuator **100**. Alternatively, the actuator may be fabricated by FLS and the linkage beam by 2PP, thereby effecting mechanical motion above the surface of the substrate instead of below it. More generally, any combination of actuator above and/or below the surface of the substrate **110** and mechanical linkage above and/or below the surface of the substrate is possible and within the scope of this disclosure.

(48) The fabrication process for FLS and SMM is given in FIGS. **4**A-**4**D. The first step is irradiation **112** of the substrate **110**, as in the FLS+2PP process illustrated in FIG. **3**A. The irradiated volume **112** forms a suspended or free-floating linkage beam **140** or other passive component to be moved by the actuator. Because the lithographic steps used in SMM must be done on a relatively planar surface, etching cannot be performed prior to SMM. Instead, in the second step, shown in FIG. **4**A, a sacrificial oxide layer **50** is disposed on the substrate **110** and patterned with the required anchor points as vias **132**. Alternatively, a sacrificial layer may be formed via irradiation of the substrate, and thereby obviate the need for the oxide **50**. For example, in the case shown in FIG. **4**A, a thin surface irradiation would be made everywhere except the anchor points **132**. In the third step, given in FIG. **4**B a doped polysilicon layer **60** is disposed on the patterned oxide **50**. The polysilicon layer **60** forms a bond **62** with the glass substrate **110** and can be used to create anchor points **132** from which cantilevered or suspended elements can be formed. In the fourth step, exhibited in FIG. **4**C, standard photolithography and selective etching are used to

pattern the polysilicon layer **60** into the comb drive elements, with the etch slowing or stopping on the sacrificial oxide **50**. In the final step of FIG. **4**D, the irradiated features and sacrificial oxide **50** are preferentially etched away to form a slot **114** for the linkage beam **140** to occupy when actuated. Also, in this way suspended elements, such as a biasing element **130**, may be formed. HF chemistry is used to etch both the sacrificial oxide **50** and the irradiated glass **112** preferentially over the polysilicon **60** and untreated substrate **110**. In this process KOH chemistry may not be used because it readily attacks polysilicon. As previously mentioned, the doped polysilicon provides the conductivity necessary for actuator **100** operation. However, it is usually necessary to form metal contacts for practical electrical coupling to the outside world. For this purpose, a coarse shadow mask may be used. Alternatively, and with a sufficiently short HF etch time, a metal layer may be disposed and patterned on the substrate and then protected from the wet chemistry by suitable methods, such as thick photoresist. Alternatively, the actuator may be fabricated by FLS and the linkage beam by SMM, thereby effecting mechanical motion above the surface of the substrate instead of below it. Any combination of actuator disposed above and/or below the surface of the substrate and one or more mechanical linkage disposed above and/or below the surface of the substrate is possible and considered to be within the scope of this disclosure.

(49) In the three fabrication methods disclosed herein, deposition of a conductive layer may be required to render insulating features conducting, strengthen mechanical features and/or form input/output electrical connections. Specifically, regarding the first requirement, it is necessary that the conductive layer be conformal to some degree to coat the sides of the tines of the comb actuator such that the electric field lines are substantially horizontal (parallel with the substrate), as illustrated in FIG. **1**. Deposition of patterned conductive layers is often achieved with standard lithographic, deposition and etch methods. However, upon reviewing FIG. **2**B, it is evident that the irradiated and etched substrate **110** now comprises the features of the actuator, such as trenches **114**, undercuts or overhangs **116**, and recesses with suspended elements **118** and is therefore no longer suitable for standard lithographic processing. Such processing involves the deposition of photoresist either as a spun-on viscous liquid or laminated film (dry resist). Either process is likely to fracture the delicate, flexible features of the actuator. Moreover, due to the fact that the actuator features may have high-aspect ratios, spun-on films such as photoresist are not likely to have the planarity required for a high-fidelity lithographic process. Finally, the development and cleaning processes, for example spin developing, immersion with sonication, and spin-rinse drying, usually include mechanical forces sufficient to compromise the integrity of the actuator. Therefore, only blanket conductive layer deposition, in which no mask is used, or a non-contact masking method, such as shadow masking, may be used. Shadow masking may be used for features with a minimum dimension on the order of 10 micrometers (microns) and therefore is a valuable method of fabrication for many MEM devices. Blanket deposition, especially conformal blanket deposition, typically produces a continuous metal layer and is therefore of little use in electrical devices. In this disclosure, however, several methods of segmenting such a layer are contemplated, allowing for maskless deposition, as discussed below. First, however, this discussion will benefit from an introduction to conformal coating deposition.

(50) Two methods of conformal coating are contemplated herein; magnetron sputter deposition or evaporation with a suitable, planetary-type rotation of the substrate. Modified magnetron sputtering techniques have been developed to provide conformal coverage through a combination of coating re-sputtering and ionized physical vapor deposition (IPVD), the latter by use of a secondary plasma source or a pulsed high target power (HiPIMS). These and other plasma-based techniques are included by reference in the following description of sputtering.

(51) Magnetron sputter deposition, commonly called sputtering, is a plasma-based coating method where positively charged energetic ions from a magnetically confined plasma collide with a negatively charged target material, ejecting (or “sputtering”) atoms from the target that are then deposited onto a substrate. In the sputtering process, the sputtered atoms travel toward the substrate

at a variety of angles. A low-power, high-pressure plasma results in a large angular distribution of the atomic flux centered around high oblique angles, whereas a high-power, low-pressure plasma results in a narrow angular distribution of the atomic flux centered around the vertical axis (i.e., the surface normal). Each distribution of angles produces a deposition layer that can conform to certain surface topographies of the substrate; these features may include vertical sidewalls, and/or even slightly re-entrant features. Continuous coating may be achieved for topographies with aspect ratios of up to 2:1 (height/width). However, under optimized conditions, contiguous conformal coating may be achieved for aspect ratios of up to 6:1 or more. As a rule of thumb, the conformal coatings are generally much thinner than the topography upon which they are deposited, as very thick deposition layers will themselves change the topography to the point where this rule no longer applies.

(52) In an alternative deposition process, source material evaporation with planetary rotation of the substrate may be utilized. Here, planetary rotation means that the normal axis of the wafer is tilted with respect to the source, as the Earth's axis is tilted with respect to the sun. Then, as the wafer is made to rotate, the non-horizontal surfaces of a 3D feature will be exposed to the atomic flux from the source and coating of the exposed portions may therefore be achieved.

(53) The present invention provides for at least three structures for segmenting a single, monolithically deposited conductive layer without the need for liftoff or post-deposition etching. Conceptually, the conformal deposition can be thought of as having uniform thickness on every surface exposed to the deposition source, regardless of its angle with respect to the substrate surface, as represented in FIG. **2**C. In practice, however, the layer thickness on a high angle surface, such as a vertical surface, tends to diminish with distance from the topmost horizontal surface. This may be a result of several factors: an atomic flux with a high angle of incidence, θ.sub.flux, shadowing effects, and atomic attraction forces. These phenomena cause the incident atoms to be preferentially deposited on the top corners of the trench and less preferentially down the sides of the trench. Therefore, a more accurate depiction of the conductive layer profile is illustrated in FIG. **5**. The following description of segmentation structures assumes a stable process condition wherein the peak angle and distribution of the incident atomic flux is fixed.

(54) In a first structure for effecting layer segmentation **800**, shown on the left side of FIG. **5**, a trench **114** is depicted wherein every surface is exposed to the incident and/or re-sputtered atomic flux. The trench may be of any shape that satisfies this condition, i.e., having no obscured surface(s). Nevertheless, the concepts and principles presented herein may be most easily understood for a trench with a rectangular profile having a vertical sidewall **114***a* of depth d and horizontal bottom **114***b* of width w. For non-rectangular profiles the width, w, is defined as the dimension of the trench opening (coincident with the substrate surface) while the depth, d, is defined as the vertical distance between the trench opening and its deepest point. With all surfaces exposed to the incident atomic flux, complete conformal coating may be expected. However, as previously described, atoms are deposited preferentially on the top corners of the trench while the conductive layer **150** deposited on the sidewall **114***a* exhibits a taper **152***a*. Therefore, a first structure for effecting layer segmentation **800** is a trench **114** of sufficiently high aspect ratio, d/w, such that the conductive layer terminates at a point **154** above the bottom of the trench **114***b* keeping the sidewall deposition layer **152***a* separated from the bottom surface **114***b* and/or deposition layer **156***a*.

(55) In a second structure for effecting layer segmentation **801**, depicted in the center of FIG. **5**, a trench **116** comprising a sidewall **116***a* and bottom **116***b* further comprises an overhang **116***c* and undercut **116***d*. The terms “overhang” and “undercut” refer to the same feature, in that at least one portion of at least one surface that is obscured from the incident and/or re-sputtered atomic flux as, for example, a downward facing portion. Thus, the terms “overhang” and “undercut” may be used interchangeably. In the case of the present structure **801**, the trench **116** may be of a sufficiently low aspect ratio such that, without the undercut **116***d* or overhang **116***c*, the sidewall **116***a* and bottom

116*b* surfaces may be coated contiguously, as, for example, layers **152***b* and **156***b*. Introducing an overhang or undercut feature results in a shadow zone where no deposition occurs. Thus, a second structure for effecting layer segmentation **801** is an undercut or overhang comprising at least one portion of at least one surface that is not exposed to the incident and/or re-sputtered atomic flux, thereby creating a deposition-free zone.

(56) In a third structure for effecting layer segmentation **802**, depicted on the right side of FIG. **5**, a trench **114** is depicted wherein every surface is exposed to the incident and/or re-sputtered atomic flux. The trench may be of any shape that satisfies this condition, i.e., having no obscured surface(s). Nevertheless, the concepts and principles presented herein may be most easily understood for a trench with a rectangular profile having a vertical sidewall **118***a* and horizontal bottom **118***b*. The trench **118** further comprises a suspended element **130** separated from the surfaces of the trench **118** by a gap wherein the suspended element obscures at least one portion of at least one surface of the trench from the incident and/or re-sputtered atomic flux. The trench **118** may be of sufficiently low aspect ratio such that, without the suspended element, the sidewall **118***a* and bottom **118***b* surfaces may be coated contiguously, as exemplified by contiguous layers **152***c* and **156***c*. Introducing a suspended element **130** of the necessary geometry and position relative to the trench **118** results in a shadow zone where no deposition occurs, as appears between the two bottom deposition layers **156***c*. Hence, a third structure for effecting layer segmentation **802**, is a suspended element of sufficient extent and proximity to the trench **118** to create a deposition-free zone.

(57) Any combination of process condition (e.g., pressure, RF power, substrate bias, substrate angle, etc.) and feature profile (e.g., aspect ratio, sidewall shape, sidewall angle, suspended element, etc.) that gives rise to a deposition-free zone is suitable for segmenting a monolithically deposited conductive layer into separate electrodes/conductors and falls within the scope of this disclosure.

(58) FIGS. **6**A-**6**D illustrate a first embodiment of the invention comprising an electrostatic comb actuator **100** fabricated on an insulating substrate **110**. The insulating substrate **110** may be transparent to facilitate FLS as previously described, and may be made of glass or sapphire. Referring to FIG. **6**A, the actuator **100** may comprise a pair of interdigitated combs, defined as fixed comb **120***a* and a moveable comb **120***b*. The fixed comb **120***a* may comprise one or more fixed tines **124***a*, which may form trench features **114**, as previously described in relation to FIG. **5**. The one or more fixed tines **124***a* may be electrically coupled at an end to a fixed electrode **150***a*. The moveable comb **120***b* may comprise a crossbeam **122** and one or more moveable tines **124***b*, which may form one or more suspended features **118**, as previously described in relation to FIG. **5**. The moveable comb **120***b* may be suspended by, or coupled to, one or more biasing elements **130**, which may be complementary in nature, disposed above one or more recess features **118**. The biasing elements **130** may be configured to provide an electrical connection to electrode **150***b* wherein the one or more biasing elements provide said connection at an end. On the other end of one or more biasing elements **130**, a linkage beam **140** may be formed, for the purpose of imparting a drive force to a mechanical load. The biasing elements **130** act as compliant mechanisms and have appropriate physical properties to provide the capability of elastically deforming to effect linear motion of the actuator **100**. A conductive layer may be disposed on the surface of the substrate **110**, wherein the features defining the actuator **100** serve to segment the conductive layer into a fixed electrode **150***a* and a moveable electrode **150***b*. Referring to FIG. **6**B, the overlapping portions of the respective ends of fixed tines **124***a* and moveable tines **124***b* are shown in greater detail. In operation, the overlapping portion of the tines **124***a*, **124***b* will vary according to the voltage applied across electrodes **150***a*, **150***b*, resulting in electrostatic attraction or repulsion of the combs **120***a*, **120***b*. Upon removal of the voltage, the moveable comb **120***b* returns to an initial rest position by action of the one or more restoring biasing elements **130**. As may be observed, the actuator **100** may utilize each of the three methods of segmenting a monolithically deposited

conductive layer, and without the need for liftoff or post-deposition etching, in order to form the electrodes. In FIG. **6**B, trench features **114** are represented by the fixed tines **124***a*. Also, in FIG. **6**B, suspended element features **118** are represented by the moveable tines **124***b*. In FIG. **6**C, various features such as the biasing elements **130** and linkage beam **140** may similarly represent suspended element features. And in FIG. **6**D, an undercut may be utilized, corresponding to the structures reflected in trench **116** as described in relation to FIG. **5**. These segmentation techniques may be applied in any combination throughout any embodiment described herein.

(59) FIGS. **7**A-**7**B illustrate a second embodiment of the invention comprising a linear-rotational actuator **200** fabricated on an insulating substrate **110**. The insulating substrate **110** may be transparent to facilitate FLS as previously described, and may be made of glass or sapphire. Referring to FIG. **7**A, linear-rotational actuator **200** may comprise first and second linear actuators, **200***a* and **200***b*, respectively. First and second linear actuators **200***a* and **200***b* may include analogous features, crossbars, tines etc., as previously described. Furthermore, linear actuators **200***a*, **200***b* may be positioned perpendicularly with respect to one another and may each be coupled to one or more biasing elements **230** and linkage beams **240**. The linkage beams **240** may be connected to a rotating joint **210**. With suitable input waveforms, first and second linear actuators **200***a*, **200***b* may be synchronized to induce a rotational motion in a wheel or cog, wherein the linkage beams **240** comprise lengths adequate to accommodate lateral bending imparted by operation of the actuator **200**. The linkage beams **240** may rotate a drive cog **220**, which, in turn, rotates a transmission cog **230**. To effectuate locomotion, three electrodes may be utilized: a fixed comb electrode **250***a*, which may also act as an electrical ground; a first moveable comb electrode **250***b* corresponding to first linear actuator **200***a*; and a second moveable comb **250***c* corresponding to second linear actuator **200***b*. The electrodes **250***a*, **250***b*, and **250***c* may be segmented with respect to one another through the use of a combination of trench features, such as along fixed tine portions of the linear actuators **200***a* and **200***b*, suspended elements, such as along the portions of actuator **200** defining biasing elements **230** and linkage beams **240**, and/or and undercut or overhang features defining structures **260***a*, **260***b*, and/or **260***c*. Importantly, the isolation of the first and second moveable comb electrodes **250***b*, **250***c* from each other may occur along the linkage beams **240**, or at their intersection close to the rotational joint **210**. Referring to the latter approach, FIG. **7**B shows a double undercut structure **260***c*, which may be used to achieve separation. A first undercut in the shape of an arc **262** may be used to create a gap in the top surface metal, while one or more secondary undercuts **264** on either side of structure **260***c* may provide for separation of the sidewall conductive layer.

(60) While the present embodiment as reflected in FIGS. **7**A and **7**B comprises two linear actuators, any number of linear actuators may be utilized, and fall within the scope of this disclosure. For example, actuator **200** may utilize three linear actuators, wherein the third actuator (not shown) may be disposed in a mirrored fashion, or otherwise arrayed around the rotational joint **210**. Similarly, four or more linear actuators may be disposed in any manner appropriate to provide the requisite output force/torque. Additionally, each linear actuator may further comprise one or more pairs of tines configured for a specific application, such as to provide a specific amount of output force or torque. These principles, or alternatives, may similarly be applied to other embodiments disclosed herein.

(61) In contrast to floating, flexible biasing elements **230** such as, for example, springs, both rotational joints and mechanically-contacting interfaces must be shielded from the conductive layer deposition process, or they may be locked in position by the deposited layer. According to the second embodiment and with reference to FIGS. **8**A-**8**B, several examples of this concept may be observed. Referring now to FIG. **8**A, one or more linkage beams **240** may be coupled to a rotational joint **210**, which, in turn, may be coupled to a drive cog **220**. Drive cog **220**, then, may be coupled to a transmission cog **225**. Additional cogs may be disposed above, below, or adjacent to the transmission cog **225** to further effect a desired gear ratio or mechanical torque. After

fabrication via FLS, the teeth of the cogs **220**, **225** may be either in contact with one another, or may be separated by a small gap. For this reason, the interference region **222** between cogs **220**, **225**, as depicted in FIG. **8**B, must be shielded from the deposition process or they may be locked in position by the deposited layer. Shielding of the cog teeth may be achieved by an overhang **260***d* disposed on the circumference of the cogs. At the intersection **222** of the two cogs **220**, **225**, the overhang **260***d* may form a suspended bridge **266**. Thus, the overhang **260***d* and suspended bridge **266** represent two ways in which localized layer deposition may be avoided, in a manner analogous to that described with reference to trenches **116** and **118** of FIG. **5**.

(62) Referring now to FIG. **8**B, another manner of avoiding localized metal deposition may be seen. Here, a spindle **250** may be formed underneath the drive cog **220** such that it does not break the top surface of the cog **220**. Similarly, the rotating joint **210** connecting the linkage beam **240** to the drive cog **220** is formed underneath, and within, the linkage beam assembly **240**. In this way both the spindle **250** and the rotating joint **210** may be shielded from the incident flux. These concepts, design features, or alternatives, may similarly be applied to other embodiments disclosed herein.

(63) Referring to FIG. **9**A, another aspect of the second embodiment is provided, which, as a primary objective, aims to obviate hysteresis from the system. FIG. **9**A shows aspects of actuator **200**, including drive cog **220**, rotational joint **210**, etc., in a post-fabricated condition wherein etching of the substrate has just been completed. As shown, the attendant gaps appear at, or along, all irradiated interfaces. These gaps, though small, may introduce some undesirable mechanical hysteresis in the motion of the actuator **200** and reduce the precision of its movement. In one aspect, and as provided in this exemplary embodiment, the present invention provides for reducing or eliminating one or more gaps by means of gravity and judicious choice of component geometry and configuration. Referring again to FIG. **9**A, the spindle **250** may comprise a cylindrical shaft **252** with a cone-shaped tip **254**. A spindle socket **256** having an offset shape from the spindle **250** may be formed in the underside of the drive cog **220**. Referring to FIG. **9**B the drive cog **220** may have dropped down under the influence of gravity and rest upon, or otherwise become coupled to, the spindle **250**. The cone-shaped tip **254** may produce a centering force for the cog **220**. In operation, as the cog **220** rotates, the spindle tip **254** and socket **256** surfaces are in constant contact, thereby eliminating any lateral movement that may be allowed or introduced to the system by the initial gap. These concepts, design features, or alternatives, may similarly be applied to other embodiments disclosed herein.

(64) Referring again to FIG. **9**A, the rotating joint **210** may comprise a cylindrical shaft **212** having a reverse cone-shaped flange **214** disposed thereon. The shaft socket **216**, having an offset shape from the joint shaft **212** and flange **214**, is formed in the underside of the linkage beam **140**. As in the case of the cog spindle **250**, the fabrication process produces a gap between components forming the rotating joint **210**, namely between the flange **214**, and socket **216**. Referring to FIG. **9**B, gravity has pulled the cog **220** onto the spindle **250**, while the flange **214** now contacts, or is otherwise made to couple to, the linkage beam socket **216**. As the cog **220** rotates, the flange **214** and socket **216** surfaces are in constant contact, eliminating any hysteresis due to the etch process-induced gap. Similarly, these concepts, design features, or alternatives, may similarly be applied to other embodiments disclosed herein.

(65) FIG. **10**A illustrates a third embodiment according to the present invention, comprising a linear ratcheting actuator (LRA) **300**. The LRA **300** may comprise a linear actuator **300***a* coupled to a ratchet pawl **320** via one or more biasing elements **330** and linkage beam **340**. The linear actuator **300***a* may thereby be configured to move the ratchet pawl **320**, which engages a ratchet **350**, causing it to rotate clockwise around a spindle (not shown), which may be disposed underneath. A pair of anti-reverse pawls **360***a*, **360***b* may also be configured to engage the ratchet **350** and, as each tooth passes by, pawls **360***a*, **360***b* may prevent the ratchet **350** from rotating counter-clockwise, as may otherwise be induced by the ratchet pawl **320** returning to an initial the rest

position. At one end of each anti-reverse pawl **360***a*, **360***b*, defined as **362***a* and **362***b*, respectively, the ends may be affixed, or otherwise coupled to the substrate such that the pawls **360***a*, **360***b* may elastically deform during operation and return to their initial position. Thus, a small, reciprocating motion of the linear actuator **300***a* may be turned into complete rotational motion of the ratchet **350**. The LRA **300** may further comprise first and second electrodes, **370***a*, **370***b*, to apply a voltage thereto and effect actuation of LRA **300**.

(66) In another aspect of the present invention the ratchet pawl **320** may comprise two branches **322***a*, **322***b* that flank the ratchet **350** on opposite sides. Each branch **322***a*, **322***b* may couple to the ratchet wheel **350**, or otherwise engage the same, in unique and opposing directions, while providing for slippage in the other directions. The movement of actuator **300** may be characterized in terms of a two-stroke actuation. First, at the start of the actuator stroke, the linear actuator **300***a* and ratchet pawl **320** are disposed in a first, rest position, as illustrated by the solid-line portions shown in FIG. **10**B, wherein left **322***a* and right branches **322***b* of the ratchet pawl **320** may be disposed to the lower side of the ratchet wheel **350**. At the limit of the actuator stroke, in a second position represented by the dashed-line portions shown in FIG. **10**B, the left branch **322***a* of the pawl **320** has engaged the ratchet **350** and rotated it by at least one tooth, while the right branch **322***b* of the pawl **320** has slipped past at least one tooth of the ratchet **350**. Upon returning to the rest position, the right branch **322***b* of the pawl **320** engages the ratchet **350** and rotates it by at least one tooth, while the left branch **322***a* of the pawl **320** slips past at least one tooth of the ratchet **350**. Thus, the ratchet wheel **350** may be made to rotate by the angular equivalent of at least two teeth per actuator cycle. Therefore, according to this configuration, the ratchet **350** turns at a rate that is at least twice as fast per drive cycle relative to a single pawl actuator. The present design, then, has advantages in both speed and efficiency.

(67) FIG. **11** illustrates a fourth embodiment of the present invention, comprising a torsional rotating actuator (TRA) **400**. The TRA **400** may comprise one or more circularly-arrayed comb drives **410**, which may each comprise a fixed comb **410***a* and a moveable comb **410***b*. Each comb **410***a*, **410***b* may comprise one or more curved tines **414**, forming one or more pairs of tines. Each comb **410***a*, **410***b* may further comprise a crossbeam **412** disposed at an end of each set of one or more tines **414**. The moveable combs **410***b* may be coupled to inner **422** and outer **440** rings. Flexible biasing elements **430** may be disposed around the circumference of the outer ring **440** and allow only rotational movement of the ring **440**. The TRA **400** may further comprise one or more ratchet pawls **420** which couple to, or otherwise engage, a ratchet **450**, causing counterclockwise rotation of the same around a spindle disposed underneath (not shown). One or more anti-reverse pawls **460** may also be configured to engage the ratchet **450** such that in operation, as each tooth passes by, they prevent the ratchet **450** from rotating clockwise with the ratchet pawls **420** during their biasing element-induced return to the initial rest position. In this way, a small, reciprocating, angular motion of the comb drives **410** may be turned into complete rotational motion of the ratchet **450**. Three electrodes, two fixed **470***a* and one moveable **470***b*, may be used to apply a voltage to the combs **410**. The fixed electrodes **470***a* may be coupled to the fixed combs **410***a* via bridges **480** that extend over, and are therefore decoupled from, the outer flexible ring **440**. The moveable combs **410***b* may be tied together electrically by means of the inner ring **422**. The inner ring **422** and moveable combs **410***b* may be coupled electrically to the outer ring **440**, which, in turn, may be be coupled to a fixed bond pad **470***b* via one or more biasing elements **430**. In this configuration of the TRA **400**, the mechanical output is in the center, while the comb drives **410** are arranged concentrically around the mechanical output. Thus, a more compact design is achieved, and a benefit is obtained, as compared to other designs such as a tangent ratchet design, wherein a ratchet wheel rings the perimeter, thus requiring more surface area and complexity of parts.

(68) The single-layer nature of the conductive layer deposition process described throughout this disclosure may, in general, present certain challenges for connecting electrodes in certain geometries. Electrodes must not only render the insulating material electrically conductive, but also

provide for electrical connection to the outside world, such as when attempting to couple the electrode to a bond pad. The present disclosure enables the fabrication of electrically isolated traces that may connect separate electrodes where surface routing is possible. In contrast, any electrically active feature formed by a mechanically isolated island will be electrically, as well as mechanically, isolated. The present disclosure, therefore, provides at least two ways of bridging an electrical gap for such mechanically isolated features.

(69) In the surface routing method, illustrated in FIGS. **12**A and **12**B, an electrically isolated trace, or wire, can be generated by using a double-undercut profile. FIG. **12**A shows a detailed view of a trace **472**, which couples two or more fixed electrode bond pads **470***a*, according to the depiction provided in FIG. **11**. The trace **472** may be routed around an anchor point **432**, such as that of the biasing element **430**, and bounded on the other side by the moveable electrode **470***b* disposed at an edge of the substrate **110**. In this example, the biasing element **430** and anchor point **432** form part of the moveable electrode **470***b*. FIG. **12**B shows a profile of the trace **472** according to the section taken in FIG. **12**A. The trace **472** may be bounded on either side by an undercut trench **116**. This ensures that the trace **472** is electrically isolated from the surrounding conductive layers **470***b*. Such traces may be routed wherever a continuous, horizontal surface connects two features that must share an electrical contact.

(70) While surface routing of interconnects may be considered to be straightforward, and even preferred, connecting mechanically isolated elements is more challenging. For example, devices arranged in a concentric fashion include enclosed geometries that must be connected electrically, such as the features and methods disclosed in accordance with TRA **400**. Referring to FIG. **11**, the moveable electrodes **410***b* may be mechanically coupled by a pair of inner **422** and outer rings **440**, with the comb crossbars **412** acting as spokes between them. Between the rings and spokes are, as shown, four fixed combs **410***a* that must receive the same electrical signal. In this embodiment/illustration, the mechanical isolation of the combs **410***a* results in electrical isolation as well.

(71) In a first bridging method, wherein an island is connected to another element, shown in FIGS. **13**A and **13**B, a bridge **480** may be formed in the substrate **110** by means of FLS that allows the intervening element, herein depicted as the outer ring **440**, to pass underneath, thereby maintaining mechanical and electrical decoupling with respect to the surrounding features. Referring to FIG. **13**A, the fixed electrode bond pad **470***a* may be coupled to the fixed comb crossbar **412** via bridge **480**, which may be processed glass, sapphire, or other FLS-processable material. Note that, in order for the ring **440** to pass under the bridge **480** without interference, a downward step **442** may be formed in the ring. In the sectional view provided by FIG. **13**B, the outer ring **440** is seen to pass below the glass bridge **480**. Alternatively, the entirety of the ring **440** may provide clearance for the bridge **480**, thereby eliminating the downward step **442**. Importantly, in this embodiment, the conductive layer is shadowed by the bridge **480** in the deposition process, resulting in moveable electrode **470***b* segmentation along the outer ring **440**. However, since no shadowing occurs on the inner ring **422**, the moveable combs **410***b* remain electrically contiguous.

(72) FIGS. **14**A and **14**B illustrate an alternate first method of bridging an island to another element. A thin layer of silicon nitride (SiN.sub.x) **482** may be disposed on the irradiated wafer, prior to FLS processing of the substrate. The layer **482** may be deposited using low-pressure chemical vapor deposition (LPCVD), which may produce a very dense and pinhole-free film that is not attacked or delaminated by the wet chemical etches used for the irradiated glass. After deposition, the SiN.sub.x layer **482** may be patterned into the bridge structure **480** using standard lithography and dry etching, as shown in FIGS. **14**A and **14**B. A downward step **442** for mechanical clearance of the outer ring **440** with respect to the bridge **480** may still be required. However, the step **442** may be made shallower with respect to the previous embodiment, because the bottom of the bridge **480** sits at the original surface of the substrate **110**, as illustrated in FIG. **14**B. One skilled in the art may observe that other layers and process sequences may be used to raise the

bridge above the original surface of the substrate **110**, thereby avoiding the need for the step **442**. The benefit of this alternative may, however, be weighed against the added complexity and cost for a given application.
(73) A second method of bridging an island to another element is shown in FIG. **15**. In a general TRA **400** the fixed electrode bond pads may be isolated from each other by the flexible electrode outer ring **440**, biasing elements **430**, and bond pad **470***b*. Using the isolated trace **472** method in accordance with that depicted in FIGS. **12**A and **12**B two pairs of the fixed electrode bond pads **470***a* may be connected in a north-south direction, leaving two bond pads **470***a* separated from each other in an east-west direction. Since the north and south biasing elements **430** are used to connect the flexible electrode outer ring **440** to the bond pad **470***b*, they must remain uncovered during the sputtering operation, removing the possibility of using a glass or SiN.sub.x bridge. Therefore, to connect the east-west halves of the fixed electrode, one or more bond wires **490***a*, **490***b* may be disposed between them, as illustrated in FIG. **15**. Bond wires, **490***a*, **490***b* should be applied to fixed surfaces only, and may not be suitable for connecting flexible elements. In an alternative connection scheme contemplated within the scope of this disclosure, coupling the four fixed electrodes **470***a* may be achieved with three isolated traces **472** positioned, for example on the west, south, and east sides, while coupling the moveable electrode bond pad **470***b* to the outer ring **440** is accomplished via a single biasing element **430**, as, for example, on the north side. Such interconnection schemes may be subject to cost/performance tradeoffs and/or the specific layout of the actuator.
(74) The femtosecond laser structuring technique used to render the designs of the present invention have also been used to demonstrate various microfluidic channels and systems. Typically lacking from these designs are active components, such as pumps and valves, though they may be later added as discrete components. In one aspect of the present invention, electromotive power to active components, which may be integrated with passive microfluidic systems, is contemplated. The advantages of such a unified technology may include, inter alia, improved performance, such as valve switching speed, high pressure capability, and low power consumption, as well as size and cost benefits, which may include integration and miniaturization of complex systems.
(75) The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein can be applied to other embodiments without departing from the spirit or scope of the invention. For example, a linear-ratcheting actuator may be configured with a vertically oriented ratchet instead of a horizontal one. It is therefore desired that the present embodiments be considered in all respects as illustrative and not restrictive, reference being made to the appended claims as well as the foregoing descriptions to indicate the scope of the invention.

Claims

1. A microelectromechanical device comprising: an insulating substrate characterized by an upper surface defining a plane including a first actuator formed therein, said first actuator comprising: a first electrode disposed on a stationary comb having a first plurality of spaced tines projecting from a first crossbeam; and a second electrode including: a moveable comb including a second plurality of spaced tines projecting from a second crossbeam in a direction, wherein said second plurality of spaced tines meshes with said first plurality of spaced tines in an interdigitated fashion; and at least one biasing element coupled to said moveable comb, wherein the stationary comb, the movable comb, and the at least one biasing element are formed below said plane, wherein said second electrode is electrically decoupled from said first electrode by at least one segmented feature selected from the group consisting of: a trench, an undercut, an overhang, and a suspended element, and wherein, in operation, a variable voltage is applied across said first electrode and said second

electrode to induce displacement of said moveable comb parallel to said plane.
2. The microelectromechanical device according to claim 1 further comprising: a first linkage projecting outwardly from said second crossbeam at a first end of said first linkage, wherein said first actuator is a linear actuator, and wherein said output force is transmitted through to a second end of said first linkage.
3. The microelectromechanical device of claim 2 further comprising: a second linear actuator similarly formed within said insulating substrate and offset at an angle of about 90 degrees with respect to said first linear actuator, said second linear actuator further characterized by a second linkage configured to operate in conjunction with said first linkage of said first linear actuator, said second linkage being electrically decoupled from said first linear actuator, said second linkage being coupled to a second crossbeam of said moveable comb of said second linear actuator at a first end of said second linkage, wherein said output force of said second linear actuator is transmitted through to a second end of said second linkage, wherein, in operation, synchronized waveforms induce rotation of a cog assembly coupled to said first and second actuator portions.
4. The microelectromechanical device of claim 3, wherein said cog assembly further comprises a rotational joint coupling said second ends of said first and second linkages to a drive cog, said drive cog comprising a spindle disposed thereunder and to spin thereon, said drive cog being coupled to a transmission cog configured to effect a desired gear ratio or output a desired mechanical torque, wherein said rotational joint and said spindle are formed within said insulating substrate in a manner which does not inhibit movement of the same after completion of a conformal deposition process.
5. The microelectromechanical device of claim 1 further comprising: a first ratchet pawl coupled to said second end of said first linkage, wherein said first actuator is a linear actuator, said first ratchet pawl configured to engage a ratchet causing the same to rotate in a forward direction about a spindle disposed thereunder, thereby converting a linear motion to a rotational motion; and one or more anti-reverse pawls configured to engage said ratchet thereby preventing the same from rotating in a reverse direction, wherein the engagement of said first ratchet pawl with said ratchet occurs during a forward stroke of the linkage beam.
6. The microelectromechanical device of claim 5 further comprising: a second ratchet pawl disposed on an opposite side of said ratchet, said second ratchet pawl configured to engage said ratchet thereby causing the same to rotate in a forward direction about a spindle disposed thereunder, wherein the engagement of said second ratchet pawl with said ratchet occurs during a reverse stroke of the linkage.
7. The microelectromechanical device of claim 1 further comprising: a circularly disposed ratchet, wherein said first actuator comprises one or more rotational actuators radially arrayed adjacent to said circularly disposed ratchet, each of said moveable combs of said one or more rotational actuators including said one or more biasing elements being disposed radially at a first end of said moveable comb, one or more ratchet pawls disposed radially at a second end of said moveable comb of said one or more rotational actuators, said one or more ratchet pawls configured to engage said ratchet causing the same to rotate in a forward direction about a central axis, thereby converting a reciprocal rotational motion of said rotational actuators into a complete rotational motion of said circularly disposed ratchet.
8. The microelectromechanical device of claim 7 further comprising a linkage configured to couple said moveable comb of said one or more rotational actuators to said one or more ratchet pawls.
9. A silicon microelectromechanical device comprising: a first, stationary comb having a first plurality of spaced fingers extending from a first crossbeam; a second, moveable comb having a first plurality of spaced fingers extending from a second crossbeam toward the first crossbeam and meshing with the first plurality of fingers in an interdigitated fashion; at least one biasing element coupled to said second comb, said second comb configured to move in one dimension, said one dimension characterized by movement in a first direction in response to an applied voltage, and

movement in a second direction upon removal of said applied voltage; and a ratchet pawl including first and second branches coupled to said second comb; and one or more anti-reverse pawls configured to engage said ratchet thereby preventing the same from rotating in an opposite rotational direction; wherein said first branch, upon movement of said second comb in said first direction, is configured to engage a ratchet wheel to cause said ratchet wheel to rotate in a rotational direction; and wherein said second branch, upon movement of said second comb in said second direction, is configured to engage said ratchet wheel to cause said ratchet wheel to rotate in said rotational direction.