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(54) **HYBRID ORGANIC-INORGANIC MICROMIRROR DEVICE AND METHOD OF MAKING A HYBRID MICRODEVICE**

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(52) **U.S. Cl.**
CPC ***G02B 26/0841*** (2013.01); ***G02B 1/02*** (2013.01); *B29C 39/025* (2013.01);
(Continued)

(58) **Field of Classification Search**
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(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,751,009 B2	6/2004	Khoshnevisan et al.
2004/0012460 A1	1/2004	Cho et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP	2 784 566 A1	10/2014

OTHER PUBLICATIONS

Armani, Deniz et al., "Re-Configurable Fluid Circuits by PDMS Elastomer Micromachining," *Micro Electro Mechanical Systems* (*MEMS* '99), Twelfth IEEE International Conference (1999) pp. 222-227.

(Continued)

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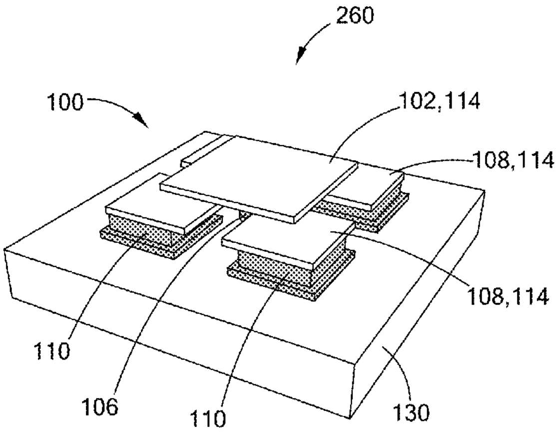
(74) *Attorney, Agent, or Firm* — Brinks Gilson & Lione

(57) **ABSTRACT**

A hybrid organic-inorganic micromirror device includes a micromirror comprising an inorganic material positioned above an elastomeric substrate. The micromirror is supported on an underside thereof by a conductive elastomeric support protruding from the elastomeric substrate. The conductive elastomeric support may function as a universal joint and is rendered electrically conductive by an electrically conductive coating thereon. A plurality of electrodes are disposed on the elastomeric substrate under the micromirror. The electrodes are spaced apart from each other and from the micromirror and are arranged around the conductive elastomeric support. Each electrode comprises an inorganic material and is in electrical contact with an elastomeric contact region protruding from the elastomeric substrate. When a voltage bias is applied between the micromirror and one or more of the electrodes, the micromirror is electrostatically actuated to move in a predetermined direction.

11 Claims, 6 Drawing Sheets



(51) **Int. Cl.**

B29C 39/02	(2006.01)
B29K 83/00	(2006.01)
B29K 105/00	(2006.01)
B29L 11/00	(2006.01)

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CPC .. *B29K 2083/00* (2013.01); *B29K 2105/0058* (2013.01); *B29L 2011/0058* (2013.01)

(58) **Field of Classification Search**
CPC B29L 2011/0058; B29K 2083/00; B29K 2105/0058; G02B 26/0841; G02B 1/02; G02B 26/08
USPC 359/221.2
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2004/0165250	A1	8/2004	Aubuchon	
2006/0038182	A1*	2/2006	Rogers	B82Y 10/00 257/77
2010/0149622	A1	6/2010	McAvoy et al.	

OTHER PUBLICATIONS

Bhaswara, A. et al., "Fabrication of Nanoplate Resonating Structures Via Micro-Masonry," *J. Micromech. Microeng.*, 24 (2014) pp. 115012-115019.

Duffy, David C. et al., "Rapid Prototyping of Microfluidic Systems in Poly(dimethylsiloxane)," *Anal. Chem.*, 70 (1998) pp. 4974-4984.

Jung, Il Woong et al., "High Fill-Factor Two-Axis Gimbaled Tip-Tilt-Piston Micromirror Array Actuated by Self-Aligned Vertical Electrostatic Combdrives," *Journal of Microelectromechanical Systems*, 15, 3 (2006) pp. 563-571.

Kim, Seok et al., "Imbricate Scales as a Design Construct for Microsystem Technologies," *Small*, 8, 6 (2012) pp. 901-906.

Kim, Seok et al., "Microstructured Elastomeric Surfaces with Reversible Adhesion and Examples of their Use in Deterministic Assembly by Transfer Printing," *PNAS*, 107, 40 (2010) pp. 17095-17100.

Milanovic, Veljko et al., "Gimbal-Less Monolithic Silicon Actuators for Tip-Tilt-Piston Micromirror Applications," *IEEE Journal of Selected Topics in Quantum Electronics*, 10, 3 (2004) pp. 462-471.

Ning, Hailong et al., "Transfer-Printing of Tunable Porous Silicon Microcavities with Embedded Emitters," *ACS Photonics*, 1 (2014) pp. 1144-1150.

Solgaard, Olav et al., "Optical MEMS: From Micromirrors to Complex Systems," *Journal of Microelectromechanical Systems*, 23, 3 (2014) pp. 517-538.

Tsai, Jui-che et al., "Gimbal-Less MEMS Two-Axis Optical Scanner Array With High Fill-Factor," *Journal of Microelectromechanical Systems*, 14, 6 (2005) pp. 1323-1328.

Tung, Yi-Chung et al., "A Single-Layer PDMS-on-Silicon Hybrid Microactuator With Multi-Axis Out-of-Plane Motion Capabilities—Part II: Fabrication and Characterization," *Journal of Microelectromechanical Systems*, 14, 3, (2005) pp. 558-566.

Zeng, Hongjun et al., "Tilting Micromirror With a Liquid-Metal Pivot," *Journal of Microelectromechanical Systems*, 15, 6 (2006) pp. 1568-1575.

Zhang, Yong et al., "Micro-Masonry of MEMS Sensors and Actuators," *Journal of Microelectromechanical Systems*, 23, 2 (2013) pp. 308-314.

* cited by examiner

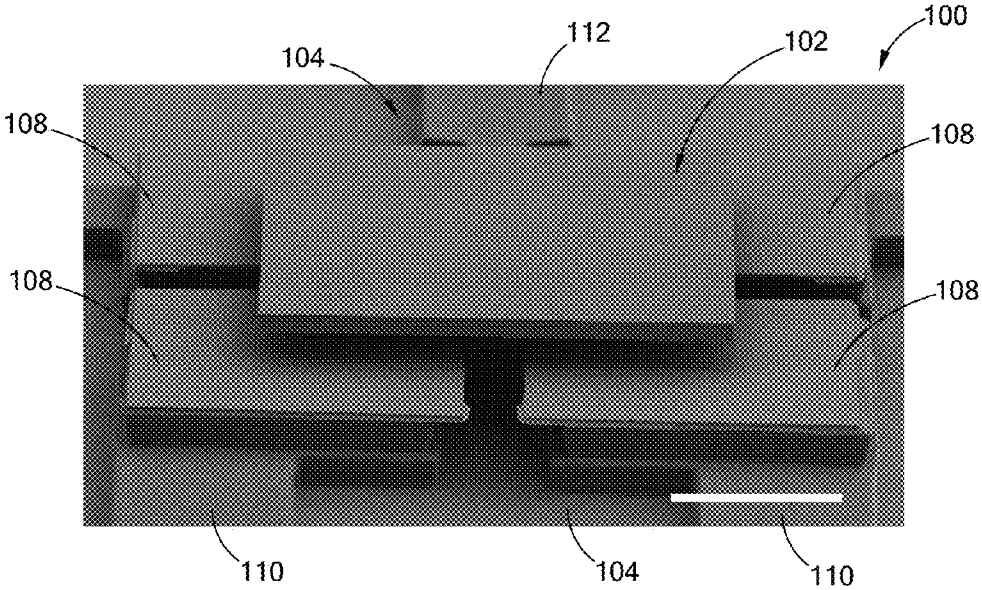
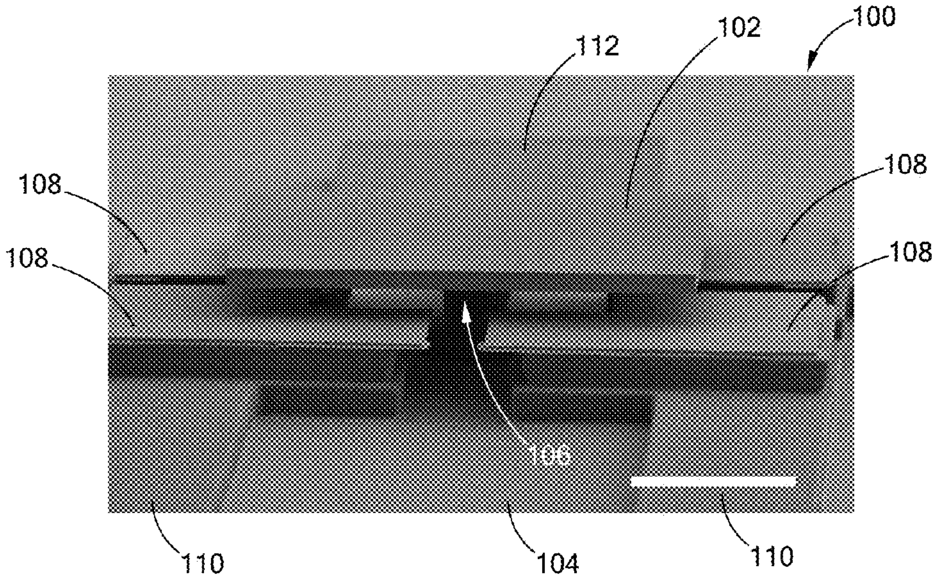

100
104
112
102
108
108
108
108
110
104
110

FIG. 1A


100
112
102
108
108
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108
106
110
104
110

FIG. 1B

FIG. 2A

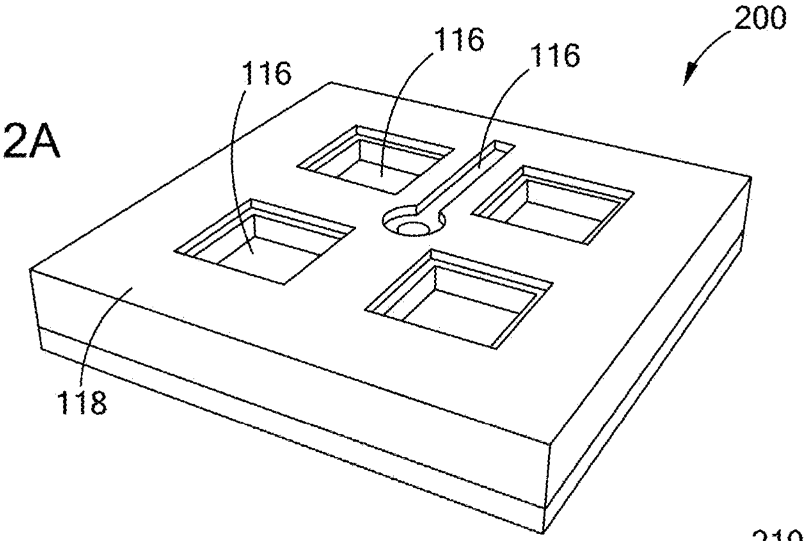


FIG. 2B

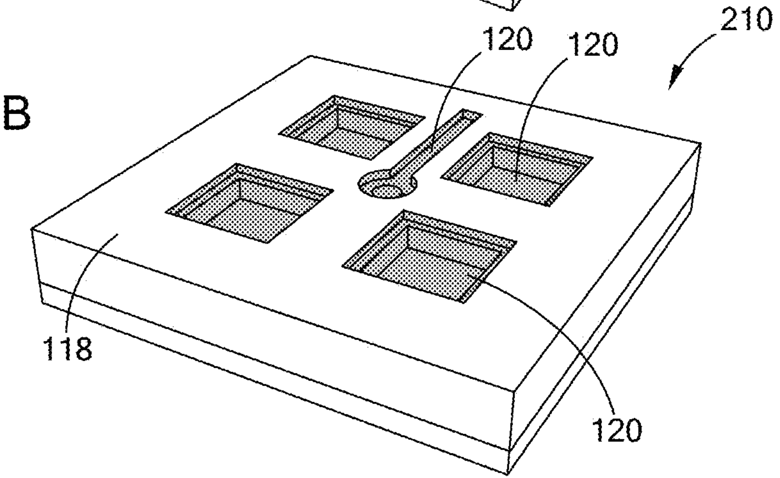


FIG. 2C

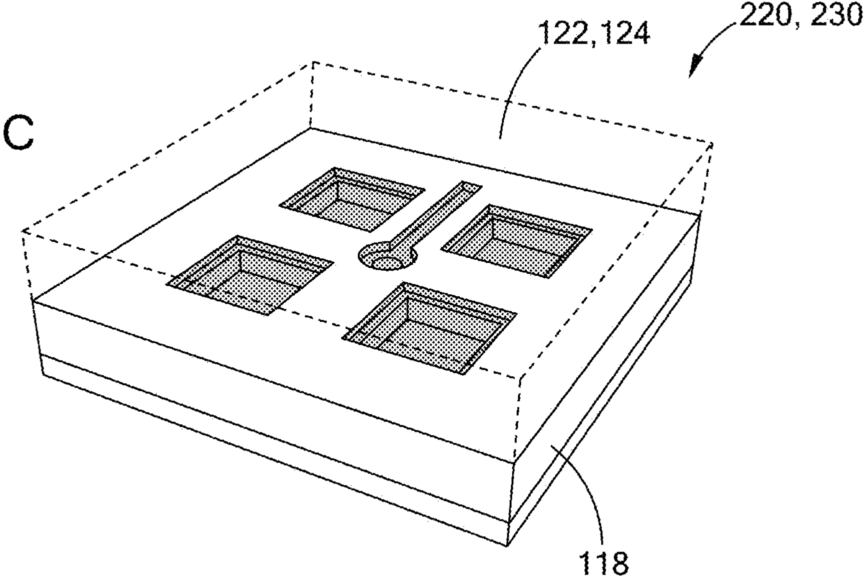


FIG. 2D

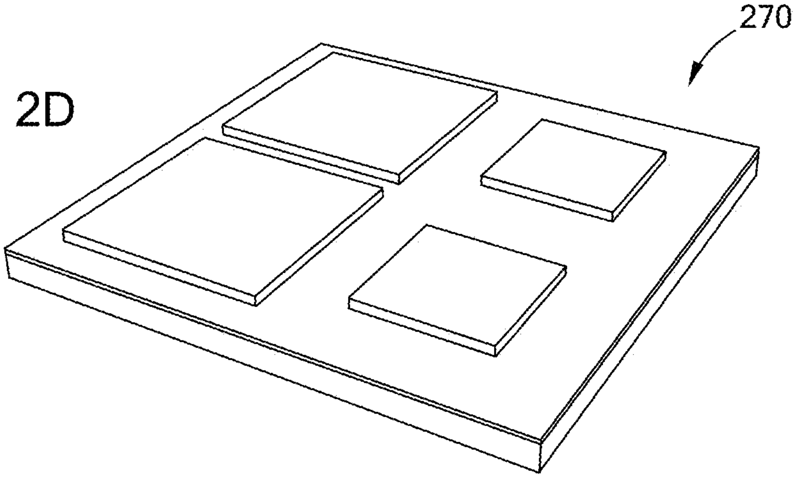


FIG. 2E

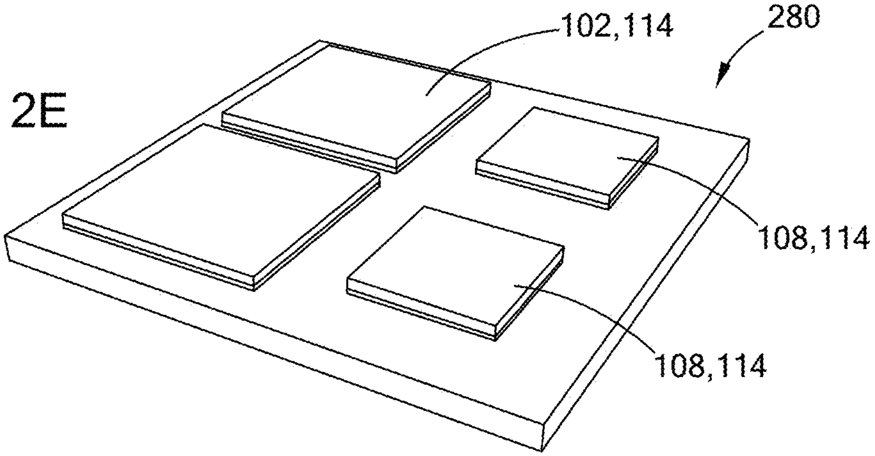
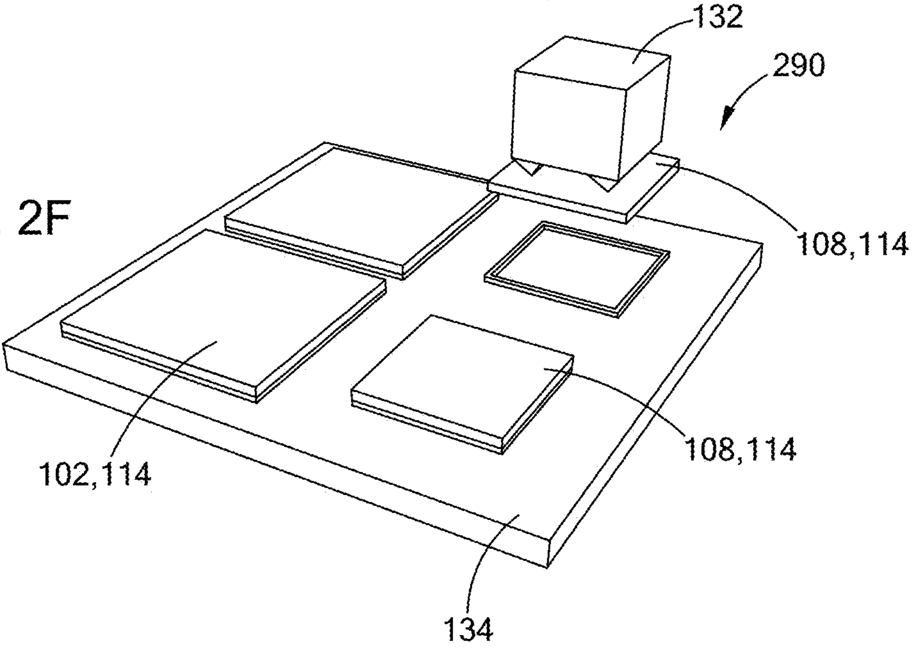


FIG. 2F



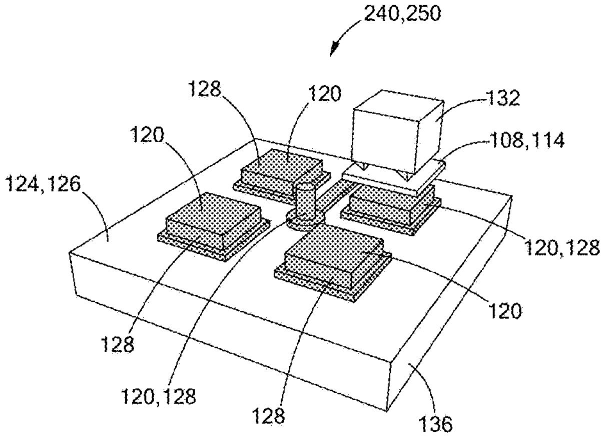

240,250
128
120
132
120
108,114
124,126
120,128
120
128
120,128
128
136

FIG. 2G

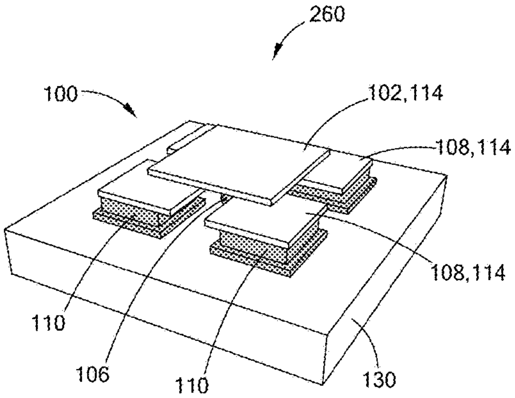

260
100
102,114
108,114
108,114
110
106
110
130

FIG. 2H

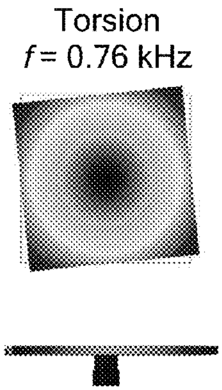


FIG. 3A

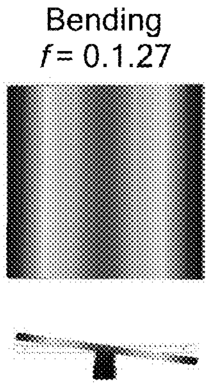


FIG. 3B

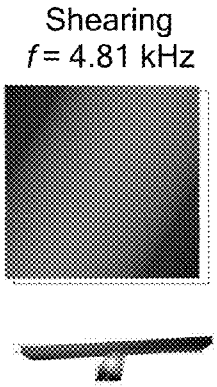


FIG. 3C

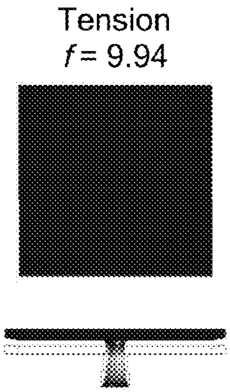


FIG. 3D

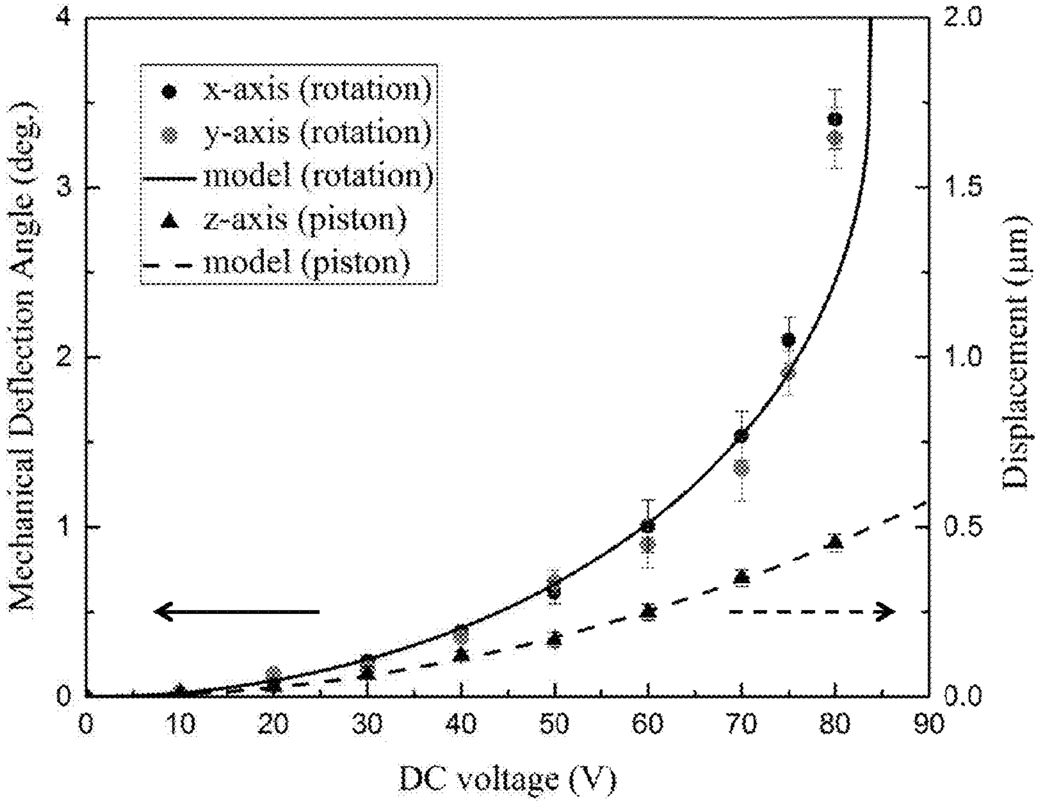


FIG. 4

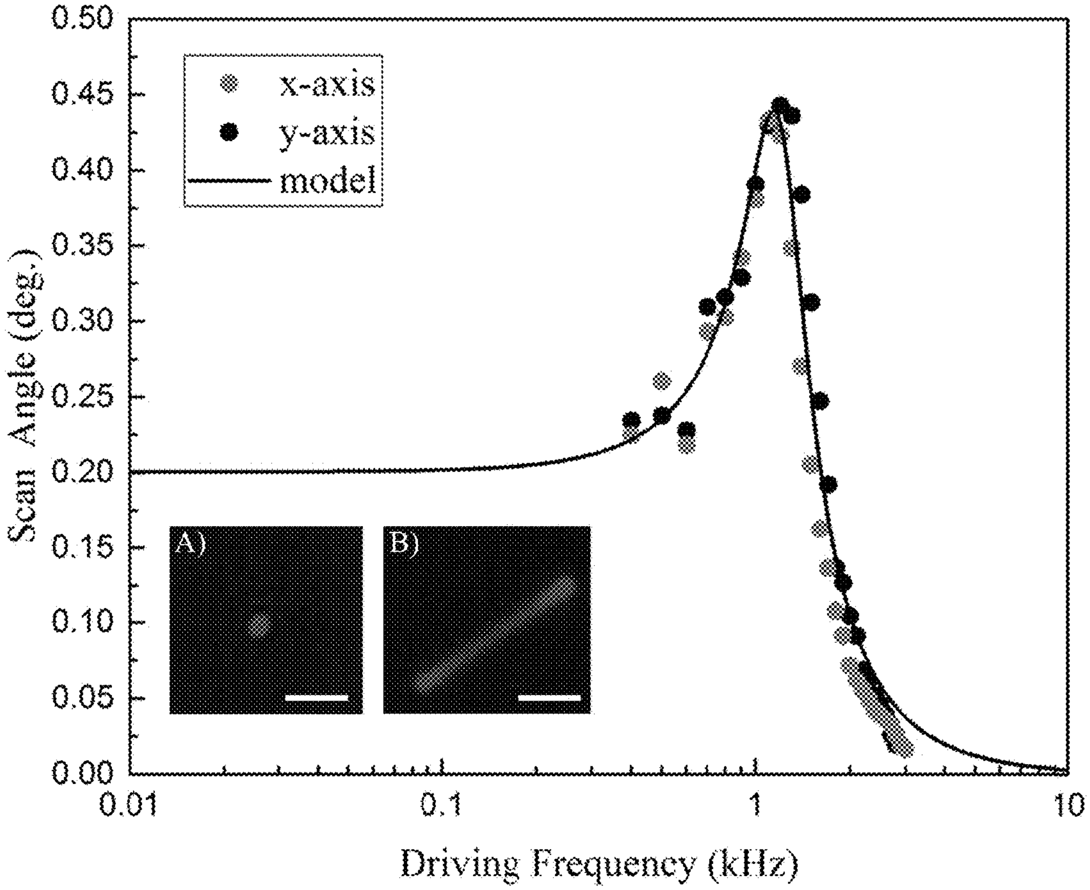

0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Scan Angle (deg.)
0.01
0.1
1
10
Driving Frequency (kHz)
x-axis
y-axis
model
A)
B)

FIG. 5

HYBRID ORGANIC-INORGANIC MICROMIRROR DEVICE AND METHOD OF MAKING A HYBRID MICRODEVICE

RELATED APPLICATIONS

The present patent document claims the benefit of priority under 35 U.S.C. §119(e) to U.S. Provisional Patent Application No. 62/113,099, filed Feb. 6, 2015, which is hereby incorporated by reference in its entirety.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under contract number 917 NSF CMMI 13-51370 CAR awarded by the National Science Foundation. The government has certain rights in the invention.

TECHNICAL FIELD

The present disclosure is related generally to microfabrication technology and more specifically to a hybrid organic-inorganic micromirror device.

BACKGROUND

Microelectromechanical systems (MEMS) technology-based micromirrors are having an impact on areas such as projection displays, telecommunications, adaptive optics and biomedical imaging. Common silicon-based MEMS micromirrors are designed with an optical reflector suspended on a set of silicon torsional springs. Monolithic microfabrication including surface micromachining and bulk micromachining processes are typically used to realize such structures. However, the conventional design and fabrication approaches exhibit several fundamental challenges. Silicon is susceptible to cleavage fracture under large deformations as well as to fatigue failure under cyclic loading. In addition, microscale springs are usually needed to obtain a reasonable (low) stiffness due to the high elastic modulus of silicon, and such small features are susceptible to photolithographic errors. Finally, complex mechanical design and fabrication steps are typically required to realize a two-axis micromirror. A gimbaled structure may provide an additional degree of freedom to enable two-axis motion, but it suffers from limitations, such as a large footprint and unequal frequency responses with respect to the two axes.

BRIEF SUMMARY

Described herein is a hybrid organic-inorganic micromirror device that has advantages over previous micromirror assemblies. Also described is a method of making a hybrid organic-inorganic microelectromechanical systems (MEMS) device.

The micromirror device includes a micromirror comprising an inorganic material positioned above an elastomeric substrate. The micromirror is supported on an underside thereof by a conductive elastomeric support protruding from the elastomeric substrate. The conductive elastomeric support may function as a universal joint and is rendered electrically conductive by an electrically conductive coating thereon. A plurality of electrodes are disposed on the elastomeric substrate under the micromirror. The electrodes are spaced apart from each other and from the micromirror and are arranged around the conductive elastomeric support.

Each electrode comprises an inorganic material and is in electrical contact with an elastomeric contact region protruding from the elastomeric substrate. When a voltage bias is applied between the micromirror and one or more of the electrodes, the micromirror is electrostatically actuated to move in a predetermined direction.

The method entails forming a plurality of trenches in a surface of a mold, and coating the trenches with an electrically conductive coating. An uncured elastomer is applied to the surface of the mold so as to fill the trenches and cover the surface. The uncured elastomer is partially cured to form a tacky elastomeric body comprising protruding regions defined by the trenches. The protruding regions contact the electrically conductive coating and attach thereto. The tacky elastomeric body is removed from the mold, and the electrically conductive coating is transferred with the protruding regions during the removal. The tacky elastomeric body may be flipped over to form a receiver substrate comprising conductive-coated protrusions. A plurality of functional inorganic components are placed on the receiver substrate, where each functional inorganic component is in contact with one of the conductive-coated protrusions. The receiver substrate is fully cured to bond the functional inorganic components to the conductive-coated protrusions.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A and **1**B are scanning electron microscope (SEM) images of an exemplary fabricated micromirror device. The scale bars are 200 microns.

FIGS. **2**A-**2**C show exemplary steps in fabricating a partially-cured elastomeric body that includes conductive surface portions and may be used as a receiver substrate; FIGS. **2**D-**2**E show exemplary steps in fabricating inorganic functional components on a donor substrate prior to transfer to the receiver substrate; and FIGS. **2**F-**2**H show exemplary steps in transfer printing to place the inorganic functional components onto the receiver substrate followed by curing to form a hybrid organic-inorganic micromirror device.

FIGS. **3**A-**3**D show the results of a finite element modal analysis of an exemplary micromirror device. The micromirror has four different resonant modes corresponding to torsion, bending, shearing and tension/compression deformation of the conductive elastomeric support (universal joint).

FIG. **4** shows DC characteristics of the micromirror device for x-axis rotation, y-axis rotation and z-axis compressive piston motion.

FIG. **5** shows frequency response for x- and y-axis rotations, where the resonant frequency is about 1.2 kHz for both axes. Inset images show the laser scanning trajectory at 0 Hz (A) and 1.2 Hz (B); the scale bars are 1 cm.

DETAILED DESCRIPTION

Hybrid organic-inorganic MEMS devices such as micromirrors that include both inorganic and organic components mechanically and electrically integrated together are described herein. An exemplary micromirror device driven by electrostatic actuation is based on a highly doped silicon mirror (inorganic component) that is mechanically bonded and electrically connected to a conductive elastomeric universal joint (organic component). To realize such hybrid organic-inorganic MEMS devices, newly developed transfer printing-based microassembly techniques that allow the inorganic and organic components to be fabricated separately and integrated afterwards may be employed.

An exemplary micromirror device **100** is shown in the scanning electron microscope (SEM) images of FIGS. **1**A and **1**B. A micromirror **102** comprising an inorganic material is positioned above an elastomeric substrate **104**. The micromirror **102** is supported on an underside thereof by a conductive elastomeric support **106** that protrudes from the elastomeric substrate **104** and functions as a universal joint to permit multi-directional motion of the micromirror **102**. Both the elastomeric substrate **104** and the conductive elastomeric support **106** comprise an elastomer. The conductive elastomeric support **106** may be rendered electrically conductive by an electrically conductive coating thereon. The electrically conductive coating may also overlie an additional portion of the elastomeric substrate to form a conductive extension portion **112** in electrical contact with the conductive elastomeric support **106**.

A plurality of (at least two) electrodes **108** are disposed on the elastomeric substrate **104** under the micromirror **102**. The electrodes **108** are spaced apart from each other and from the micromirror **102** and are arranged around the conductive elastomeric support **106**. Each electrode **108** comprises an inorganic material and is in electrical contact with an elastomeric contact region **110** protruding from the elastomeric substrate **104**. Each elastomeric contact region **110** comprises an elastomer and may be rendered electrically conductive by an electrically conductive coating thereon.

The micromirror **102** and the electrodes **108** may form a parallel-plate electrostatic actuator. When a voltage bias is applied to one or more of the electrodes (e.g., via one or more of the elastomeric contact regions **110**) and to the micromirror (e.g., via the conductive elastomeric support **106** and the conductive extension portion **112**), the micromirror **102** may be electrostatically actuated to move in a predetermined direction. A voltage bias of at least 10 V, at least 20 V or at least 40 V may be suitable for electrostatic actuation. Typically, the voltage bias is 100 V or less, and may be 80 V or less, or 60 V or less. Due to the flexibility of the elastomer, the hybrid organic-inorganic micromirror device can sustain enormous deformations and accommodate three-dimensional motion, such as tip-tilt-piston, with a compact gimbal-less design.

As described in detail below in reference to FIGS. **2**A-**2**H, the elastomeric contact regions **110** and the conductive elastomeric support **106** may be integrally formed with the elastomeric substrate **104** as a monolithic elastomeric body that includes a substantially nonconductive bulk portion **136** and a number of conductive surface portions **128** (e.g., the elastomeric contact regions, the conductive elastomeric support, and/or the conductive extension portion). The conductive surface portions **128** may be rendered conductive by application of an electrically conductive coating **120** thereto, and may also be referred to as conductive-coated protrusions **128**.

The electrically conductive coating may comprise a plurality of conductive particles. The conductive particles may be arranged in one or more layers or in another percolating arrangement that covers all or at least a portion of the elastomeric region of interest. The conductive particles may comprise any suitably electrically conductive material, such as carbon, a metal or an alloy. For example, the conductive particles may be selected from the group consisting of: carbon particles (e.g., carbon black), carbon nanotubes and metal particles. The size of the conductive particles typically ranges from the nanoscale to the microscale (e.g., from about 1 nm to about 10 microns in average diameter or width, or from about 10 nm to about 1 micron in average diameter or width). Suitable conductive particles may include VULCAN® XC-72 carbon black particles produced by Cabot Corporation (Boston, Mass.).

The elastomeric body, including the elastomeric substrate, the elastomeric contact regions, the conductive elastomeric support and/or the conductive extension portion, may comprise one or more elastomers selected from the group consisting of polydimethylsiloxane (PDMS) and polyurethane (PU). In the example described below, PDMS (e.g., Sylgard® 184 from Dow Corning) is employed due to its excellent mechanical properties and well-established fabrication processes.

The micromirror and the electrodes may comprise the same inorganic material or different inorganic materials. The inorganic material advantageously has a low resistivity so as to be electrically conductive, and it may be single crystalline or polycrystalline in structure. Suitable inorganic materials may include metals, alloys, or doped semiconductors. In one example, the inorganic material may be doped silicon or, more specifically, single-crystalline doped silicon. The doped silicon or other doped semiconductor may include one or more suitable dopants, such as boron and/or phosphorus, preferably at a dopant level sufficient to achieve a resistivity ρ of about 0.01 Ω-cm or less, about 0.005 Ω-cm or less, or about 0.001 Ω-cm or less. Highly doped single-crystalline silicon may be obtained from Ultrasil Corporation (Hayward, Calif.), for example.

To achieve tilting of the micromirror about a single axis, the micromirror device may be constructed using two electrodes, and the elastomeric substrate may include two elastomeric contact regions. Advantageously, to permit tilting of the micromirror in any direction, four (or more) electrodes may be used in conjunction with four (or more) elastomeric contact regions. The conductive elastomeric support may be referred to as a universal joint because it can permit translational and rotational motion of the micromirror in any direction (e.g., x translation, y translation, z translation, x rotation, y rotation, z rotation).

The dimensions of the micromirror and the spacing between the micromirror and the electrodes may be influenced by the size and stiffness of the conductive elastomeric support. Typically, the micromirror may have a length and/or width in the range of from about 10 microns to about 1 mm. The length and width of the micromirror may be the same, as shown in FIGS. **1**A and **1**B, or different. The thickness of the micromirror is typically considerably smaller than the length or width (e.g., about 30% or less, or about 10% or less, of the length or width). The electrodes may have similar or smaller dimensions to the micromirror. In the example shown in FIGS. **1**A and **1**B, the mirror and the electrodes have dimensions of $500\times500\times20\ \mu m^3$ and $350\times350\times3\ \mu m^3$, respectively, and the conductive elastomeric support (or universal joint) has a cylindrical shape with a height of 80 microns and a diameter of 60 microns. The conductive elastomeric support need not be cylindrical, although this shape may be advantageous to promote symmetric tilting of the micromirror. Generally speaking, the conductive elastomeric support may have a height in the range of from about 10 microns to about 200 microns and a diameter or thickness from about 5 microns to about 150 microns. The air gap between the mirror and the electrodes in the example of FIGS. **1**A and **1**B is 37 microns, but may more generally range from about 5 microns to about 100 microns.

A method of making a hybrid organic-inorganic microelectromechanical systems (MEMS) device, such as the micromirror device described above, is now described in reference to FIGS. **2**A-**2**H.

Referring to FIG. **2**A, the method entails forming **200** a plurality of trenches **116** in a surface of a mold **118**, and then coating **210** surfaces of the trenches **116** with an electrically conductive coating **120**, as shown in FIG. **2**B. An uncured elastomer **122** is applied **220** to the surface of the mold **118** so as to fill the trenches **116** and cover the surface, as illustrated in FIG. **2**C. The uncured elastomer **122** is then partially cured **230** to form a tacky elastomeric body **124** comprising protruding regions defined by the trenches that contact and attach to the electrically conductive coating **120**. The tackiness of the elastomeric body **124** is due to the (only) partial curing of the elastomer.

Referring to FIG. **2**G, the tacky elastomeric body **124** is removed **240** from the mold and may be flipped over to form a (tacky) receiver substrate **126**. During the removal, the electrically conductive coating **120** remains attached to and is transferred with the protruding regions, and thus the receiver substrate **126** includes conductive-coated protrusions **128**.

A plurality of functional inorganic components **114** may be placed **250** on the receiver substrate **126**. More specifically, each functional inorganic component **114** may be placed in contact with one of the conductive-coated protrusions **128**, as illustrated in FIG. **2**G. The receiver substrate is then fully cured **260** to obtain an elastomeric substrate **130** and to bond the functional inorganic components **114** to the conductive-coated protrusions **128**, as shown in FIG. **2**H; thus, a hybrid organic-inorganic MEMS device is formed. When the MEMS device is a micromirror device **100**, the functional inorganic components **114** may include a micromirror **102** and a plurality of electrodes **108**, each comprising an electrically conductive material such as a doped semiconductor, a metal or an alloy, as described above. The uncured elastomer employed to form the receiver substrate **126** may comprise an uncured polymer selected from the group consisting of uncured polydimethylsiloxane (PDMS) and uncured polyurethane (PU). The mold **118** shown in FIG. **2**A may comprise an epoxy structure formed on a substrate (such as silicon wafer or glass), and the trenches **116** may be formed in the surface of the mold **118** by photolithographic patterning of the epoxy.

The coating of the trenches **116** with the conductive coating **120** may entail applying a dispersion of conductive particles in a solvent to the mold and then evaporating the solvent, thereby depositing the conductive particles in one or more layers on the surface of the mold and in the trenches. The conductive particles may be removed from the surface of the mold (e.g., using pressure sensitive tape), leaving the conductive particles only in the trenches, and thereby forming the desired conductive coating.

Partially curing the uncured elastomer may comprise heating the uncured elastomer to a suitable curing temperature for a time duration insufficient to achieve complete curing or crosslinking. Thus, the uncured elastomer may be partially cured and may have a tacky or sticky consistency. Typically, partial curing is achieved by heating at the curing temperature of the elastomer (e.g., in the range of about 50° C.-70° C. for PDMS) for a time duration less than half of the full curing duration (e.g., about 1 hour or less at 60° C. for PDMS). Fully curing the tacky elastomeric body may entail heating the body at the curing temperature (e.g., in the range of about 50° C.-70° C.) for a time duration sufficient to achieve complete curing or crosslinking (e.g., at least 2 hours at 60° C. for PDMS).

Placing the functional inorganic components **114** on the tacky receiver substrate **126** may be carried out by transfer printing using a microscale stamp **132**, as shown in FIGS. **2**F-**2**G. For example, the methods described in U.S. Patent Application Publication No. 2015-0352586A1, entitled "Microscale Stamp with Reversible Adhesion," which is hereby incorporated by reference in its entirety, may be employed. The microscale stamp **132** used for transfer printing may comprise a shape memory polymer.

EXAMPLE

An exemplary fabrication procedure of a micromirror device is described here. The method may include the preparation of donor and receiver substrates **134**,**126** and the assembly of the final devices **100**. Referring to FIGS. **2**D-**2**F, silicon mirrors **102** and electrodes **108** may be batch fabricated on their donor substrates **134** using two types of silicon-on-insulator (SOI) wafers with 20-μm-thick and 3-μm-thick device layers. FIG. **2**D shows etching **270** of the device layer of an SOI wafer; FIG. **2**E shows undercutting **280** of the buried oxide (BOX) layer and patterning of photoresist anchors; and FIG. **2**F shows etching away of the remaining BOX layer using hydrofluoric acid, so that the inorganic functional components **114** (silicon mirrors **102** and electrodes **108**) can be picked up **290** and transferred (e.g., by a microtip stamp **132**) to a receiver substrate **126**.

The fabrication of the elastomeric body **124** that becomes the receiver substrate **126** is shown in FIGS. **2**A-**2**C. In this example, a three-layer-SU8 mold **118** is patterned using photolithography and is then silanized to help demolding (FIG. **2**A). A carbon black (CB)/toluene dispersion is applied on the mold. After complete evaporation of the toluene, the entire mold is left coated with a substantially uniform layer of carbon black particles. Excess carbon black particles on the surface of the mold **118** can be removed by commercial pressure sensitive tapes such that only the surfaces of the trenches **116** remain coated with a conductive coating **120** of carbon black particles (FIG. **2**B).

A PDMS precursor **122** is then poured onto the mold **118** and partially cured at 60° C. for 30 min, as shown in FIG. **2**C. After demolding, the partially cured PDMS body **124**, including conductive PDMS regions **128** and a non-conductive PDMS base **136**, is mounted on a rigid glass substrate to complete the preparation of a receiver substrate **126** (FIG. **2**G). Referring to FIG. **2**F-**2**G, a deterministic transfer printing technique using a microtip elastomeric stamp **132** is employed to pick up the silicon components **114** from the donor substrate **134** and place them on the receiver substrate **126** with about 3 μm alignment accuracy. Upon completion of the pick-and-place procedure via transfer printing, the PDMS receiver substrate **124** is further cured at 60° C. for approximately 12 hours to form a fully cured elastomeric substrate **130**. Accordingly, the silicon and PDMS components may be bonded together through surface hydroxyl condensation reactions. The entire transfer printing-based microassembly process, including transfer printing and thermal bonding, may be carried out with a yield of at least about 90%.

The resulting micromirror device **100** may include an elastomeric support or universal joint **106** extending from the substrate **104**, a top mirror **102** on the elastomeric support **106**, and four bottom electrodes **108**, as shown in FIGS. **1**A, **1**B and **2**H. In this example, the mirror **102** and electrodes **108** are made of highly doped single crystal silicon with minimal resistivity (ρ=0.001 Ω-cm), which can be obtained from Ultrasil Corporation. PDMS (Sylgard® 184, Dow Corning) is employed as the elastomeric material, and carbon black (CB) particles (VULCAN® XC-72, Cabot Corporation) are embedded at selected regions of the PDMS structures to form the conductive coating **120**. The size of the mirror **102** and the electrodes **108** are 500 μm×500 μm×20 μm and 350 μm×350 μm×3 μm, respectively, and the universal joint **106** is 80 μm in height with a 60 μm diameter. In this example, the spacing or air gap between the mirror **102** and electrodes **108** is 37 μm.

To model the static and dynamic behaviors of the exemplary micromirror, finite element analysis is performed using COMSOL 4.3b. Referring to FIGS. **3A**-**3D**, four modes with resonant frequencies of 0.76 kHz, 1.27 kHz, 4.81 kHz and 9.94 kHz are captured by modal analysis, corresponding to the torsion (z-axis), bending (x- and y-axis), shearing (x- and y-axis) and tension (z-axis) of the elastomeric support (or universal joint). The Young's modulus of PDMS is assumed to be 0.75 MPa in this modal analysis. It is noted that two modes exist at 1.27 kHz corresponding to the bending motions about two orthogonal scanning axes. With perfect symmetry, they degenerate to a single mode due to their identical resonant frequencies. The same holds for the two shearing modes.

The static behavior of the exemplary micromirror is characterized by applying a DC voltage to the device and measuring the resultant deflection using an optical profiler (NT1000, Veeco). The results for both x- and y-axis rotations and z-axis piston from three devices are shown in FIG. **4**. Due to its symmetric shape, the micromirror exhibits almost identical DC characteristics about x and y axes. Snap-down occurs under a DC voltage of 90 V. The piston stroke is also characterized by applying the same voltage to all the electrodes simultaneously. The frequency response of the exemplary device is also characterized, as shown in FIG. **5**. A sinusoidal actuation signal with an DC offset expressed as $V(t)=10\sin(2\pi f_{act}t)+10$ (V) is applied to actuate the mirror about the x- or y-axis while a collimated laser is directed onto the mirror. The length of each reflected pattern is measured under different driving frequencies to calculate the scan angles. The results are fitted to a Lorentzian function in FIG. **5**. Resonant frequencies for x and y-axis rotations are determined to be 1.2 kHz, which match with the values estimated by the prior finite element analysis. The quality factors for both axes are also determined to be equal to 2.1.

Observations from FIGS. **4** and **5** reveal that the characteristics for both x and y-axes are almost identical, which is difficult to achieve using a gimbaled structure. This property can be quite beneficial as it fully utilizes the advantage of the universal joint, e.g., a maximized response along all possible directions at a single resonant frequency. In addition, the measured scan angles and resonant frequencies of the micromirror devices in this example are comparable to those of existing microfabricated mirrors, and they validate the device fabrication capabilities of the transfer printing-based microassembly technique described in this disclosure.

Although the present invention has been described in considerable detail with reference to certain embodiments thereof, other embodiments are possible without departing from the present invention. The spirit and scope of the appended claims should not be limited, therefore, to the description of the preferred embodiments contained herein. All embodiments that come within the meaning of the claims, either literally or by equivalence, are intended to be embraced therein.

Furthermore, the advantages described above are not necessarily the only advantages of the invention, and it is not necessarily expected that all of the described advantages will be achieved with every embodiment of the invention.

The invention claimed is:

1. A hybrid organic-inorganic micromirror device comprising:

a micromirror comprising an inorganic material positioned above an elastomeric substrate, the micromirror being supported on an underside thereof by a conductive elastomeric support protruding from the elastomeric substrate, the conductive elastomeric support functioning as a universal joint and being rendered electrically conductive by an electrically conductive coating thereon;

a plurality of electrodes disposed on the elastomeric substrate under the micromirror, the electrodes being spaced apart from each other and from the micromirror and being arranged around the conductive elastomeric support, each electrode comprising an inorganic material and being in electrical contact with an elastomeric contact region protruding from the elastomeric substrate,

wherein, when a voltage bias is applied between the micromirror and one or more of the electrodes, the micromirror is electrostatically actuated to move in a predetermined direction.

2. The hybrid organic-inorganic micromirror device of claim **1**, wherein the inorganic material is selected from the group consisting of: a doped semiconductor, a metal and an alloy.

3. The hybrid organic-inorganic micromirror device of claim **2**, wherein the inorganic material is doped silicon.

4. The hybrid organic-inorganic micromirror device of claim **2**, wherein the inorganic material comprises a single-crystalline structure.

5. The hybrid organic-inorganic micromirror device of claim **1**, wherein the electrically conductive coating comprises a plurality of conductive particles.

6. The hybrid organic-inorganic micromirror device of claim **5**, wherein the conductive particles are selected from the group consisting of: carbon particles, carbon nanotubes and metal particles.

7. The hybrid organic-inorganic micromirror device of claim **1** comprising four of the electrodes symmetrically positioned about the conductive elastomeric support.

8. The hybrid organic-inorganic micromirror device of claim **1**, wherein the elastomeric substrate, the conductive elastomeric support and the elastomeric contact regions comprise an elastomer selected from the group consisting of: polydimethylsiloxane (PDMS) and polyurethane (PU).

9. The hybrid organic-inorganic micromirror device of claim **1**, wherein the elastomeric substrate, the conductive elastomeric support and the elastomeric contact regions are integrally formed as a monolithic elastomeric body comprising a plurality of conductive surface portions and a substantially non-conductive bulk portion.

10. The hybrid organic-inorganic micromirror device of claim **1**, wherein the micromirror comprises a length or width in the range of from about 10 microns to about 1 mm.

11. The hybrid organic-inorganic micromirror device of claim **1**, wherein the voltage bias is in the range of from about 10 V to about 100 V.

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