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Micromechanical arm array with micro-spring structures in micro-electromechanical system (MEMS) actuators

Abstract

MEMS actuators having micro spring structures and methods of fabricating the same are provided. An example MEMS actuator includes a first micromechanical arm array including multiple first micromechanical arms spaced from each other in a first horizontal direction and a second micromechanical arm array including multiple second micromechanical arms spaced from each other in the first horizontal direction. The first and the second micromechanical arm arrays are interposed in the first horizontal direction. The MEMS actuator further includes a metal connection structure connected to each first micromechanical arm, and a vertical micro spring structure disposed between the metal connection structure and one of the second micromechanical arms. The vertical micro spring structure includes an upper portion connected to the metal connection structure and a lower portion connected to a top end of the second micromechanical arm.

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Background/Summary

FIELD

(1) Embodiments of the present disclosure relate generally to micro-electromechanical systems (MEMS) or nano-electromechnical systems (NEMS) devices, and more particularly to micromechanical arm array used in MEMS actuators.

BACKGROUND

(2) Micro-electromechanical systems ("MEMS") are becoming increasingly popular, particularly as such devices are miniaturized and are integrated into integrated circuit manufacturing processes. MEMS are typically made up of components between 1 and 100 micrometers in size, and MEMS devices generally range in size from 20 micrometers to a millimeter. MEMS merge at the nanoscale into nano-electromechnical systems (NEMS) and nanotechnology.

(3) MEMS devices include mechanical and electrical features formed by one or more semiconductor manufacturing processes. Examples of MEMS devices include micro-sensors, which convert mechanical signals into electrical signals; micro-actuators, which convert electrical signals into mechanical signals; and motion sensors, which are commonly found in automobiles (e.g., in airbag deployment systems) and smartphones. For many applications, MEMS devices are electrically connected to application-specific integrated circuits (ASICs), and to external circuitry to form complete MEMS systems. However, if a MEMS device breaks, for example, due to some impact when being used, it is difficult, if not infeasible, to repair or replace the broken MEMS device. Therefore, there is a need to fabricate reliable and impact-resistant MEMS devices.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

(2) FIG. **1** is a schematic diagram illustrating a cross-sectional view of an exemplary MEMS system including micromechanical arm arrays and a micro spring structure in accordance with some embodiments.

(3) FIG. **2**A is a schematic diagram illustrating a cross-sectional view of a selected region shown in FIG. **1** in accordance with some embodiments.

(4) FIG. **2**B is a schematic diagram illustrating a cross-sectional view of a selected region shown in FIG. **2**A in accordance with some embodiments.

(5) FIG. **2**C is a schematic diagram illustrating a cross-sectional view of another selected region shown in FIG. **2**A in accordance with some embodiments.

(6) FIG. **2**D is a schematic diagram illustrating an exemplary mechanism of forming a micro spring structure shown in FIG. **2**A in accordance with some embodiments.

(7) FIG. **3** is a schematic diagram illustrating a cross-section view taken at an imaginary line A-A′ shown in FIG. **1** in accordance with some embodiment.

(8) FIG. **4** is a flow diagram illustrating an exemplary method of forming a MEMS system in accordance with some embodiment.

(9) FIGS. **5**A-**5**S are schematic diagrams illustrating cross-sectional views of a MEMS system and a selected region thereof at various stages of fabrication of the MEMS system in accordance with some embodiments.

(10) FIG. **6** is a flow diagram illustrating another exemplary method of forming a MEMS system in accordance with some embodiment.

(11) FIGS. **7**A-**7**H are schematic diagrams illustrating cross-sectional views of a MEMS system and a selected region thereof at various stages of fabrication of the MEMS system in accordance with some embodiments.

(12) FIG. **8** is a schematic diagram illustrating a cross-sectional view of a portion of another exemplary MEMS system in accordance with some embodiments.

(13) FIG. **9** is a schematic diagram illustrating a perspective view of an exemplary sensor-shift

optical image stabilization (OIS) system including a MEMS system in accordance with some embodiments.

DETAILED DESCRIPTION OF THE INVENTION

(14) The following disclosure provides many different embodiments, or examples, for implementing different features of the subject matter provided. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

(15) Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

(16) In addition, source/drain region(s) may refer to a source or a drain, individually or collectively dependent upon the context. For example, a device may include a first source/drain region and a second source/drain region, among other components. The first source/drain region may be a source region, whereas the second source/drain region may be a drain region, or vice versa. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

(17) Some embodiments of the disclosure are described. Additional operations can be provided before, during, and/or after the stages described in these embodiments. Some of the stages that are described can be replaced or eliminated for different embodiments. Some of the features described below can be replaced or eliminated and additional features can be added for different embodiments. Although some embodiments are discussed with operations performed in a particular order, these operations may be performed in another logical order.

(18) Overview

(19) Optical image stabilization (OIS) is a family of techniques that reduce blurring associated with the motion of a camera or other imaging devices during exposure. Image stabilization is typically used in high-end image-stabilized binoculars, still and video cameras, astronomical telescopes, and high-end smartphones. Lens-based OIS works by moving the lens to compensate for the change in the optical path. Sensor-shift OIS, on the other hand, works by moving the image sensor instead of the lens to compensate for the change in the optical path.

(20) The advantage of moving the image sensor, instead of the lens, is that the image can be stabilized even on lenses made without stabilization. This may allow the stabilization to work with many otherwise-unstabilized lenses. It also reduces the weight and complexity of the lenses. Further, when sensor-shift OIS technology improves, it requires replacing only the camera to take advantage of the improvements, which is typically far less expensive than replacing all existing lenses if relying on lens-based image stabilization.

(21) In some implementations, sensor-shift OIS is based on a MEMS actuator which can move in, for example, five axes (i.e., X, Y, Roll, Yaw, and Pitch). An image sensor is attached to the MEMS actuator and thus can move in five axes accordingly. In some implementations, a MEMS actuator includes at least one micromechanical arm array. Each micromechanical arm array includes multiple micromechanical arms. Each micromechanical arm is typically an elongated structure

fabricated using semiconductor processes.
(22) However, the impact on the MEMS actuator can render the micromechanical arms inside MEMS actuators broken. For instance, a smartphone that has MEMS actuators accidentally falls on the ground, and the impact could result in a fractured touchscreen and broken micromechanical arms in the MEMS actuators inside the smartphone. While it is feasible to replace the touchscreen, it is impractical, if not impossible, to replace the broken micromechanical arms, given that the critical dimensions of the broken micromechanical arms are at the microscale or even the nanoscale. As a result, the functioning of the sensor-shift OIS may be significantly compromised. Thus, the robustness and impact resistance of micromechanical arms are desirable. In addition, it is desirable to have MEMS actuators with high sensitivity and conductivity.
(23) The present disclosure provides techniques to address the above-mentioned challenges. In accordance with some aspects of the disclosure, a novel MEMS actuator is provided. In some embodiments, the MEMS actuator includes a first micromechanical arm array and a second micromechanical arm array. The first micromechanical arm array includes multiple first micromechanical arms spaced from each other, and the second micromechanical arm array includes multiple second micromechanical arms spaced from each other. The first and second micromechanical arm arrays are interposed, such that each second micromechanical arm is located between two neighboring first micromechanical arms. The MEMS actuator further includes a metal connection structure connected to each of the first micromechanical arms. The MEMS actuator also includes at least one micro spring structure configured to resist vibration of the micromechanical arms under external or environmental forces.
(24) According to some embodiments, the MEMS actuator may include at least one vertical micro spring structure disposed between and interconnecting the metal connection structure and one of the second micromechanical arms in a vertical direction. According to some embodiments, the MEMS actuator may include at least one horizontal micro spring structure disposed between and interconnecting sidewalls of a first micromechanical arm and a second micromechanical arm adjacent to the first micromechanical arm in a horizontal direction. According to some embodiments, the MEMS actuator may include at least one vertical micro spring structure and at least one horizontal micro spring structure.
(25) The micro spring structures advantageously provide vibration isolation, resonance control, as well as damping and energy dissipation for the MEMS actuator. The vertical micro spring structure provides vibration resistance/isolation between the micromechanical arm and the metal connection structure. Likewise, the horizontal micro spring structure provides vibration resistance/isolation between the neighboring micromechanical arms. When external vibrations or disturbances occur, the micro spring structures may absorb and dampen the vibrations, preventing their direct transmission to the micromechanical arms. By vibrationally isolating the micromechanical arm from the rest of the MEMS system, the micro spring structures can reduce the impact of vibrations on the motion of the micromechanical arms during operation of the MEMS actuator and thus minimize unwanted oscillations. In addition, the micro spring structure can also control resonance by altering the resonant frequency of the MEMS system and damping unwanted resonance, which may help reducing the amplitude of vibrations and stabilizing the motion of the micromechanical arms.
(26) Moreover, the vertical micro spring structure may add another layer of buffering between the metal connection structure and the second micromechanical arm, protecting the metal connection structure and the second micromechanical arm from contact/collision under external vibrational forces. Likewise, the horizontal micro spring structure may also add another layer of buffering between the neighboring micromechanical arms, protecting the neighboring micromechanical arms and from contact/collision.
(27) Example MEMS System and MEMS Actuator Having Micro Spring Structure
(28) FIG. **1** is a schematic diagram illustrating a cross-sectional view of an exemplary MEMS

system **100** including a MEMS actuator **101** in accordance with some embodiments. FIG. **2**A is a schematic diagram illustrating a cross-sectional view of the region **190** shown in FIG. **1** in accordance with some embodiments. FIG. **2**B is a schematic diagram illustrating a cross-sectional view of the region **192** shown in FIG. **2**A in accordance with some embodiments. FIG. **2**C is a schematic diagram illustrating a cross-sectional view of the region **194** shown in FIG. **2**A in accordance with some embodiments. FIG. **2**D is a schematic diagram illustrating an exemplary mechanism of the formation of the micro spring structure **150** shown in FIGS. **1** and **2**A-**2**C in accordance with some embodiments.

(29) In the illustrated example, the MEMS system **100** includes, among other components, a top wafer **102** (also referred to and used interchangeably with a "device wafer"), a bottom wafer **103** (also referred to and used interchangeably with a "handle wafer") bonded to the top wafer **102**, a cavity **106**, a passivation layer **104** disposed on the top wafer **102**, and a MEMS actuator **101** including a first micromechanical arm array **110***a*, a second micromechanical arm array **110***b*, a metal connection structure **116**, and at least one micro spring structure **150**. Additional components may be included in the MEMS system **100**.

(30) As shown in FIG. **1**, the top wafer **102** (i.e., the device wafer) extends downwardly from a top surface **107** to a bonding layer **108** (also referred to as a bonding interface), the bottom wafer **103** extends upwardly from a bottom surface **109** to the bonding layer **108**, and the top wafer **102** and the bottom wafer **103** are bonded through the bonding layer **108**. In some embodiments, the bonding layer **108** is a fusion bonding layer. In other words, the top wafer **102** and the bottom wafer **103** are bonded through fusion bonding, for example, through a heating and/or pressing process without the need for adhesives or intermediate layers. In some embodiments, the top wafer **102** may have a bonding dielectric layer (not shown) at a bottom surface thereof, and the bottom wafer **103** similarly has a bonding dielectric layer (not shown) at a top surface thereof, and the top wafer **102** and the bottom wafer **103** are bonded through fusion of the bonding dielectric layers to form a bonding layer **108**. The top wafer **102** and the bottom wafer **103** may each include a silicon substrate.

(31) All or a substantial portion of the cavity **106** is between the top surface **107** of the top wafer **102** and the bottom surface **109** of the bottom wafer **103**. The cavity **106** defines a continuous space to allow the micromechanical arms or other movable microstructure to be disposed therein and freely move and operate. In some embodiments, a portion of the cavity **106** is across the bonding layer **108** between the top wafer **102** and the bottom wafer **103**.

(32) The MEMS system **100** may have multiple sections along the horizontal direction, including a MEMS actuator section **181** (also referred to as a "driving comb section"), a hinge section **182**, an inner frame section **183**, a spring section **184**, and an outer frame section **185**. MEMS actuator section **181** includes the MEMS actuator **101**, which provides controlled movement or displacement in response to electrical signals. The hinge section **182** may include one or more hinges configured to enable pivotal movement of the MEMS actuator **101** or allow for the controlled rotation of other components within the MEMS system **100**. The inner frame section **183** may provide structural support and stability to the MEMS system **100** to maintain the alignment of various components within the MEMS system **100**. The hinge section **182** may include flexible spring-like structures that provide mechanical support and elasticity to maintain the desired positioning and movement of the components within the MEMS system **100** and also provide a restoring force to bring the MEMS actuator **101** back to its original position after actuation. The outer frame section **185** is configured to provide structural integrity, protecting the internal components from external and environmental forces.

(33) In the illustrated example, the first and second micromechanical arm arrays **110***a* and **110***b* are within the MEMS actuator section **181** and substantially disposed within the top wafer **102**. The first micromechanical arm array **110***a* includes, among other components, multiple micromechanical arms **112***a* and a metal connection structure **116** connecting the micromechanical

arms **112***a*. The micromechanical arms **112***a* are spaced from each other in a first horizontal direction (i.e., the X-direction shown in FIG. **1**). The micromechanical arms **112***a* are elongated and extend in parallel in a second horizontal direction (i.e., the Y-direction). In some embodiments, each micromechanical arm **112***a* has a free end **121** (i.e., a bottom end) and a fixed end **119** (i.e., a top end). The fixed end **119** is connected to the metal connection structure **116**. In some embodiments, the micromechanical arms **112***a* are suspended in the cavity **106** (i.e., a gap may exist between the top surface **107** of the top wafer **102** and the fixed end **119** of each micromechanical arm **112***a*). As a result, the free end **121** of each micromechanical arm **112***a* can move freely due to the suspension of the micromechanical arm **112***a* in the cavity **106**.
(34) In some embodiments, each micromechanical arm **112***a* further includes a major body **123** and a cover layer **118** disposed on and surrounding the major body **123**. The cover layer **118** encloses the major body **123** and isolates the major body **123** from the cavity **106** and the metal connection structure **116**. In some embodiments, the cover layer **118** may serve as an etch stop film that prevents etchants from etching the corresponding micromechanical arm **112***a* during the silicon release process, which will be described below. The metal connection structure **116** extends in the X-direction and connects neighboring micromechanical arms **112***a*. The metal connection structure **116** is attached to the fixed end **119** (i.e., the portion of the cover layer **118** at the fixed end **119** of each micromechanical arm **112***a*).
(35) In some embodiments, the micromechanical arms **112***a* are composed of polycrystalline silicon (“poly”), the cover layers **118** are composed of silicon dioxide (SiO.sub.2), and the metal connection structure **116** is composed of metal such as aluminum copper alloy (AlCu). It should be understood that other combinations of materials can be employed in other embodiments. For example, the micromechanical arms **112***a* are composed of single crystal silicon or amorphous silicon. For example, the cover layers **118** are composed of silicon nitride (Si.sub.3N.sub.4), silicon carbide (SiC), undoped silicon glass (USG), fluorosilicate glass (FSG), borophosphosilicate glass (BPSG). For example, the metal connection structure **116** may be composed of titanium nitride (TiN), tantalum nitride (TaN), Al—Si—Cu alloy, copper (Cu), or other suitable materials.
(36) Likewise, the second micromechanical arm array **110***b* includes, among other components, multiple micromechanical arms **112***b*. In some embodiments, the second micromechanical arm array **110***b* also includes a metal connection structure (like the metal connection structure **116** shown in FIG. **1**) connecting the micromechanical arms **112***b*, and the metal connection structure is not shown in the cross-section shown in FIG. **1**. The micromechanical arms **112***b* are spaced from each other in the X-direction. The micromechanical arms **112***b* are elongated and extend in parallel in the Y-direction. In some embodiments, each micromechanical arm **112***b* extends downwardly from a fixed end **119** (i.e., a top end) to a free end **121** (i.e., a bottom end). The micromechanical arms **112***b* may also be suspended in the cavity **106**, in a similar manner as the micromechanical arms **112***a*. As a result, the free end **121** of each micromechanical arm **112***b* can move freely due to the suspension of the micromechanical arm **112***b* in the cavity **106**. Likewise, each micromechanical arm **112***b* may further include a major body **123** and a cover layer **118** disposed on and surrounding the major body **123**. The cover layer **118** of the micromechanical arm **112***b* similarly serves as an etch stop film that prevents etchants from etching the corresponding micromechanical arm **112***b* during the silicon release process.
(37) It should be understood that although two micromechanical arms **112***a* and one micromechanical arm **112** are illustrated in FIG. **1**, it is not intended to be limiting. In other embodiments, the first micromechanical arm array **110***a* may include another number (e.g., eight) of micromechanical arms **112***a*, while the second micromechanical arm array **110***b* may include another number (e.g., seven) of micromechanical arms **112***b*. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.
(38) The micromechanical arms **112***a* and the micromechanical arms **112***b* are interposed in the X-direction. In the example shown in FIG. **1**, the micromechanical arm **112***b* is located, in the X-

direction, between two neighboring micromechanical arms **112***a*. A gap in the Z-direction may exist between the top surface of the micromechanical arm **112***b* and the metal connection structure **116** connected to the micromechanical arms **112***a*.
(39) As mentioned above, in some embodiments, the second micromechanical arm array **110***b* includes its own metal connection structure, which extends in the X-direction and connects neighboring micromechanical arms **112***b*. The metal connection structure is attached to the micromechanical arms **112***b*, with the cover layer **118** disposed therebetween. In some embodiments, the micromechanical arms **112***b* are composed of poly, and the cover layer **118** disposed on each micromechanical arm **112***b* is composed of oxide. It should be understood that other combinations of materials can be employed in other embodiments.
(40) In some embodiments, the at least one micro spring structure **150** includes a vertical micro spring structure **150***a* disposed between and interconnecting the metal connection structure **116** and the second micromechanical arm **112***b* in the vertical direction. In some embodiments, the at least one micro spring structure **150** includes a horizontal micro spring structure **150***b* disposed between and interconnecting a first micromechanical arm **112***a* and a neighboring second micromechanical arm **112***b* in the horizontal direction. In some embodiments, the at least one micro spring structure **150** includes both a vertical micro spring structure **150***a* and a horizontal micro spring structure **150***b*.
(41) As shown in FIG. **2**B, the vertical micro spring structure **150***a* has a curved configuration and includes a first layer **151***a* and a second layer **152***a*. The first layer **151***a* is composed of an expansive material (i.e., an expansive layer), and the second layer **152***a* is composed of a compressive material (i.e., a compressive layer). The first layer **151***a* and the second layer **152***a* are bonded to each other, stacked in the horizontal direction (i.e., the X-direction), and conformable to each other in shape. The vertical micro spring structure **150***a* has a first portion **153***a* (i.e., an upper portion) and a second portion **154***a* (i.e., a lower portion). The upper portion **153***a* and the lower portion **154***a* are jointed at a center (i.e., along a center line **193**) of the vertical micro spring structure **150***a* to form a corner **155***a*. The corner **155***a* is oriented and positioned to face horizontally (i.e., in a direction from the first layer **151***a* (i.e., the expansive layer) to the second layer **152***a* (i.e., the compressive layer)). The corner **155***a* has an angle (α) at least partially representing the degree of curvature of the vertical micro spring structure **150***a*. In some embodiments, the upper portion **153***a* and the lower portion **154***a* are substantially symmetrical about the center line **193**. The upper portion **153***a* is connected to the metal connection structure **116**, and the lower portion **154***a* is connected to the cover layer **118** of the second micromechanical arm **112***b*. During operation, the vertical micro spring structure **150***a* may undergo elastic deformation and stretch or compress along the vertical direction.
(42) As mentioned above, the vertical micro spring structure **150***a* includes an expansive layer and a compressive layer bonded and stacked together, and thus is composed of composite materials having different or opposite tensile properties. In some embodiments, vertical micro spring structure **150***a* may include more than two layers having different tensile properties (i.e., multiple expansive layers and/or multiple compressive layers). In some embodiments, the first layer **151***a* (i.e., the expansive layer) has a first coefficient of thermal expansion (CTE), and the second layer **152***a* (i.e., the compressive layer) has a second CTE, wherein the first CTE is substantially higher than the second CTE. In some embodiments, the first CTE is 10 to 50 parts per million per degree Celsius (ppm/° C.) or micrometers per meter per degree Celsius (μm/m/° C.). In some embodiments, the second CTE is about 0.1 to 1.0 ppm/° C.
(43) In some embodiments, the first layer **151***a* is composed of a metal, a metal alloy, or a metal compound. Examples of the materials included in the first layer include but are not limited to Aluminum (Al), Copper (Cu), Tungsten (W), Nickel (Ni), AlCu alloy, etc. In some embodiments, the second layer **152***a* is composed of silicon, silicon oxide, borosilicate glass, FeNi alloy, etc. In some embodiments, the first layer **151***a* is composed of AlCu alloy, and the second layer **152***a* is

composed of silicon oxide.

(44) In some embodiments, the upper portion **153***a* and the metal connection structure **116** form an angle (θ) therebetween, and the lower portion **154***a* and the top surface of the second micromechanical arm **112***b* similarly form an angle (θ) therebetween. In some embodiments, the angle (θ) is at least 15 degrees, at least 30 degrees, at least 45 degrees, at least 60 degrees, or at least 75 degrees. In some embodiments, the angle (α) of the corner **155***a* is at least 15 degrees, at least 30 degrees, at least 60 degrees, at least 90 degrees, at least 120 degrees, at least 150 degrees, or at least 170 degrees.

(45) In some embodiments, the vertical micro spring structure **150***a* has a length (L) (i.e., a vertical dimension in the Z-direction) of at least 1.6 μm. The length (L) is approximate the distance between the metal connection structure **116** and the top surface of the second micromechanical arm **112***b*. In some embodiments, the vertical micro spring structure **150***a* has a critical dimension (CD) (i.e., a horizontal dimension in the X-direction) of at least 1 μm. In some embodiments, the first layer **151***a* has a thickness of at least 100 nm, at least 200 nm, or at least 500 nm. Likewise, the second layer **152***a* may have a similar thickness compared with the first layer **151***a*, and the thickness of the second layer **152***a* may be at least 100 nm, at least 200 nm, or at least 500 nm.

(46) As shown in FIG. **2**C, the horizontal micro spring structure **150***b* also has a curved configuration in a similar manner as the vertical micro spring structure **150***a*. In some embodiments, the horizontal micro spring structure **150***b* includes a first layer **151***b* and a second layer **152***b*. The first layer **151***b* is composed of an expansive material (i.e., an expansive layer), and the second layer **152***b* is composed of a compressive material (i.e., a compressive layer). The first layer **151***b* and the second layer **152***b* are bonded to each other, stacked in the vertical direction (i.e., the Z-direction), and conformable to each other in shape. The horizontal micro spring structure **150***b* has a first portion **153***b* (i.e., a left portion shown in FIG. **2**C) and a second portion **154***b* (i.e., a right portion shown in FIG. **2**C). The first portion **153***b* and the second portion **154***b* are jointed at a center (i.e., along a center line **195**) of the horizontal micro spring structure **150***b* to form a corner **155***b*. The corner **155***b* of the horizontal micro spring structure **150***b* may be oriented and positioned to face vertically (i.e., in a direction from the first layer **151***b* (i.e., the expansive layer) to the second layer **152***b* (i.e., the compressive layer)). The corner **155***b* similarly has an angle (α) at least partially representing the degree of curvature of the horizontal micro spring structure **150***b*. The first portion **153***b* and the second portion **154***b* may be substantially symmetrical about the center line **195**. The first portion **153***b* is connected to the cover layer **118** on the sidewall of a first micromechanical arms **112***a*, and the second portion **154***b* is connected to the cover layer **118** on the sidewall of a second micromechanical arm **112***b* adjacent to the first micromechanical arms **112***a*. During operation, the horizontal micro spring structure **150***b* may undergo elastic deformation and stretch or compress along the horizontal direction to resist vibration of the first and second micromechanical arms **112***a* and **112***b*.

(47) Similar to the vertical micro spring structure **150***a*, the horizontal micro spring structure **150***b* is also composed of composite materials having different or opposite tensile properties. In some embodiments, horizontal micro spring structure **150***b* may include more than two layers having different tensile properties (i.e., multiple expansive layers and/or multiple compressive layers). In some embodiments, the first layer **151***b* (i.e., the expansive layer) has a first CTE, and the second layer **152***b* (i.e., the compressive layer) has a second CTE, wherein the first CTE is substantially higher than the second CTE. In some embodiments, the first CTE is 10 to 50 ppm/° C. In some embodiments, the second CTE is about 0.1 to 1.0 ppm/° C.

(48) In some embodiments, the first layer **151***b* is composed of a metal, a metal alloy, or a metal compound. Examples of the materials included in the first layer include but are not limited to Aluminum (Al), Copper (Cu), Tungsten (W), Nickel (Ni), AlCu alloy, etc. In some embodiments, the second layer **152***b* is composed of silicon, silicon oxide, borosilicate glass, FeNi alloy, etc. In some embodiments, the first layer **151***b* is composed of AlCu alloy, and the second layer **152***b* is

composed of silicon oxide. In some embodiments, the vertical micro spring structure **150***a* and the horizontal micro spring structure **150***b* are composed of the same materials.

(49) In some embodiments, the first portion **153***b* and the first micromechanical arm **112***a* form an angle (θ) therebetween, and the second portion **154***b* and the second micromechanical arm **112***b* also form an angle (θ) therebetween. In some embodiments, the angle (θ) is at least 15 degrees, at least 30 degrees, at least 45 degrees, at least 60 degrees, or at least 75 degrees. In some embodiments, the angle (α) of the corner **155***b* is at least 15 degrees, at least degrees, at least 60 degrees, at least 90 degrees, at least 120 degrees, at least 150 degrees, or at least 170 degrees.

(50) Similar to the vertical micro spring structure **150***a*, the horizontal micro spring structure **150***b* has a length (L) (i.e., a horizontal dimension in the X-direction) of at least 1.6 μm. The length (L) is approximate the distance between the neighboring first and second micromechanical arms **112***a* and **112***b*. In some embodiments, the horizontal micro spring structure **150***b* has critical dimension (CD) (i.e., a vertical dimension in the Z-direction) of at least 1 μm. In some embodiments, the first layer **151***b* has a thickness of at least 100 nm, at least 200 nm, or at least 500 nm. Likewise, the second layer **152***b* may have a similar thickness compared with the first layer **151***b*, and the thickness of the second layer **152***b* may be at least 100 nm, at least 200 nm, or at least 500 nm. In some embodiments, the vertical and horizontal micro spring structures within the MEMS actuator **101** are substantially the same in dimension.

(51) In some embodiments, the MEMS actuator **101** includes multiple vertical micro spring structures **150***a* and multiple horizontal micro spring structures **150***b*. Each one of the vertical micro spring structures **150***a* may connect a second micromechanical arm **112***b* and the metal connection structure **116**, and each one of the horizontal micro spring structures **150***b* may connect a first micromechanical arm **112***a* and a second micromechanical arm **112***b* that are neighboring to each other. In some embodiments, more than one (e.g., in a row or an array) vertical micro spring structures **150***a* may be used to connect each one of the second micromechanical arms **112***b* and the metal connection structure **116**, and more than one (e.g., in a column or an array) horizontal micro spring structures **150***b* may be used to connect the neighboring micromechanical arms **112***a* and **112***b*.

(52) The micro spring structure **150** according to the present disclosure advantageously provides vibration isolation, resonance control, as well as damping and energy dissipation. The vertical micro spring structure **150***a* provides vibration resistance/isolation between the micromechanical arm **112***b* and the metal connection structure **116**. Likewise, the horizontal micro spring structure **150***b* provides vibration resistance/isolation between the neighboring micromechanical arms **112***a* and **112***b*. When external vibrations or disturbances occur, the micro spring structures **150***a* and **150***b* may absorb and dampen the vibrations, preventing their direct transmission to the micromechanical arms **112***a* and **112***b*. By vibrationally isolating the micromechanical arm from the rest of the MEMS system **100**, the micro spring structures **150** can reduce the impact of vibrations on the motion of the micromechanical arms **112***a* and **112***b* during operation of the MEMS actuator **101** and thus minimize unwanted oscillations. In addition, the micro spring structure **150** can also control resonance by altering the resonant frequency of the MEMS system **100** and damping unwanted resonance, which helps reducing the amplitude of vibrations and stabilizing the motion of the micromechanical arms **112***a* and **112***b*. Moreover, the vertical micro spring structure **150***a* may add another layer of buffering between the metal connection structure **116** and the second micromechanical arm **112***b*, protecting the metal connection structure **116** and the second micromechanical arm **112***b* from contact/collision under external vibrational forces. Likewise, the horizontal micro spring structure **150***b* may also add another layer of buffering between the neighboring micromechanical arms **112***a* and **112***b*, protecting the neighboring micromechanical arms **112***a* and **112***b* from contact/collision.

(53) As shown in FIG. 2D, a mechanism for the formation of an example micro spring structure **150** from a multi-layer composite structure **140** is illustrated. In the illustrated example, a multi-

layer composite structure **140** has a bilayer structure, including an expansive layer **141** and a compressive layer **142**. The expansive layer **141** and the compressive layer **142** are extending in the vertical direction, bonded together, and stacked in the horizontal direction (i.e., the X-direction). The expansive layer **141** and a compressive layer **142** have substantially different (or opposite) tensile properties. The expansive layer **141** may have a high CTE, and the compressive layer **142** may have a substantially lower CTE. While not wishing to be bound to any particular theory, it is believed that when an annealing process is performed to heat the multi-layer composite structure **140** at an elevated temperature (e.g., 800° C.), a middle portion of the expansive layer **141** may undergo substantial expansion under the expansive stress in the X-direction toward the compressive layer **142**, and a middle portion of the compressive layer **142** may undergo compression under the compressive stress in the same direction toward the compressive layer **142** itself. Because the expansion direction of the middle portion of the expansive layer **141** and the compression direction of the middle portion of the compressive layer **142** are the same (as indicated by the two arrows of FIG. **2**D), the multi-layer composite structure **140** may bend toward horizontally in a direction from the expansive layer **141** to a compressive layer **142** to form the micro spring structure **150** having a curved and bended configuration with a corner **155** in the middle of the micro spring structure **150**. The degree of curvature (i.e., the angle (α) of the corner **155**) may depend on the CTE and materials of the expansive layer **141** and the compressive layer **142**, the thickness of the expansive layer **141** and the compressive layer **142**, as well as the annealing conditions. It should be understood that the mechanism and examples of FIG. **2**D are for illustrative purposes only and are not intended to be limiting. Other mechanisms are also possible in alternative embodiments to explain the formation of the micro spring structure **150**.

(54) FIG. **3** is a diagram illustrating a cross-section taken at A-A′ shown in FIG. **1** in accordance with some embodiment. It should be understood that FIG. **3** is not drawn to scale. In the example shown in FIG. **3**, the MEMS actuator **101** includes the first micromechanical arm array **110***a* and the second micromechanical arm array **110***b*. The first micromechanical arm array **110***a* includes the micromechanical arms **112***a* extending in the Y-direction, a spine beam **302***a* extending in the X-direction, and a main beam **304***a* extending in the Y-direction. Likewise, the second micromechanical arm array **110***b* includes the micromechanical arms **112***b* extending in the Y-direction, a spine beam **302***b*, and a main beam **304***b* extending in the Y-direction.

(55) Each micromechanical arm **112***a* has a free end and a fixed end, which is attached to the spine beam **302***a*. The spine beam **302***a* connects the multiple micromechanical arms **112***a* together. Similarly, each micromechanical arm **112***b* has a free end and a fixed end, which is attached to the spine beam **302***b*. The spine beam **302***b* connects the multiple micromechanical arms **112***b* together.

(56) As mentioned above, the micromechanical arms **112***a* and the micromechanical arms **112***b* are interposed in the X-direction. When a voltage or electrical potential tension is applied between the neighboring micromechanical arms **112***a* and **112***b*, the first micromechanical arm array **110***a* and the second micromechanical arm array **110***b* are attracted to each other due to an electrostatic force. In one example, the electrostatic force is proportional to the square of the applied voltage. On the other hand, a restoring force that separates the first micromechanical arm array **110***a* and the second micromechanical arm array **110***b* may be used to balance the electrostatic force. In one implementation, the restoring force is provided by a spring structure. As a result, a relative movement (shown by the arrow in FIG. **3**) in the Y-direction between the first micromechanical arm array **110***a* and the second micromechanical arm array **110***b* occurs. One of ordinary skill in the art would appreciate that movement in more directions can be achieved by combining multiple MEMS actuators that are capable of moving in different directions.

(57) In one example, the main beam **304***a* is fixed with respect to the main body of the MEMS actuator **101**, and the main beam **304***b* moves relative to the main body of the MEMS actuator. In another example, the main beam **304***b* is fixed with respect to the main body of the MEMS actuator **101**, and the main beam **304***a* moves relative to the main body of the MEMS actuator. Either way,

electrical signals are converted into mechanical signals, and the movement of the MEMS actuator **101** is controlled by the electrical signals.
(58) It should be understood that the structures shown in FIG. **3** is simplified to illustrate the principle of operation of the example MEMS actuator **101**. The MEMS actuator **101** can include other components as needed. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.
(59) Example Fabrication Process Flow
(60) FIG. **4** is a flowchart diagram illustrating an example method for fabricating a MEMS system **500** in accordance with some embodiments. In the example shown in FIG. **4**, the method **400** includes operations **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**, **418**, **420**, **422**, **424**, **426**, **428**, **430**, **432**, **434**, **436**, **438**, and **440**. Additional operations may be performed. Also, it should be understood that the sequence of the various operations discussed above with reference to FIG. **4** is provided for illustrative purposes, and as such, other embodiments may utilize different sequences. These various sequences of operations are to be included within the scope of embodiments. FIGS. **5**A-**5**S are schematic diagrams illustrating cross-sectional views of the MEMS system **500** and a region **590** thereof at various stages of fabrication of the MEMS system **500** in accordance with some embodiments.
(61) At operation **402**, a base structure for forming a MEMS system is provided. In the example of FIG. **5**A, the base structure **500** (i.e., the base structure for the to-be-generated MEMS system **500**) includes a top wafer **102** (i.e., device wafer) and a bottom wafer **103** (i.e., handle wafer) bonded at a bonding layer **108**. The top wafer has a top surface **107**. The bottom wafer **103** may further include one or more cavities **501** disposed therein. The cavities **501** may be isolated from each other.
(62) At **404**, the top wafer is etched to form a trench and one or more protrusions disposed therein. The trench and the protrusions will be used for forming the MEMS actuator and micro spring structures in subsequent operations. The trench may be formed by performing a patterning and etching process to remove a desired portion of the top wafer. The protrusions may be formed by performing a selective etching process. In the example of FIG. **5**A, a trench **502** is formed in the top wafer **102**. The trench **502** extends upwardly from a bottom surface **508** to a top open end **506** and is defined by a first sidewall **503** and a second sidewall **505**. At least one protrusion **504** is formed within the trench **502**. Each protrusion **504** extends vertically from the bottom surface **508** to a top surface **510** and further includes a sidewall **512**. The protrusions **504** may has a height less than the depth of the trench **502**, such that the top surface **510** of each protrusion **504** is between the bottom surface **508** and the top open end **506** of the trench **502**. The protrusion **504** provides a support for the to-be-formed horizontal micro spring structure, and therefore the height of the protrusion **504** may determine the relative position of the to-be-formed horizontal micro spring structure in the vertical direction.
(63) At **406**, a first oxide layer is formed. The first oxide layer (i.e., silicon oxide layer) may be formed by performing a thermal oxidation process. In some embodiments, the base structure is placed in a thermal tube (also referred as a high-temperature furnace or oxidation furnace), and the thermal tube is purged with inert gas, such as nitrogen (N.sub.2), to create an oxygen-free atmosphere. The thermal tube is then heated to the desired temperature (e.g., from 800 to 1600° C.). Once the desired temperature is reached, oxygen or an oxygen-containing gas, such as dry air or pure oxygen, is introduced into the tube. The oxygen reacts with the silicon surface, leading to the formation of a thermal silicon oxide layer through dry oxidation. The reaction proceeds until the desired thickness of the thermal silicon oxide layer is achieved.
(64) In the example of FIG. **5**B, a first oxide layer **520** is formed on the top surface of the top wafer **102**. The first oxide layer **520** is also deposited on and covers the bottom surface **508** and sidewalls of the trench **502** as well as the top surface **510** and sidewalls **512** of each protrusion **504**. A portion of the first oxide layer **520** on the top surface **510** of the protrusion **504** is denoted as an oxide layer

520*a*, which will serve as the compressive layer of the to-be-formed micro spring structure in subsequent operations. The first oxide layer **520** may have a compressive property have a relatively low CTE in a range from 0.1 to 1.0 ppm/° C.

(65) At **408**, a first metal layer is formed. The first metal layer may be formed by a suitable method such as electroplating, physical vapor deposition (PVD), or sputtering deposition. In some embodiments, the first metal layer is composed of AlCu alloy. For example, the first metal layer containing AlCu may be formed by bombarding a first garget substrate of Al and a second target substrate of Cu with high-energy ions, and the ejected and sputtered Al and Cu atoms from their respective target substrate are co-deposited on the base structure to form the metal layer containing Al and Cu. An annealing or other post-sputtering treatment process may be performed subsequent to the sputtering deposition. Similarly, an electroplating process may be performed to form a metal layer of Al and Cu on the base structure by placing the base structure in an electroplating bath containing Al ions and Cu ions, applying an electric current to initiate the reduction of the Al ions and Cu ions and co-depositing Al and Cu on the base structure. In some embodiments, a planarization process (e.g., a chemical-mechanical polishing (CMP) process) is performed on the first metal layer.

(66) In the example of FIGS. **5**B-**5**C, the first metal layer **524** is formed and deposited on the first oxide layer **520**. The first metal layer **524** fills the trench **502** and the space between the sidewalls **503**/**505** and the protrusions **504** as well as the space between two neighboring protrusions **504**.

(67) At **410**, the first metal layer is etched to form horizontal bilayer composite structures respectively on the protrusions in the trench. In some embodiments, a dry etching technique is used to etch the metal layer. Examples of the dry etching techniques include but are not limited to Reactive Ion Etching (RIE), Plasma Etching, Ion Beam Etching (IBE), Deep Reactive Ion Etching (DRIE), Inductively Coupled Plasma (ICP) Etching, etc. One or more non-liquid or gas etchants may be used in the dry etching process. Example enchants for etching the second metal layer include but are not limited to Chlorine (Cl.sub.2), Boron Trichloride (BCl.sub.3), Chlorine Trifluoride (CIF.sub.3), a mixture of Oxygen (O.sub.2) and Carbon Tetrafluoride (CF.sub.4), or a combination thereof.

(68) In the example of FIGS. **5**C-**5**D, a patterned mask may be applied on the top of the first metal layer **524** to protect/cover the area of the first metal layer **524** corresponding to and aligned with each protrusion **504** as well as the portions of the first oxide layer **520** disposed on the sidewall **512** thereof. A first dry etching process is performed to remove the unprotected or uncovered first metal layer **524** and form a metal residual layer **524***a* on the oxide layer **520***a* corresponding to and vertically aligned with each protrusion **504**. In some embodiments, a second etching process may be performed to further control the thickness of the metal residual layer **524***a* and arrive at a desired thickness. Accordingly, a horizontal bilayer composite structure **140***b* is formed on each protrusion **504**, and the horizontal bilayer composite structure **140***b* includes the oxide layer **520***a* and the metal residual layer **524***a* disposed on the oxide layer **520***a*. The horizontal bilayer composite structure **140***b* is disposed on the top surface **510** of the corresponding protrusion **504**. The horizontal bilayer composite structure **140***b* is used as precursor for the formation of the horizontal micro spring structure **150***b* (shown in FIG. **5**S) in subsequent operations. After the dry etching process, the first oxide layer **520** formed in operation **404** is re-exposed and the trench **502** is re-formed.

(69) At **412**, a silicon layer is formed. The silicon layer may be formed by performing a two-step process. In some embodiments, a two-step process is performed to form the silicon layer, starting with the deposition of a "seed layer" using a Chemical Vapor Deposition (CVD) technique, followed by the growth of silicon on the seed layer using a thermal deposition technique. In the first step, a thin seed layer of silicon is deposited onto the substrate surface through the CVD process. For example, a precursor gas, such as silane (SiH.sub.4), may be introduced into a reaction chamber where it decomposes in the presence of a catalyst or high-energy plasma, to deposit a thin

layer of silicon atoms onto the exposed first oxide layer of the base structure. The seed layer may act as a nucleation site for subsequent silicon growth. In the second step, a thermal deposition technique, such as thermal evaporation, is performed to grow a thicker silicon layer on top of the seed layer. A high-temperature environment (e.g., 800 to 1,600° C.) may be used, to evaporate silicon atoms from a source material. A thicker silicon layer is then formed on the thin layer of silicon atoms formed in the first step. In some embodiments, a CMP process may be performed on the silicon layer. In the example shown in FIG. 5E, the silicon layer **526** is formed on the re-exposed first oxide layer **520**. The silicon layer **526** also fills the re-formed trench **502** and covers the horizontal bilayer composite structure **140***b*.

(70) At **414**, the silicon layer is etched to form silicon residual layers respectively on the horizontal bilayer composite structure. Similar to operation **410**, a suitable dry etching technique is used to etch the metal layer to remove the desired portion of the silicon layer and form a silicon residual layer on the metal residual layer of each horizontal bilayer composite structure.

(71) In the example of FIGS. 5E-5F, the patterned mask used in operation **410** may be re-applied on the base structure **500** to protect the area of the silicon layer **526** corresponding to and vertically aligned with the protrusions **504**. Then a dry etching process is performed to remove the portion of the silicon layer **526** corresponding to the exposed regions defined by the patterned mask. As a result, silicon residual layers **526***a* are formed respectively corresponding to the protrusions **504**. Each silicon residual layer **526***a* is formed on the metal residual layer **524***a* of the corresponding horizontal bilayer composite structure **140***b*. After dry etching, the first oxide layer **520** is re-exposed and the trench **502** is re-formed. Each silicon residual layer **526***a* extends downwardly from the top open end **506** of the trench **502** to the top surface of the metal residual layer **524***a*. Each silicon residual layer **526***a* is vertically aligned with the metal residual layer **524***a* and the underlying protrusion **504**, and their horizontal dimensions are substantially the same. Each silicon residual layer **526***a* may have a top surface substantially coplanar with the top surface of the first oxide layer **520**. For purposes of simplicity, each protrusion **504**, the corresponding horizontal bilayer composite structure **140***b* (i.e., the oxide layer **520***a* and the metal residual layer **524***a*), as well as the silicon residual layer **526***a* formed on the corresponding horizontal bilayer composite structure **140***b* form a heterogeneous structure **540** extending downwardly from a top surface **541** to the bottom surface **508** of the trench **502**. The heterogeneous structures **540** are partially covered by the first oxide layer **520** (i.e., the first oxide layer **520** disposed on the sidewalls **512** of the protrusions **504**).

(72) At **416**, a second oxide layer is formed to cover the silicon residual layer and the metal residual layer on each protrusion. The second oxide layer may be formed in a similar manner as the operation **406**. In some embodiments, each silicon residual layer is further etched to further remove a top portion thereof such that the top surface of the silicon residual layer is substantially coplanar with the top surface of the top wafer, before the second oxide layer is formed.

(73) In the example of FIG. 5G, the second oxide layer **528** is formed on the re-exposed first oxide layer **520** and also covers the top surface and the sidewall of the silicon residual layer **526***a* corresponding to each protrusion **504**. Before the second oxide layer **528** is formed, each silicon residual layer **526***a* is further etched to remove a small top portion thereof such that the top surface **541** of the silicon residual layer **526***a* is substantially coplanar with the top surface **107** of the top wafer **102**. As such, the second oxide layer **528** and the first oxide layer **520** covers the sidewall and the top surface of each heterogenous structure **540** entirely. The portion of the second oxide layer **528** directly formed on the top surface **541** of the silicon residual layer **526***a* is denoted as **528***a*.

(74) At **418**, a first polysilicon layer is formed to form a major body portion of each to-be-generated micromechanical arm. The first polysilicon layer may be formed using suitable techniques such as thermal deposition or atom layer deposition (ALD). For example, a silicon-containing gas such as SiH.sub.4 or SiH.sub.2Cl.sub.2 may be used as a precursor to form the

polysilicon layer on the base structure placed in a thermal tube at high temperature. Likewise, an ALD process may be performed to form the polysilicon layer using the silicon-containing gas precursor and deposit the polysilicon layer on the base structure.
(75) In the example of FIGS. **5G-5H**, the first polysilicon layer **532** is formed and deposited on the second oxide layer **528**. The first polysilicon layer **532** also fills the trench **502**. Multiple polysilicon portions **532***a* may be formed, which serve as the major body of the micromechanical arms formed in subsequent operations. For example, the space in the trench **502** between the sidewall **503** and the neighboring heterogeneous structure **540** is filled with a portion of the first polysilicon layer **532**, denoted as polysilicon portion **532***a*, which later serves as the major body **123** of a first micromechanical arm **112***a* (shown in FIG. **5**J). The space in the trench **502** between two neighboring heterogeneous structures **540** is filled with a portion of the first polysilicon layer **532**, denoted as polysilicon portion **532***b*, which later serves as the major body **123** of a second micromechanical arm **112***b* (shown in FIG. **5**J). Likewise, the space in the trench **502** between the sidewall **505** the neighboring heterogeneous structure **540** is filled with a portion of the first polysilicon layer **532**, denoted as polysilicon portion **532***a*, which later serves as the major body **123** of another first micromechanical arm **112***a* (shown in FIG. **5**J). Accordingly, the two heterogenous structures **540** are interposed in the multiple polysilicon portions **532***a*/**532***b*/**532***a*. It should be understood that the number of the heterogenous structures **540** and the polysilicon portions **532***a*/**532***b* may vary. For example, more than two heterogenous structures **540** and more than three polysilicon portions **532***a*/**532***b* may be formed.
(76) At **420**, the first polysilicon layer is etched to form a top surface of the polysilicon portion below the top surface of the second oxide layer. In some embodiments, a two-step process is performed. First, a CMP process is performed to remove excess material of the first polysilicon layer and to expose a top surface of each polysilicon portion. Second, a patterning and etching process is performed to remove a small top portion of each polysilicon portion to form a top surface that is below the top surface of the silicon residual layer. In some embodiments, a wet etching technique may be utilized to etch off small top portion of each major body portion. As shown in FIG. **51**, after etching the first polysilicon layer, the second oxide layer **528** is re-exposed, and a top surface **534** of each polysilicon portion **532***a*/**532***b* is exposed and below the top surface **541** of the silicon residual layer **526***a* of the corresponding heterogenous structures **540**.
(77) At **422**, a third oxide layer is formed. The third oxide layer is formed and deposited on the top surface of the polysilicon portions. The third oxide layer may be formed in a similar manner as forming the first and second oxide layers in the operations **406** and **416**, respectively. In the example of FIG. **5**J, the third oxide layer **536** is formed on the re-exposed first oxide layer **520** and also covers the top surface **534** of each polysilicon portion **532***a*/**532***b*. The portion of the third oxide layer **536** formed on the top surface **534** of each polysilicon portion **532***a*/**532***b* is denoted as **536***a*. As shown in the region **590**, each polysilicon portion **532***a*/**532***b* is entirely covered by oxide derived from a portion of the first oxide layer **520** (disposed on and covering the sidewall **503**/**505** and the bottom surface **508** of the trench **502** as well as the sidewall of the protrusion **504**), a portion of the second oxide layer **528** (disposed on and covering the sidewalls of the residual metal layer **524***a* and the silicon residual layer **526***a*), and the third oxide layer portion **536***a* (disposed on and covering the top surface **534** of the polysilicon portion **532***a*/**532***b*). These portions of the first, second, and third oxide layers that cover each polysilicon portion **532***a*/**532***b* together form the cover layer **118** for each polysilicon portion **532***a*/**532***b*. Accordingly, the micromechanical arms **112***a* and **112***b* are formed. Each one of the micromechanical arms **112***a* and **112***b* includes a polysilicon portion **532***a*/**532***b* as well as the cover layer **118** disposed thereon.
(78) At **424**, a multi-layer structure having alternating polysilicon layers and oxide layers is formed. In some embodiments, a patterning and etching process is performed to expose the top surface of each silicon residual layer, before the multi-layer structure is formed. The multi-layer structure may be formed by sequentially and alternatingly depositing a polysilicon layer and an oxide layer to

cover the exposed top surface of each silicon residual layer. In the example of FIG. **5**K, the top surface **541** of each silicon residual layer **526***a* (i.e., also the top surface of each heterogeneous structure **540**) is exposed before a multi-layer structure **544** is formed. The multi-layer structure **544** is formed and deposited on the top wafer **102** to cover the top surface of each silicon residual layer **526***a* as well as the third oxide layer **536***a* on each polysilicon portion **532***a*/**532***b*. In some embodiments, an etching process may be performed to remove the oxide layer **528***a* on the top surface of the silicon residual layer **526***a* to expose the top surface of the silicon residual layer **526***a*, before the multi-layer structure is formed.
(79) At **426**, the multi-layer structure is etched to form multiple spacers respectively on the top surfaces of the silicon residual layers (or the top surfaces of the heterogenous structures). In some embodiments, a patterning and etching process is performed to remove undesired portions of the multi-layer structure and leave the residuals of the multi-layer structure as the spacers in desired regions. Suitable etching techniques, such as drying etching, plasma etching, or wet etching, may be used to etch the multi-layer structure and form the spacers. A first opening between two neighboring spacers is formed, and the first opening is vertically aligned with the polysilicon portion of one of the micromechanical arms. In the example of FIG. **5**L, multiple spacers **546** including a first spacer **546***a* and a second spacer **546***b* are formed as residuals of the multi-layer structure **544**. The first spacer **546***a* is disposed on and substantially aligned with the heterogeneous structure **540** (proximate to the sidewall **503**) in the vertical direction, and the second spacer **546***b* is disposed on and substantially aligned with the heterogeneous structure **540** (proximate to the sidewall **505**) in the vertical direction. A first opening **548** is formed between the first and the second spacers **546***a* and **546***b*. The first opening **548** is substantially aligned with the polysilicon portion **532***b* of the second micromechanical arm **112***b*, and the third oxide layer portion **536***a* disposed on the polysilicon portion **532***b* is exposed to the opening **548**.
(80) At **428**, a fourth oxide layer is formed. The fourth oxide layer is formed on the top wafer and fills the first opening between two neighboring spacers. The fourth oxide layer may be formed in a similar manner as forming the first, second, and third oxide layers in the operations **406**, **416**, and **422**, respectively. In the example of FIGS. **5**L-**5**M, the fourth oxide layer **552** is formed and deposited on the top wafer **102** to fill the openings between the neighboring spacers **546**. The first opening **548** between the first and second spacers **546***a* and **546***b* is also filled with a portion of the fourth oxide layer **552**, denoted as **552***a*.
(81) At **430**, the fourth oxide layer is etched to form an oxide residual layer and a second opening adjacent to the oxide residual layer. In some embodiments, a patterning and etching process is performed to remove a portion of the oxide layer filled in the first opening between the two neighboring spacers and leave the oxide residual layer therein. Suitable etching techniques, such as drying etching or plasma etching may be used, optionally in combination with appropriate etchants, to etch the fourth oxide layer and form the oxide residual layer. A second opening adjacent to the oxide residual layer is accordingly formed. The second opening will be used to receive and accommodate a metal residual layer, which will be formed in subsequent operations. In the example of FIGS. **5**M-**5**N, the fourth oxide layer **552** is etched to remove a portion of the oxide layer portion **552***a* disposed on the first opening **548** (FIG. **5**L). As a result, the unremoved portion of the oxide layer portion **552***a* remains in the opening **548** (FIG. **5**L) and forms the oxide residual layer **554***a*. A second opening **555** (i.e., a left portion of the first opening **548** of FIG. **5**L) corresponding to the removed portion of the oxide layer portion **552***a* is formed and adjacent to the oxide residual layer **554***a*. It should be noted that the relative position of the second opening **555** and the oxide residual layer **554***a* may vary. For example, the second opening may be in the right and the oxide residual layer **554***a* may be in the left. Multiple openings **556** may be formed above other micromechanical arms (e.g., the micromechanical arms **112***a* of FIG. **5**N).
(82) At **432**, a second metal layer is formed. The second metal layer may be formed in a similar manner as the first metal layer of operation **408**. The second metal layer is deposited on the top

wafer and also fills the openings between the spacers. As a result, a vertical bilayer composite structure is formed. In some embodiments, the second metal layer is composed of AlCu alloy. In the example of FIGS. 5N-5Q, the second metal layer **558** is formed and deposited on the top wafer **102**. The second metal layer **558** fills the openings **556** above the micromechanical arms **112***a* as well as the opening **555** above the micromechanical arm **112***b*. The portion of the second metal layer **558** filled in the opening **555** is denoted as **558***a*, which will serve as a metal residual layer in the subsequent operation. The metal layer portion **558***a* and the oxide residual layer **554***a* form a vertical bilayer composite structure **140***a* aligned with the polysilicon portion **532***b* of the micromechanical arm **112***b*.
(83) At **434**, the second metal layer is etched to form a metal connection structure. In some embodiments, a patterning and etching process is performed, using a suitable etching technique such as dry etching, wet etching, or plasma etching, to remove undesired portions of the second metal layer. In some embodiments, the second metal layer is composed of AlCu alloy. In the example of FIG. 5P, the unremoved portion of the second metal layer **558** forms the metal connection structure **116**, which is connected to the first micromechanical arms **112***a* as well as the vertical bilayer composite structure **140***a* (i.e., the metal layer portion **558***a* and the oxide residual layer **554***a*). Other metal connection structures (not shown) connected to the second micromechanical arms **112***b* are also formed in the same process.
(84) At **436**, a passivation layer is formed and deposited on the metal connection structure. The passivation layer may be composed of a dielectric material that acts as a protective barrier, providing insulation and preventing moisture, contaminants, and electrical leakage from affecting the MEMS system. In some embodiments, the passivation layer may be composed of silicon oxide (SiO_2), silicon nitride (Si_3N_4), silicon oxynitride (SiON), aluminum oxide (Al_2O_3), titanium nitride (TiN), or a combination thereof. The passivation layer may be formed by using a suitable deposition technique such as CVD, low-pressure CVD (LPCVD), plasma-enhanced CVD (PECVD), PVD, PEPVD, ALD, PEALD, and so on. In the example of FIG. 5Q, the passivation layer **104** is formed and deposited on the metal connection structure **116**.
(85) At **438**, a silicon release process is performed to remove the silicon and the spacers (i.e., the unremoved multi-layer structure) to form a continuous cavity. The silicon release process is sometimes also referred to as a “sacrificial release process.” The silicon release process is a process where a structure is formed on the sacrificial layer that is later removed to leave a gap between the structure and a stop layer under the sacrificial layer. In one example, the sacrificial layer is made of silicon or polysilicon, and the stop layer is made of silicon oxide (e.g., the first, second, third, and fourth oxide layer). The sacrificial layer, which may be made of poly, is later etched using, for example, plasma etching. Sulfur hexafluoride (SF_6), for example, can be used as the etchant. During the plasma etching, a fraction of the sulfur hexafluoride breaks down into sulfur and fluorine, with the fluorine ions performing a chemical reaction with the sacrificial layer, which is made of polysilicon. It should be understood that the examples above are not intended to be limiting, and other materials, etchants, etching processes can be employed as needed.
(86) In some embodiments, a release aperture is fabricated using, for example, various lithography and etch techniques. The release aperture then provides access to the sacrificial layer for the etchant used in the sacrificial release process. The etchant starts etching through the release aperture and etches its way into the cavity. The size of the release aperture, along with other parameters such as the temperature, determines the etch rate of the sacrificial layer and can be designed accordingly. It should be understood that the above examples are not intended to be limiting. In some implementations, multiple release apertures can be used.
(87) In the example of FIG. 5Q-5R, selected portions of the top wafer **102**, selected portions of the heterogeneous structures **540** (i.e., the protrusions **504** and the silicon residual layers **526***a*), as well as the spacers **546** are respectively removed in the silicon release process. Accordingly, a continuous cavity **106** is formed and also connected to the cavities **501** in the base structure of FIG.

5A, and the first micromechanical arm array **110***a* and the second micromechanical arm array **110***b* are formed. The first and second micromechanical arms **112***a* and **112***b* are disposed in the cavity **106**. The horizontal bilayer composite structures **140***b* and the vertical bilayer composite structure **140***a* are also disposed in the cavity **106**. The horizontal bilayer composite structures **140***b* are disposed between and interconnecting the two neighboring micromechanical arms, and the vertical bilayer composite structure **140***a* is disposed between and interconnecting the metal connection structure **116** and the second micromechanical arm **112***b*.
(88) At **440**, an annealing process is performed to form micro spring structures. The annealing process may be performed in a thermal chamber at an elevated temperature (e.g., 800 to 1,600° C.) to transform the horizontal bilayer composite structures **140***b* and the vertical bilayer composite structure **140***a* into the horizontal micro spring structure **150***b* and the vertical micro spring structure **150***a*, respectively, according to the example mechanism illustrated in FIG. **2**D.
(89) FIG. **6** is a flowchart diagram illustrating an example method for fabricating a MEMS system **700** in accordance with some embodiments. The method **600** is a close variation of the method **400** and may be used to form only the vertical micro spring structure. Various aspects of the operations included in the method **600** are similar to the operations of method **400** and will not be repeated here unless otherwise indicated.
(90) In the example shown in FIG. **6**, the method **600** includes operations **602**, **604**, **606**, **608**, **610**, **612**, **614**, **616**, **618**, **620**, **622**, **624**, **626**, **628**, and **630**. Additional operations may be performed. Also, it should be understood that the sequence of the various operations discussed above with reference to FIG. **6** is provided for illustrative purposes, and as such, other embodiments may utilize different sequences. These various sequences of operations are to be included within the scope of embodiments. FIGS. **7**A-**7**H are schematic diagrams illustrating cross-sectional views of a region of the MEMS system **700** at various stages of fabrication of the MEMS system **700** in accordance with some embodiments.
(91) At **602**, a base structure comprising a top wafer and a bottom wafer is provided. At **604**, the top wafer is etched to form a trench and at least on protrusion therein. At **602**, a first oxide layer is formed and deposited in the trench to cover the protrusion. In the example of FIG. **7**A, a trench **502** is formed, and the protrusions **702** extend downwardly from the top open end **506** to the bottom surface **508** of the trench **502**. The protrusions **702** is similar to the heterogeneous structure **540** shown in FIG. **5**F in dimension, but without the horizontal bilayer composite structure **140***b* formed in the heterogeneous structure **540**. The first oxide layer **520** is deposited on the bottom surface **508**, sidewalls **503** and **505** of the trench **502**, as well as the top surface and sidewall of each protrusion **702**.
(92) At **608**, a first polysilicon layer is formed to fill the trench. In the example of FIG. **7**B, the first polysilicon layer **532** is deposited to fill the space between the sidewall **503**/**505** of the trench and the neighboring protrusion **702** as well as the space between two neighboring protrusions **702**.
(93) At **610**, the first polysilicon layer is etched to form polysilicon portions for the to-be-generated micromechanical arms. At **612**, a second oxide layer is formed to cover the polysilicon portions entirely to form micromechanical arms. In the example of FIG. **7**C, the first polysilicon layer **532** is etched to form the polysilicon portions **532***a* and **532***b*. An additional etching step may be performed to remove a top small portion of each polysilicon portion **532***a*/**532***b*, such that the top surface of the polysilicon portions **532***a*/**532***b* is below the top surface **541** of the protrusions **702** in the vertical direction. The second oxide layer **528** is formed to cover the top surface of each polysilicon portion **532***a*/**532***b*, such that each polysilicon portion **532***a*/**532***b* is entirely covered by the first and second oxide layers **520** and **528**. Thus, the cover layer **118** is formed and disposed on each polysilicon portion **532***a*/**532***b*, and the micromechanical arms **112***a* and **112***b* are accordingly formed.
(94) At **614**, a multi-layer structure is formed. In the example of FIG. **7**D, a patterning and etching process is performed to expose the top surface **541** of each protrusion **702**. Then a multi-layer

structure **544** is formed on the top surface **541** of the protrusions **702** as well as the top surface of the micromechanical arms **112***a* and **112***b*.
(95) At **616**, the multi-layer structure is etched to form spacers on the protrusions. In the example of FIG. **7**E, multiple spacers including a first spacer **546***a* and a second spacer **546***b* are formed respectively on the top surfaces of the protrusions **702**. A first opening **548** between the first spacer **546***a* and the second spacer **546***b* is also formed.
(96) At **618**, a third oxide layer is formed and fills the first opening between the two spacers respectively disposed on the top surfaces of the protrusions. At **620**, the third oxide layer is etched to form an oxide residual layer and a second opening adjacent to the oxide residual layer. At **622**, a metal layer is deposited to form a metal residual layer in the second opening. A vertical bilayer composite structure is accordingly formed. In the example of FIG. **7**F, the vertical bilayer composite structure **140***a*, including the oxide residual layer **704***a* and the metal residual layer **706***a* adjacent to the oxide residual layer **704***a*, is formed on the second micromechanical arm **112***b*.
(97) At **624**, the metal layer is etched to form a metal connection structure. At **626**, a passivation layer is formed on the metal connection structure. At **628**, the silicon and spacers are removed by performing a silicon release process to form a continuous cavity and a first micromechanical arm array and a second micromechanical arm array in the cavity. In the example of FIG. **7**G, the metal connection structure **116** is formed, and the passivation layer **104** is formed on the metal connection structure **116**. Selected portions of the top wafer **102**, the protrusions **702**, and the spacers **546***a* and **546***b* are respectively removed in the silicon release process. Accordingly, the first micromechanical arm array **110***a* and the second micromechanical arm array **110***b* are formed. The vertical bilayer composite structure **140***a* is disposed between and interconnecting the metal connection structure **116** and the second micromechanical arm **112***b*.
(98) At **630**, an annealing process is performed to form vertical micro spring structure. In the example of FIG. **7**H, the vertical bilayer composite structure **140***a* is transformed into the vertical micro spring structure **150***a* through the annealing process.
(99) FIG. **8** is a schematic diagram illustrating a cross-sectional view of a portion of an exemplary MEMS system in accordance with some embodiments. In the illustrated example, the MEMS system **800** includes a MEMS actuator having only horizontal micro spring structures **150***b* between the neighboring micromechanical arms **112***a* and **112***b*. No vertical micro spring structures may be included in the MEMS system **100**. The MEMS system **800** having only horizontal micro spring structure(s) may be fabricated using modified method **400**, for example, by skipping selected operations (e.g., operations **428** and **430**) to bypass the formation of the vertical micro spring structure according to some embodiments.
(100) Example Sensor-Shift OIS System Using the MEMS System
(101) FIG. **9** is a diagram illustrating a sensor-shift OIS system **900** in accordance with some embodiments. The sensor-shift OIS system **900** includes, among other components, the MEMS system **100** like the one shown in FIG. **1**, an image sensor **902**, and a lens **904**.
(102) The image sensor **902** is attached to the MEMS system **100** and is operable to detect and convey information used to make an image. The image sensor **902** converts the variable attenuation of light waves coming through the lens **904** into signals. In one implementation, the image sensor **902** is a charge-coupled device (CCD). In another implementation, the image sensor **902** is a CMOS image sensor (CIS). A CMOS image sensor typically includes a micro-lens that gathers light, color filters that separate out the red, green, and blue (i.e., “RGB”) components, and a photodiode that captures the filtered light. In some examples, the CMOS image sensor is a front-side illumination (FSI) CMOS image sensor. In another example, the CMOS image sensor is a backside illumination (BSI) CMOS image sensor.
(103) As explained above, the MEMS system **100** includes, for example, four MEMS actuators **101***a*, **101***b*, **101***c*, and **101***d* (collectively as MEMS actuators **101**), each of which may move in one direction, and the movement is controlled by electrical signals. As a result, the image sensor **902**

attached to the MEMS system **100** can be moved accordingly under the control of electrical signals, thus achieving sensor-shift OIS.

SUMMARY

(104) In accordance with some aspects of the disclosure, micro-electromechanical system (MEMS) actuators are provided. In one example, a MEMS actuator includes a first micromechanical arm array including multiple first micromechanical arms spaced from each other in a first horizontal direction and extending in a second horizontal direction. The MEMS actuator further includes a second micromechanical arm array including multiple second micromechanical arms spaced from each other in the first horizontal direction and extending in the second horizontal direction. The first micromechanical arm array and the second micromechanical arm array are interposed in the first horizontal direction. The MEMS actuator further includes a metal connection structure extending in the first horizontal direction and connected to a top end of each first micromechanical arm. The MEMS actuator further includes a vertical micro spring structure disposed between the metal connection structure and one of the multiple second micromechanical arms. The vertical micro spring structure includes an upper portion connected to the metal connection structure and a lower portion connected to a top end of the second micromechanical arm. The upper portion and the lower portion are connected at a center of the vertical micro spring structure and form a first corner facing horizontally.

(105) In another example, a MEMS actuator includes a first micromechanical arm array including multiple first micromechanical arms spaced from each other in a first horizontal direction and extending in a second horizontal direction, and a second micromechanical arm array including multiple second micromechanical arms spaced from each other in the first horizontal direction and extending in the second horizontal direction. The first micromechanical arm array and the second micromechanical arm array are interposed in the first horizontal direction. The MEMS actuator further includes a metal connection structure extending in the first horizontal direction, and the metal connection structure is connected to a top end of each first micromechanical arm. The MEMS actuator further includes a vertical micro spring structure disposed between the metal connection structure and at least one of the second micromechanical arms. The vertical micro spring structure includes an upper portion connected to the metal connection structure and a lower portion connected to a top end of the second micromechanical arm. The upper portion and the lower portion are connected at a center of the vertical micro spring structure and form a first corner facing horizontally. The MEMS actuator further includes a horizontal micro spring structure disposed between one of the first micromechanical arms and one of the second micromechanical arms adjacent to the first micromechanical arm. The horizontal micro spring structure further includes a first portion connected to a sidewall of the first micromechanical arm, and a second portion connected to a sidewall of the second micromechanical arm. The first portion and the second portion are connected at a center of the horizontal micro spring structure and form a second corner facing vertically.

(106) In accordance with some aspects of the disclosure, a method for fabricating a MEMS actuator is provided. In one example, a method includes providing a base structure including a top wafer, a bottom wafer bonded to the top wafer, and a sacrificial portion. The method further includes forming a trench in the top wafer and a first protrusion and a second protrusion spaced from each other in the trench, forming multiple first micromechanical arms and multiple second micromechanical arms. The first micromechanical arms and the second micromechanical arms are interposed, each one of the first and second micromechanical arms extends downwardly from a top end to a bottom end, and one of the second micromechanical arms is disposed between the first and second protrusions. The method further includes forming a first spacer, a second spacer, and an opening between the first and second spacers. The first spacer and the second spacer are respectively disposed on and in contact with top surfaces of the first and second protrusions, and the opening is located on and vertically aligned with the second micromechanical arm between the

first and second protrusions. The method further includes forming a vertical bilayer composite structure in the opening and disposed on the top end of the second micromechanical arm between the first and second protrusions. The vertical bilayer composite structure includes an oxide layer and a metal layer horizontally bonded to and stacked with the oxide layer. The method further includes forming a metal connection structure. The metal connection structure is connected to the top end of each first micromechanical arm, and the vertical bilayer composite structure interconnects the metal connection structure and the top end of the second micromechanical arm between the first and second protrusions. The method further includes removing the sacrificial portion of the base structure, the first and second spacers, and the first and second protrusions to form a cavity in the base structure, and vertical bilayer composite structure is disposed in the cavity. The method further includes performing an annealing process to transform the vertical bilayer composite structure into a vertical micro spring structure.

(107) The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1. A micro-electromechanical system (MEMS) actuator, comprising: a first micromechanical arm array comprising a plurality of first micromechanical arms spaced from each other in a first horizontal direction and extending in a second horizontal direction; a second micromechanical arm array comprising a plurality of second micromechanical arms spaced from each other in the first horizontal direction and extending in the second horizontal direction, wherein the first micromechanical arm array and the second micromechanical arm array are interposed in the first horizontal direction; a metal connection structure extending in the first horizontal direction, wherein the metal connection structure is connected to a top end of each first micromechanical arm; and a vertical micro spring structure disposed between the metal connection structure and one of the plurality of the second micromechanical arms, wherein the vertical micro spring structure comprises: an upper portion connected to the metal connection structure; and a lower portion connected to a top end of said one of the second micromechanical arms, wherein the upper portion and the lower portion are connected at a center of the vertical micro spring structure and form a first corner facing horizontally.
2. The MEMS actuator of claim 1, wherein each one of the first micromechanical arms and the second micromechanical arms further comprises a major body and a cover layer disposed on and surrounding the major body, the major body is composed of polysilicon, and the cover layer is composed of thermal oxide.
3. The MEMS actuator of claim 1, wherein the vertical micro spring structure further comprises a first layer and a second layer bonded to and staked with each other in the first horizontal direction.
4. The MEMS actuator of claim 3, wherein the first layer is composed of an expansive material having a first coefficient of thermal expansion (CTE), the second layer is composed of a compressive material having a second coefficient of thermal expansion (CTE), and the first CTE is at least 10 times higher than the second CTE.
5. The MEMS actuator of claim 4, wherein the first CTE is from 10 to 50 ppm/° C., and the second CTE is from 0.1 to 1.0 ppm/° C.
6. The MEMS actuator of claim 3, wherein the first layer is a metal layer composed of AlCu alloy.

7. The MEMS actuator of claim 3, wherein the second layer is an oxide layer composed of thermal silicon dioxide.
8. The MEMS actuator of claim 1, wherein the first corner has an angle (α) of 15 degrees to 170 degrees.
9. The MEMS actuator of claim 1, wherein the upper portion forms a first angle (θ) with the metal connection structure, the lower portion also forms a second angle (θ) with the top end of the second micromechanical arm, and the first and second angles (θ) are at least 15 degrees.
10. The MEMS actuator of claim 1, wherein the vertical micro spring structure has a critical dimension in the first horizontal direction of at least 1 μm.
11. The MEMS actuator of claim 1, wherein the vertical micro spring structure has a vertical dimension of at least 1.6 μm.
12. A MEMS actuator, comprising: a first micromechanical arm array comprising a plurality of first micromechanical arms spaced from each other in a first horizontal direction and extending in a second horizontal direction; a second micromechanical arm array comprising a plurality of second micromechanical arms spaced from each other in the first horizontal direction and extending in the second horizontal direction, wherein the first micromechanical arm array and the second micromechanical arm array are interposed in the first horizontal direction; a metal connection structure extending in the first horizontal direction, wherein the metal connection structure is connected to a top end of each first micromechanical arm; a vertical micro spring structure disposed between the metal connection structure and at least one of the plurality of the second micromechanical arms, wherein the vertical micro spring structure comprises: an upper portion connected to the metal connection structure; and a lower portion connected to a top end of said one of the second micromechanical arms, wherein the upper portion and the lower portion are connected at a center of the vertical micro spring structure and form a first corner facing horizontally; and a horizontal micro spring structure disposed between one of the first micromechanical arms and one of the second micromechanical arms adjacent to one of the first micromechanical arms, wherein the horizontal micro spring structure further comprises: a first portion connected to a sidewall of said one of the first micromechanical arms; and a second portion connected to a sidewall of said one of the second micromechanical arms; wherein the first portion and the second portion are connected at a center of the horizontal micro spring structure and form a second corner facing vertically.
13. The MEMS actuator of claim 12, wherein, the vertical micro spring structure further comprises a first layer and a second layer bonded to and staked with each other vertically; and the horizontal micro spring structure further comprises a third layer and a fourth layer bonded to and staked with each other vertically.
14. The MEMS actuator of claim 13, wherein the first layer and the third layer are composed of an expansive material having a first CTE, the second layer and the fourth layer is composed of a compressive material having a second CTE, and the first CTE is at least 10 times higher than the second CTE.
15. The MEMS actuator of claim 13, wherein the first layer and the third layer are a metal layer composed of AlCu alloy.
16. The MEMS actuator of claim 13, wherein the second layer and the fourth layer are an oxide layer composed of thermal silicon dioxide.
17. The MEMS actuator of claim 12, wherein the upper portion of the vertical micro spring structure forms a first angle (θ) with the metal connection structure, the lower portion of the vertical micro spring structure also forms a second angle (θ) with the top end of said one of the second micromechanical arms, the first portion of the horizontal micro spring structure forms a third angle (θ) with said one of the first micromechanical arms, the second portion of the horizontal micro spring structure forms a fourth angle (θ) with said one of the second micromechanical arms, and the first, second, third, and fourth angles (θ) are at least 15 degrees.

18. A method for fabricating a MEMS actuator, the method comprising: providing a base structure comprising a top wafer, a bottom wafer bonded to the top wafer, and a sacrificial portion; forming a trench in the top wafer and a first protrusion and a second protrusion spaced from each other in the trench; forming a plurality of first micromechanical arms and a plurality of second micromechanical arms, wherein the plurality of first micromechanical arms and the plurality of second micromechanical arms are interposed, each one of the first and second micromechanical arms extends downwardly from a top end to a bottom end, and one of the plurality of second micromechanical arms is disposed between the first and second protrusions; forming a first spacer, a second spacer, and an opening between the first and second spacers, wherein the first spacer and the second spacer are respectively disposed on and in contact with top surfaces of the first and second protrusions, and the opening is located on and vertically aligned with said one of the second micromechanical arms between the first and second protrusions; forming a vertical bilayer composite structure in the opening and disposed on the top end of the second micromechanical arm between the first and second protrusions, wherein the vertical bilayer composite structure comprises an oxide layer and a metal layer horizontally bonded to and stacked with the oxide layer; forming a metal connection structure, wherein the metal connection structure is connected to the top end of each first micromechanical arm, and the vertical bilayer composite structure interconnects the metal connection structure and the top end of said one of the second micromechanical arms between the first and second protrusions; removing the sacrificial portion of the base structure, the first and second spacers, and the first and second protrusions to form a cavity in the base structure, wherein the vertical bilayer composite structure is disposed in the cavity; and performing an annealing process to transform the vertical bilayer composite structure into a vertical micro spring structure.
19. The method of claim 18, further comprising: forming a passivation layer on the metal connection structure.
20. The method of claim 18, wherein the metal layer is composed of AlCu.