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(54) **INTEGRATED STRUCTURE WITH BIDIRECTIONAL VERTICAL ACTUATION**

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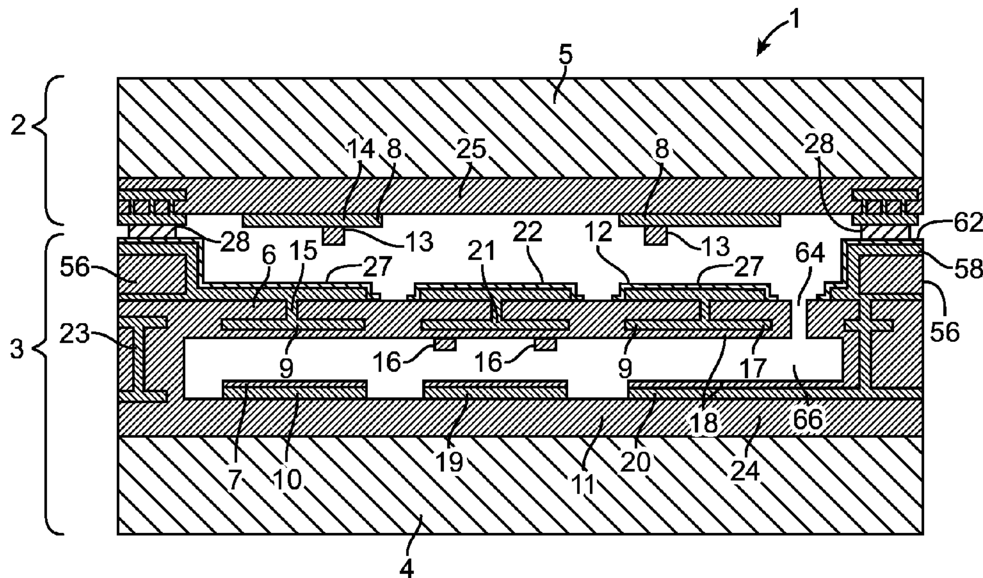
(57) **ABSTRACT**

A Micro-Electro-Mechanical Systems (MEMS) device includes a first substrate with a first surface and a second surface, the first substrate including a base layer, a moveable beam disposed on the base layer, at least one metal layer, and one or more standoffs disposed on the base layer such that one or more metal layers are situated on the top surface of the one or more standoffs. The MEMS device further includes a second substrate including one or more metal layers bonded to the one or more standoffs resulting in an electrical connection between at least a portion of the one or more metal layers of the second substrate and one or more of the at least one electrode on the bottom surface and the at least one electrode on the top surface.



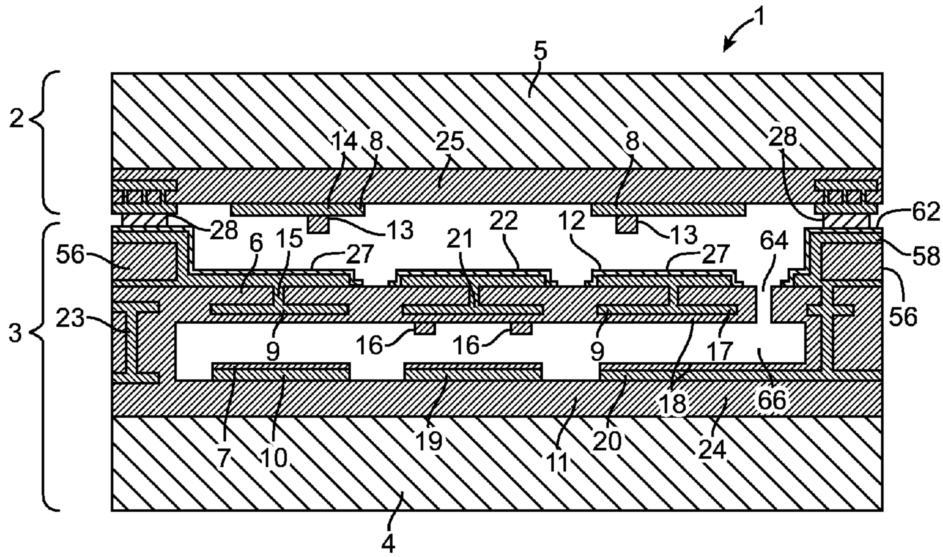


FIG. 1A

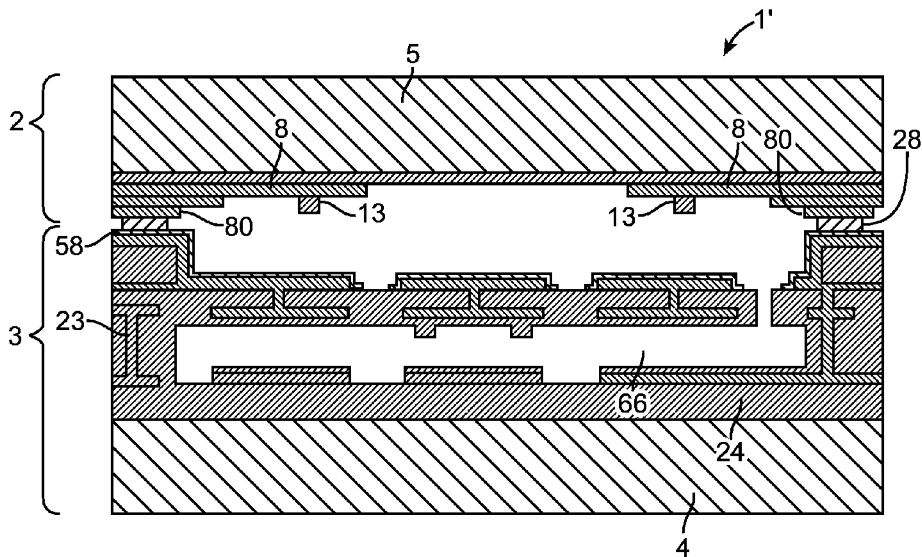


FIG. 1B

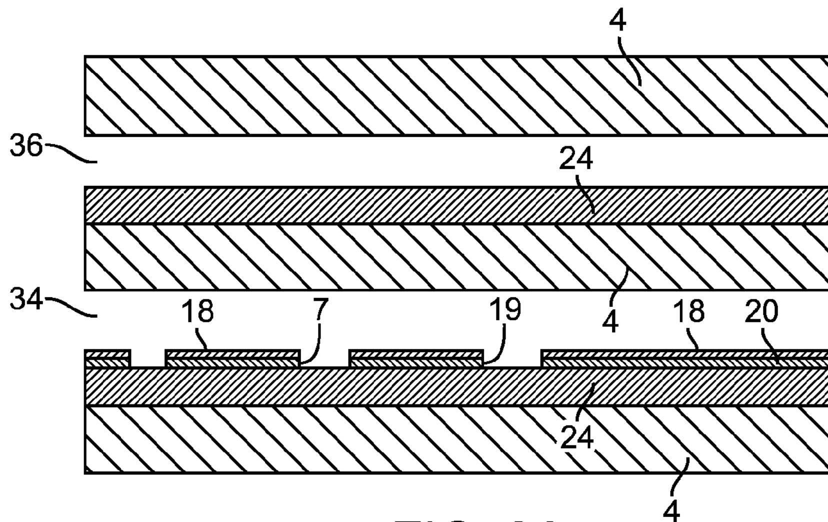


FIG. 2A

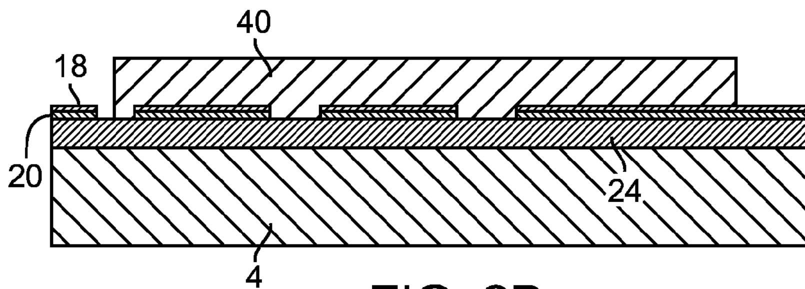


FIG. 2B

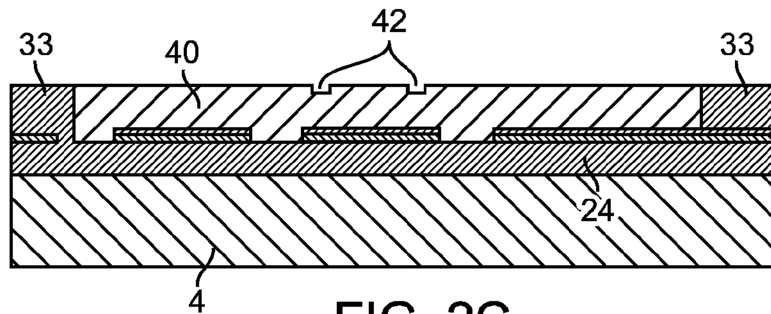


FIG. 2C

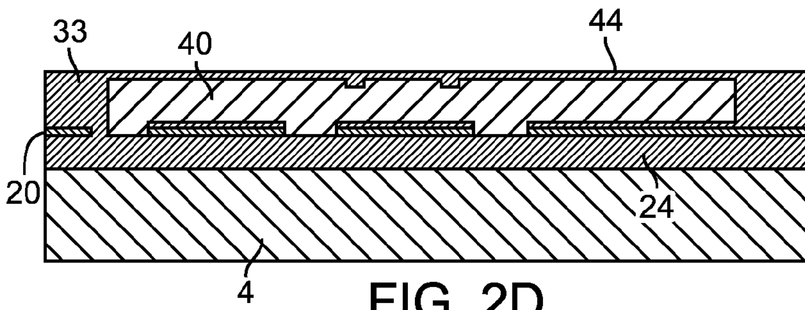


FIG. 2D

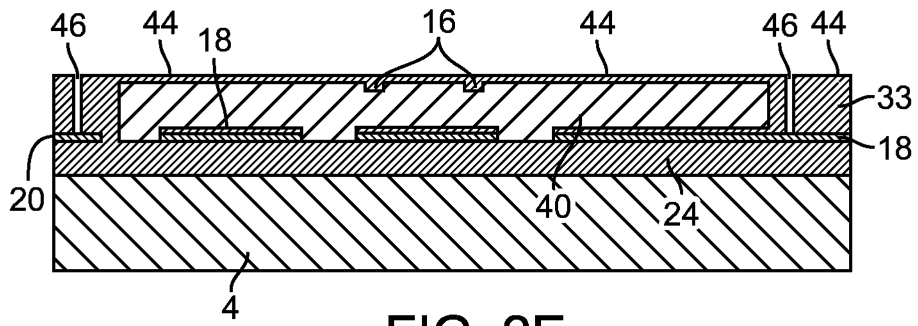


FIG. 2E

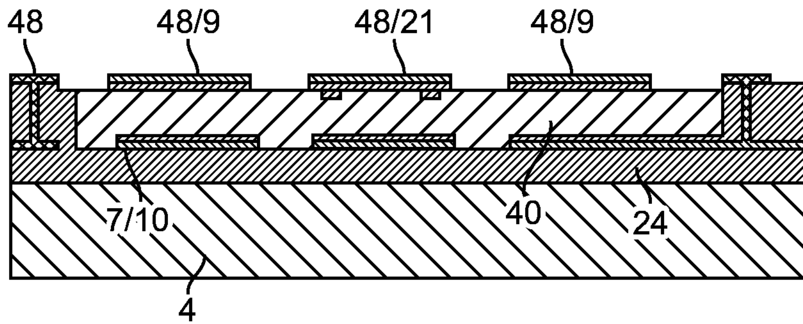


FIG. 2F

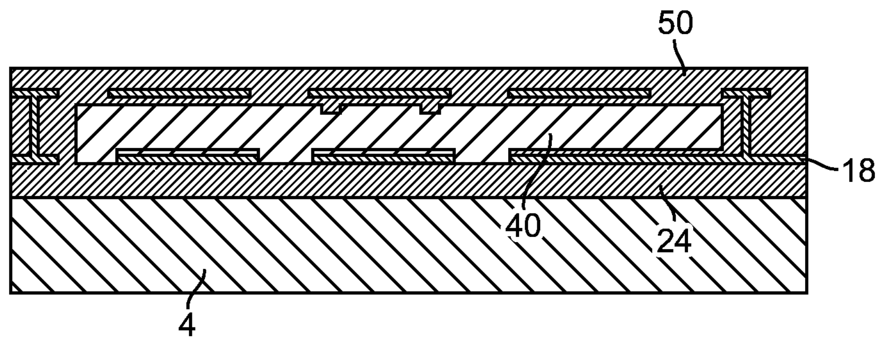


FIG. 2G

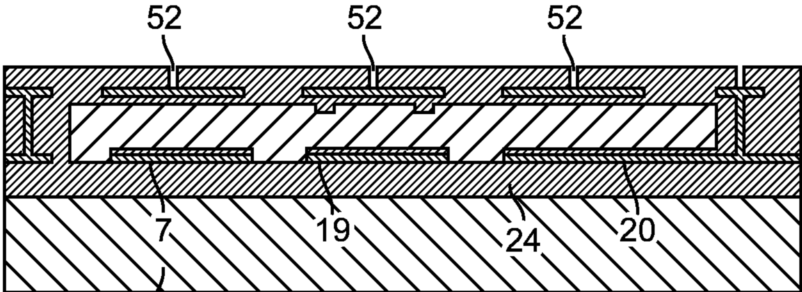


FIG. 2H

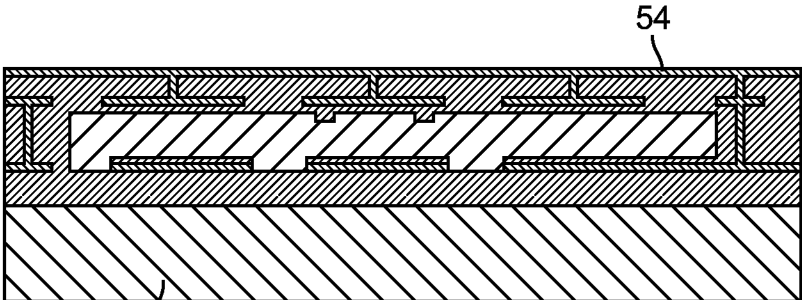


FIG. 2I

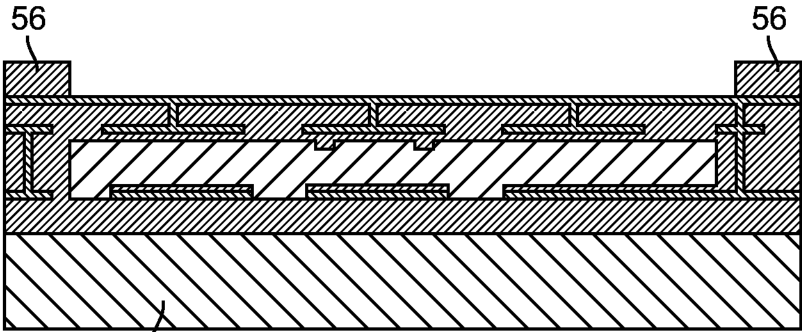


FIG. 2J

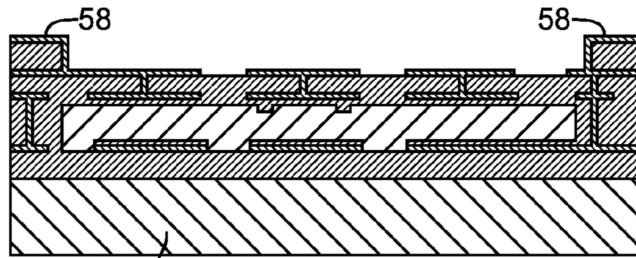


FIG. 2K

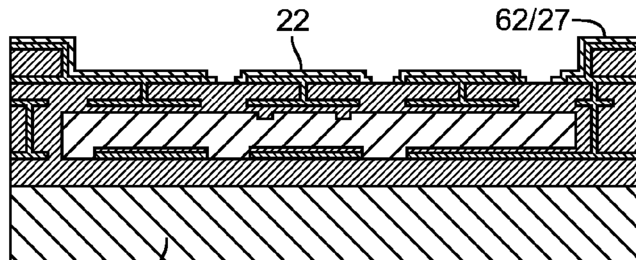


FIG. 2L

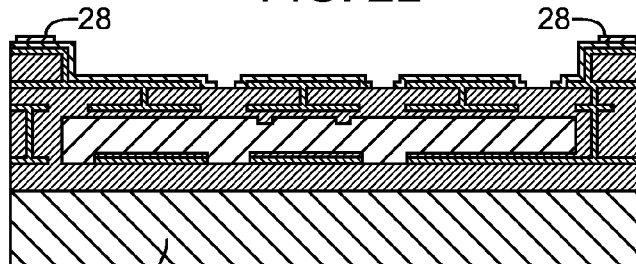


FIG. 2M

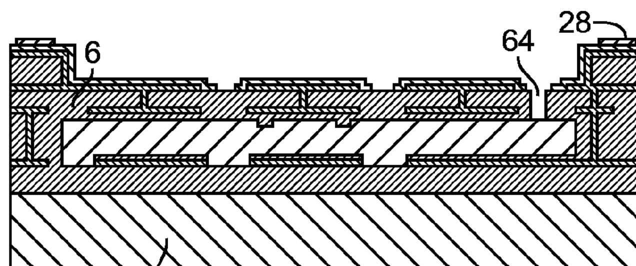


FIG. 2N

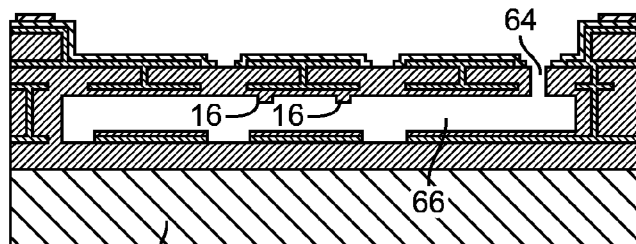


FIG. 2O

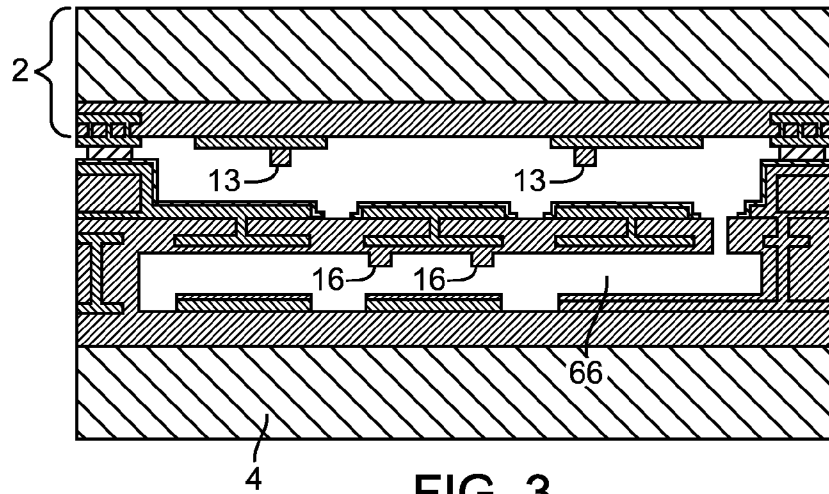


FIG. 3

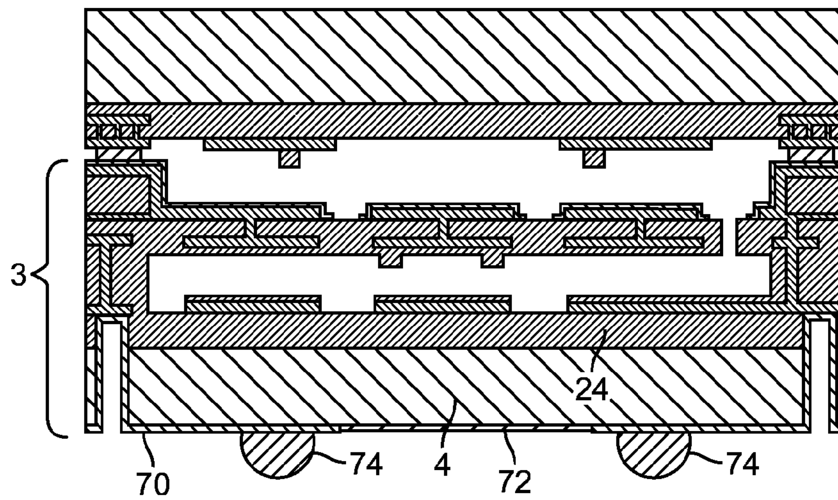


FIG. 4

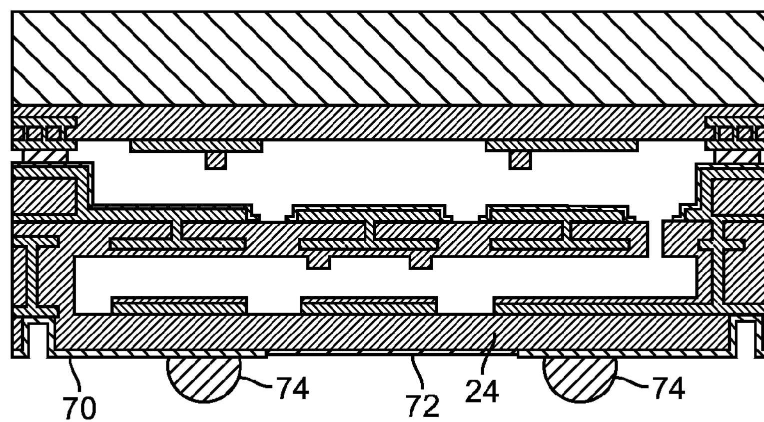


FIG. 5

INTEGRATED STRUCTURE WITH BIDIRECTIONAL VERTICAL ACTUATION

BACKGROUND

[0001] Various methods and embodiments of the invention relate generally to a Micro-Electro-Mechanical Systems (MEMS) device and particularly to a MEMS device integrally fabricated with CMOS devices.

[0002] High frequency devices, such as switches, radio frequency (RF) communication devices, and variable capacitors have been long manufactured using photolithography techniques. However, manufacturing of such high frequency devices presents challenges not otherwise experienced by other devices, such as accelerometers and sensors.

[0003] Capacitors are typically made of two plates, or electrodes, separated by a dielectric. A variable capacitor is made of the same except that one of the plates, or electrodes, is moveable thereby varying capacitance. MEMS devices readily implement variable capacitors.

[0004] A particular variable capacitor, namely, MEMS tunable capacitors with a moveable electrode are able to achieve high capacitance on-off ratios. However, existing designs often have to balance the actuation voltage against the possibility of self-actuation due to the RF signal passing through the capacitor. High actuation voltages are difficult to generate on-chip and can lead to undesirable effects such as dielectric break-down and arcing. However, if the actuation voltage is too low, the moveable capacitor electrode may move and self-actuate due to the effective direct current (DC) electrostatic force produced by the RF signal. Another issue with existing MEMS variable capacitor designs is integration with control electronics.

[0005] In some prior art designs, the variable capacitors have either been built on top of a CMOS wafer or using side-by-side system-in-package (SIP) module approach. The former approach has the disadvantage of requiring a very thick isolation layer between the CMOS and MEMS to avoid RF parasitics and potential process conflicts between the MEMS and CMOS processes. The latter SIP approach produces larger package size which is undesirable for space-conscious mobile applications. Finally, sealing the MEMS devices is challenging. In some approaches a silicon cap wafer with etched cavities may be bonded to the MEMS/CMOS wafer, however, this step may be expensive requiring multiple lithography and deposition steps.

[0006] Alternately, a sacrificial layer and dielectric cap layer with release holes may be deposited over the MEMS, followed by a sacrificial release and another deposition to seal the holes in the cap layer. This approach has two disadvantages: 1) The release process can be long and non-uniform due to the requirement to keep the release holes in the cap layer small, and 2) The resulting dielectric cap is thin and fragile and may be damaged by deposition of solder balls and printed circuit board (PCB) attachment thereby forcing a larger chip foot-print due to the requirement to place solder balls outside of the cap surface.

[0007] Accordingly, the need arises for MEMS devices integrally manufactured with CMOS devices and suitable for high frequency applications.

SUMMARY

[0008] Briefly, an embodiment of the invention includes a Micro-Electro-Mechanical Systems (MEMS) device having a first substrate with a first surface and a second surface, the first substrate including a base layer, a moveable beam disposed on the base layer, at least one metal layer, and one or more standoffs disposed on the base layer such that one or more metal layers are situated on the top surface of the one or more standoffs. The MEMS device further includes a second substrate including one or more metal layers bonded to the one or more standoffs resulting in an electrical connection between at least a portion of the one or more metal layers of the second substrate and one or more of the at least one electrode on the bottom surface and the at least one electrode on the top surface.

[0009] A further understanding of the nature and the advantages of particular embodiments disclosed herein may be realized by reference of the remaining portions of the specification and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1***a* shows a MEMS device, in accordance with an embodiment of the invention.

[0011] FIG. **1***b* shows a MEMS device, in accordance with another embodiment of the invention.

[0012] FIGS. **2***a*-**2***o* show the relevant steps for manufacturing the MEMS device of FIGS. **1***a* and **1***b*.

[0013] FIG. **3** shows the MEMS device of FIG. **1***a* and FIG. **1***b* after the CMOS substrate has been bonded to the MEMS substrate.

[0014] FIG. **4** shows the MEMS device of FIGS. **1***a* and **1***b* manufactured in preparation for packaging, in accordance with an embodiment of the invention.

[0015] FIG. **5** shows the MEMS device of FIGS. **1***a* and **1***b* manufactured in preparation for packaging, in accordance with another embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0016] In the described embodiments Micro-Electro-Mechanical Systems (MEMS) refers to a class of structures or devices fabricated using semiconductor-like processes and exhibiting mechanical characteristics such as the ability to move or deform. MEMS often, but not always, interact with electrical signals. MEMS devices include but are not limited to gyroscopes, accelerometers, magnetometers, microphones, pressure sensors, and radio-frequency (RF) components. Silicon wafers containing MEMS structures are referred to as MEMS wafers.

[0017] In the described embodiments, a MEMS device may refer to a semiconductor device implemented as a micro-electro-mechanical system. MEMS structure may refer to any feature that may be part of a larger MEMS device. An engineered silicon-on-insulator (ESOI) wafer may refer to a SOI wafer with cavities beneath the silicon device layer or substrate. Handle wafer typically refers to a thicker substrate used as a carrier for the thinner silicon device substrate in a silicon-on-insulator wafer. Handle substrate, handle wafer, can be interchanged.

[0018] In the described embodiments, a cavity may refer to an opening or recession in a substrate wafer and enclosure may refer to a fully enclosed space. Bond chamber may be an enclosure in a piece of bonding equipment where the wafer bonding process takes place. The atmosphere in the bond chamber determines the atmosphere sealed in the bonded wafers.

[0019] The following description describes a MEMS devices and methods for manufacturing the same, in accordance with various techniques.

[0020] Particular embodiments and methods of the invention disclose a MEMS device having a first substrate that has a first surface and a second surface. The first substrate includes a base layer, and a moveable beam, which is disposed on the base layer. Further, at least one metal layer, and one or more standoffs are disposed on the base layer such that the one or more metal layers are situated on the top surface of the one or more standoffs. The MEMS device further includes a second substrate, bonded to the first substrate, that includes one or more metal layers bonded to the one or more standoffs resulting in an electrical connection between at least a portion of the one or more metal layers of the second substrate and the one or more of the at least one electrode on the bottom surface and the at least one electrode on the top surface.

[0021] Referring now to FIG. **1***a*, a MEMS device **1** is shown, in accordance with an embodiment of the invention. The MEMS device **1** is shown to have a substrate **2** and a MEMS substrate **3** that are bonded together and vertically, as will become evident shortly.

[0022] The MEMS substrate **3** is shown to include the base layer **4** on top of which is shown formed a thick insulator layer **24**. In an embodiment, base layer **4** may be made of a semiconductor material. On top of the layer **24** is shown formed from a first metal layer **10** bottom actuation electrodes **7** and on top of the electrodes **7** are shown formed a thin insulating layer **18**. The layer **18** is also shown formed above a cavity **66**, which is shown disposed between the layers **18** as well as on top of the layer **24**. Further formed on top of the layer **24** and in between the bottom actuation electrodes **7** is a second capacitor electrode **19**.

[0023] The MEMS substrate **3** is additionally shown to include spacers **16** on the bottom surface of the layer **18**, shown above the cavity **66**. Center actuation electrodes **9** are shown formed above the cavity **66** and the layer **18**, shown positioned above the cavity **66** and on either side of a first capacitor electrode **21**. Accordingly, the electrode **7** and the electrode **9**, which is shown positioned directly above the electrode **7**, in FIG. **1***a*, form center actuation electrodes. Additionally, the electrodes **7** and **9** and the layer **18** are shown formed on the electrode **7**, on a bottom surface, and the layer **18** is shown formed below the electrode **9**, on a top surface, all of which define a moveable beam.

[0024] Shown formed on top of the electrodes **9** and **21** is an insulator layer **6** and on top of the insulator layer **6** is shown formed a patterned metal layer **58**.

A barrier layer **22** is formed above the layer **58**. Above the MEMS substrate **3**, as described above in reference to FIG. **1***a*, the substrate **2** is formed and bonded to the MEMS substrate **3** by a germanium (Ge) layer **28**.

The substrate **2** may be a CMOS wafer containing electrodes and one or more circuits and active elements.

[0025] The substrate **3** is shown to include standoffs **56** that are disposed on top of the layer **6** and substantially above the electrodes **9**. Each of the electrodes **9** is shown to have a spacer formed on a bottom surface thereof. An insulator layer **25** is shown formed below the substrate **5** and above the electrodes **8** and between the substrate **5** and the standoffs **56**.

[0026] It is noted that the electrode **21** is suspended over the base layer **4** and in operation, when a voltage is applied between the electrodes **9** and the electrodes **7**, an electrostatic force pulls the moveable element towards the base layer **4**. The spacers **16** serve to prevent the electrodes **9** and **21** and the electrodes **7** and **19** from coming in contact with each other when the moveable element is pulled down. Similarly, the spacers **13** of the substrate **2** serve to prevent the electrodes **8** and the metal layer **27** from coming in contact with each other. Alternatively, additional spacers may be formed below the layer **25** but their height need be suitable to prevent contact between the electrodes **8** and the layer **27**.

[0027] The capacitance between the first and second capacitor electrodes, i.e. electrodes **21** and **19** in FIG. **1***a*, is a function of the gap between them and the thickness and dielectric constant of the thin insulating layer **18**, the gap shown in FIG. **1***a* as the cavity **66**, varies as the distance between the moveable element and the base layer **4** varies. More specifically, as the gap varies, so does the capacitance of the capacitor formed from the electrode **21** and **19**, which makes this capacitor a variable one.

[0028] During operation, when the electrode **21** is pulled down, the capacitance increases. That is, when voltage is applied to the device **1**, the electrodes **9** and **21** are pulled up and down, relative to the base layer **4**, as a function of the electrodes **8** pulling up or electrodes **7** pulling down, relative to the base layer **4**. Stated differently, when a voltage is applied between the electrodes **8** and **9**, the moveable element is pulled towards the substrate **2** and away from the base layer **4**, while when a voltage is applied between electrodes **7** and **9**, the moveable element is pulled towards base layer **4** and away from substrate **2**.

[0029] FIG. **1***b* shows a MEMS device **1'**, in accordance with another embodiment of the invention. The device **1'** is analogous to the device **1** except that it includes standoffs **80** formed in the substrate **2** instead of the substrate **3**. The standoffs **80** are shown formed from a portion of the top metal layer **34** and insulator layer **35** of the substrate **2** with the electrodes **8** formed from a lower CMOS metal layer in FIG. **1***b*, as opposed to the embodiment of FIG. **1***a*.

[0030] FIGS. **2***a*-**2***o* show the relevant steps for manufacturing the MEMS device of FIGS. **1***a* and **1***b*. For the sake of brevity, FIG. **2***a* shows three steps in that first, the base layer **4** comprising a silicon substrate is provided, next the insulating layer **24** is formed on top of the base layer **4**, followed by a third step of forming the electrodes **7**, **19**, and **20** on top of the layer **24** by first depositing a metal layer on top of the layer **24**, and optionally subsequently depositing and etching the thin insulating layer **18**. Accordingly, the electrodes **7**, **20** and **19** are formed.

[0031] Next in FIG. **2***b*, a sacrificial layer **40** is deposited on top of the insulating layers **18**, **24**, and the first metal layer **20**. An exemplary material of which the layer **40** is made is polycrystalline silicon. A silicon oxide layer **33** shown in FIG. **2***c*, of thickness greater than the sacrificial layer **40**, is then deposited and subsequently, as shown in FIG. **2***c*, polished using, for example, chemical-mechanical polishing (CMP) or another technique to planarize the surface and expose the sacrificial layer **40**. Shallow indents **42** are then etched in the sacrificial layer **40** to enable forming the spacers in the following layers.

[0032] Next, in FIG. **2***d*, another thin oxide layer **44** is then optionally deposited. FIG. **2***e* illustrates vias **46** formed through the insulating layers, such as the layer **44**, the layer **33**, and the layer **18**, to the first metal **20**. In FIG. **2***f*, vias **46** are then filled with a conformally deposited conductive material **47** (such as CVD Tungsten) and a second metal layer **48** is deposited and is connected to the conductive material **47**

The second metal layer **48** is then patterned to form the electrodes **9** and **21** of the moveable element. The insulating layer **44** is also patterned together with second metal layer **48**.

[0033] In FIG. **2***g*, an insulating structural layer **50**, such as SiO2, is deposited and planarized using CMP or other suitable methods for planarizing. Subsequently, in FIG. **2***h*, the vias **52** are formed through the insulating structural layer **50** to the second metal layer **48** or the electrodes **9** and **21** of FIG. **1***a*. The vias **52** are filled with a conformal conductive material and a thin metal layer **54** is deposited on top of them, as shown in FIG. **2***i*.

[0034] Next, in FIG. **2***j*, a standoff **56** is formed from a deposited and patterned insulating layer. Then, in FIG. **2***k*, a third metal layer **58** is deposited and patterned to form electrodes on top of the moveable element. An optional conductive barrier layer **22** is deposited onto the metal layer **58** and patterned, shown at FIG. **21**.

In an embodiment where a eutectic bond is used to bond the substrate **2** to the substrate **3**, the barrier layer **22** prevents the solder from reacting and liquefying the MEMS metal during the eutectic bond.

[0035] Next, in FIG. **2***m*, the Germanium (Ge) layer **28** is deposited and patterned such that it remains on the metal layer **58** on top of standoffs **56**. The insulating layer **44**, and insulating structural layer **50** are patterned, as shown in FIG. **2***n*, to define the moveable element, stopping on the sacrificial layer **40**. Next, in FIG. **2***o*, the sacrificial layer **40** is removed in an isotropic sacrificial etch that selectively etches the sacrificial layer **40** but that does not etch or minimally etch the metal and oxide layers above and below the layer **40**, such as the insulating layers **50**, **44**, **24**, and **18**. In a preferred embodiment, the sacrificial etch uses XeF_2.

[0036] At this point in the process, the moveable element is released and capable of moving. FIG. **3** shows the MEMS device of FIG. **1***a* and FIG. **1***b* after the CMOS substrate **2** has been bonded to the MEMS substrate **3**.

[0037] Next in the manufacturing process of the device **1**, as shown in FIG. **3**, the substrate **3** is bonded to a substrate **2** using a eutectic bond, for example. Between the Germanium layer **28** deposited onto the MEMS and Aluminum **29** on the CMOS. The bond creates a hermetic seal around the MEMS elements as well as establishes electrical connections between the MEMS metal and CMOS metal.

[0038] FIG. **4** shows the MEMS device of FIGS. **1***a* and **1***b* manufactured in a Chip-Scale-Packaging (CSP) configuration, in accordance with an embodiment of the invention. As a packaging approach, the device **1** may be packaged using Through-Silicon-Via (TSV) Chip-Scale-Packaging (CSP) technology, shown in FIG. **4**. In this embodiment, vias **71** are etched in the back of the substrate **3** exposing the first metal layer **10**. An insulating layer **72** is deposited onto the back surface of substrate **3** and into the vias. Then, the insulating layer **72** is removed at the bottom of the vias and a redistribution metal layer **70** is deposited into the vias and on the back surface of the substrate **3** such that the metal **70** makes electrical contact with the first metal layer **10** inside the vias. The redistribution layer **70** is patterned, and an optional insulating solder mask layer is then deposited and patterned, and then solder balls **74** are optionally formed on the redistribution layer **70** to enable assembly of the device **1** onto a printed circuit board (PCB) or other types of substrates.

[0039] FIG. **5** shows the MEMS device of FIGS. **1***a* and **1***b* manufactured in a Chip-Scale-Packaging configuration, in accordance with another embodiment of the invention. As shown in FIG. **5**, optionally, the base layer **4** illustrated in FIG. **4** is removed prior to via formation by grinding, etching, or another method, exposing the bottom insulating layer which acts as the cap for the device **1** or **1'**, leaving only an insulating cap that advantageously reduces parasitic capacitances in the via metallization.

[0040] Although the invention has been described with respect to particular embodiments thereof, these particular embodiments are merely illustrative, and not restrictive.

[0041] As used in the description herein and throughout the claims that follow, "a", "an", and "the" includes plural references unless the context clearly dictates otherwise. Also, as used in the description herein and throughout the claims that follow, the meaning of "in" includes "in" and "on" unless the context clearly dictates otherwise.

[0042] Thus, while particular embodiments have been described herein, latitudes of modification, various changes, and substitutions are intended in the foregoing disclosures, and it will be appreciated that in some instances some features of particular embodiments will be employed without a corresponding use of other features without departing from the scope and spirit as set forth. Therefore, many modifications may be made to adapt a particular situation or material to the essential scope and spirit.

1. A MEMS device comprising:

a first substrate having a first surface and a second surface, the first substrate comprising,

a base layer,

a moveable beam attached to the base layer and having a top surface and a bottom surface, the bottom surface facing the base layer, the moveable beam comprising,

one or more first electrodes disposed on the bottom surface of the moveable beam,

one or more second electrodes disposed on the top surface of the moveable beam,

one or more standoffs disposed on the first surface of the first substrate such that one or more conductive layers are situated on the top surface of the one or more standoffs; and

a second substrate comprising one or more metal layers bonded to the one or more standoffs resulting in an electrical connection between at least a portion of the one or more metal layers and one of the one or more of the first electrodes or the one or more of the second electrodes.

2. The MEMS device of claim **1**, wherein an insulating layer is disposed between the one or more first electrodes and the one or more second electrodes.

3. Device of claim **1** further comprising one or more third electrodes disposed between the moveable beam and the base layer, such that the moveable beam is displaced when an electric potential is applied between the at least one of the one or more third electrodes and the at least one of the one or more first electrodes.

4. The MEMS device of claim **3**, wherein the at least one of the one or more first electrodes carries a radio frequency signal.

5. The MEMS device of claim **3**, wherein the at least one of the one or more third electrodes carries a radio frequency signal.

6. The MEMS device of claim **3**, further comprising one or more spacers disposed between the one or more first electrodes and the one or more third electrodes.

7. The MEMS device of claim **3**, further comprising one or more fourth electrodes disposed on the second substrate, the one or more fourth electrodes exerting an electrostatic force on the moveable beam when an electric potential is applied between the one or more fourth electrodes and the at least one of the one or more second electrodes.

8. The MEMS device of claim **7**, further comprising one or more spacers disposed between the one or more second electrodes and one or more fourth electrodes.

9. The MEMS device of claim **1**, further comprising at least one CMOS circuit on the second substrate.

10. The MEMS device of claim **1** further comprising a redistribution layer, the redistribution layer disposed on the second surface of the first substrate.

11. The MEMS device of claim **10**, further comprising an insulating layer disposed between the first substrate and the redistribution layer.

12. The MEMS device of claim **10**, further comprising an electrical conducting path from the redistribution layer to at least one of the one or more third electrodes.

13. The MEMS device of claim **12** further comprising solder balls disposed on the redistribution layer.

14. The MEMS device of claim **12**, further comprising one or more vias in the first substrate wherein the one or more vias contains a conductive material.

15. A MEMS device comprising:

a first substrate having a first surface and a second surface, the first substrate comprising,

a base layer,

a moveable beam attached to the base layer and having a top surface and a bottom surface, the bottom surface facing the base layer, the moveable beam comprising,

one or more first electrodes disposed on the bottom surface of the moveable beam,

one or more second electrode disposed on the top surface of the moveable beam,

a first insulating layer disposed between the one or more first electrodes and the one or more second electrodes; and

a second substrate comprising

one or more metal layers separated by one or more second insulating layers;

one or more stand offs having a top surface and formed from a portion of the one or more metal layers and one or more second insulating layers, a portion of the one or more metal layers situated on the top surface of the one or more stand offs and bonded to the first substrate such that an electrical connection is formed between the portion of one or more metal layers and at least one of the one or more first electrodes or at least one of the one or more second electrodes.

16. Device of claim **15** further comprising one or more third electrodes disposed between the moveable beam and the base layer, such that the moveable beam is displaced when an electric potential is applied between the at least one of the one or more third electrodes and the at least one of the one or more first electrodes.

17. The MEMS device of claim **16**, wherein the at least one of the one or more first electrodes carries a radio frequency signal.

18. The MEMS device of claim **16**, wherein the at least one of the one or more third electrodes carries a radio frequency signal.

19. The MEMS device of claim **16**, further comprising one or more spacers disposed between the one or more first electrodes and the one or more third electrodes.

20. The MEMS device of claim **16**, further comprising one or more fourth electrodes disposed on the second substrate, the one or more fourth electrodes exerting an electrostatic force on the moveable beam when an electric potential is applied between the one or more fourth electrodes and the at least one of the one or more second electrodes.

21. The MEMS device of claim **20**, further comprising one or more spacers disposed between the one or more second electrodes and one or more fourth electrodes.

22. The MEMS device of claim **15**, further comprising at least one CMOS circuit on the second substrate.

23. A MEMS device comprising:

a base layer having a first surface;

at least one first actuation electrode disposed on the first surface of the base layer;

at least one first capacitor electrode disposed on the first surface of the base layer;

a moveable beam having a top surface and a bottom surface, the moveable beam disposed above the at least one first actuation electrode and the at least one first capacitor electrode,

wherein the moveable beam is attached to the base layer,

wherein the bottom surface is facing the base layer,

wherein the moveable beam further comprises,

at least one second actuation electrode disposed on the bottom surface of the moveable beam,

at least one third actuation electrode disposed on the top surface of the moveable beam,

at least one second capacitor electrode disposed on the bottom surface of the moveable beam,

at least one fourth actuation electrode disposed above the moveable beam,

wherein applying an electric potential between the at least one first actuation electrode and the at least one second actuation electrode displaces the moveable beam towards the at least one first actuation electrode,

wherein applying an electric potential between the at least one third actuation electrode and the at least one fourth actuation electrode produces an electrostatic force on the moveable beam towards the at least one fourth actuation electrode.

24. The MEMS device of claim **23** further comprising:

a first electrostatic force generated by an electrical signal applied between the at least one first capacitor electrode and the at least one second capacitor electrode; and

a second electrostatic force generated by a second electric potential applied between the at least one third actuation electrode and the at least one fourth actuation electrode, wherein the second electrostatic force counteracts the first electrostatic force.

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