MEMS SWITCH WITH BEAM CONTACT PORTION CONTINUOUSLY EXTENDING BETWEEN INPUT AND OUTPUT TERMINAL ELECTRODES

Field of the Disclosure

[0001] The present invention relates to a microelectromechanical system (MEMS) switch, systems, and devices. In particular, the present invention relates to a MEMS switch with a beam contact portion continuously extending between input and output terminal electrodes to limit on-state resistance.

Background

[0002] Microelectromechanical system (MEMS) switches provide high-performance relays that operate across a wide variety of frequency ranges. Unwanted or parasitic resistance may occur in MEMS switches, such as between the input terminal electrode and the output terminal electrode. Such parasitic resistance is undesirable as it results in electrical loss.

Summary

[0003] Embodiments of the disclosure are directed to microelectromechanical system (MEMS) switches with a beam contact portion continuously extending between input and output terminal electrodes. In exemplary aspects disclosed herein, the movable beam includes a body and a contact with more conductivity and stiffness than the body. The contact continuously extends between and electrically couples the contact of the movable beam with the input and output terminal electrodes. Differing materials between the body and the contact allow for inclusion of the mechanical properties of the body (e.g., to reduce mechanical fatigue, creep, etc.) while utilizing the electrical properties of the contact (e.g., to reduce on-state electrical resistance). Accordingly, the MEMS switch provides low resistance loss during an on-state while maintaining high levels of isolation during an off-state.

[0004] One embodiment of the disclosure relates to a microelectromechanical system (MEMS) switch including an input terminal electrode, an output terminal

electrode, a pull-down electrode positioned between the input terminal electrode and the output terminal electrode, and a movable beam positioned proximate the input terminal electrode and the output terminal electrode. The movable beam includes a body comprising a first conductivity and first stiffness and a contact comprising a second conductivity and a second stiffness more than the first conductivity and the first stiffness. The contact is proximate to and continuously extending between the input terminal electrode and the output terminal electrode to limit on-state resistance therebetween. The movable beam is configured to move between an on-state and an off-state. The on-state electrically couples the contact of the movable beam with the input terminal electrode and the output terminal electrode. The off-state electrically isolates the contact of the movable beam from the input terminal electrode and the output terminal electrode.

[0005] An additional embodiment of the disclosure relates to a microelectromechanical system (MEMS), including a plurality of MEMS switches. Each switch includes an input terminal electrode, an output terminal electrode, a pull-down electrode positioned between the input terminal electrode and the output terminal electrode, and a movable beam positioned proximate the input terminal electrode and the output terminal electrode. The movable beam includes a body comprising a first conductivity and first stiffness and a contact comprising a second conductivity and a second stiffness more than the first conductivity and the first stiffness. The contact is proximate to and continuously extending between the input terminal electrode and the output terminal electrode to limit on-state resistance therebetween. The movable beam is configured to move between an on-state and an off-state. The on-state electrically couples the contact of the movable beam with the input terminal electrode and the output terminal electrode. The off-state electrically isolates the contact of the movable beam from the input terminal electrode and the output terminal electrode.

[0006] Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

Brief Description of the Drawing Figures

[0007] The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description, serve to explain the principles of the disclosure.

[0008] **FIG. 1A** is a schematic diagram of microelectromechanical system (MEMS) switch in an off-state, including a non-continuous contact extending between terminal electrodes;

[0009] **FIG. 1B** is a schematic diagram of the MEMS switch of **FIG. 1A** in an on-state;

[0010] **FIG. 2A** is a schematic diagram cross-sectional side view of a MEMS switch in an off-state including a pull-up electrode and a continuous contact extending between terminal electrodes;

[0011] **FIG. 2B** is a schematic diagram of the MEMS switch of **FIG. 2A** in an on-state;

[0012] **FIG. 3A** is a cross-sectional side view of one embodiment of the MEMS switch of **FIGS. 2A-2B** in an off-state;

[0013] **FIG. 3B** is a cross-sectional side view of the MEMS switch of **FIG. 3A** in an on-state;

[0014] **FIG. 4A** is a schematic diagram of a MEMS switch in an off-state including a continuous contact extending between the terminal electrodes and devoid of a pull-up electrode;

[0015] **FIG. 4B** is a schematic diagram of the MEMS switch of **FIG. 4A** in an on-state;

[0016] **FIG. 5A** is a cross-sectional side view of one embodiment of the MEMS switch of **FIGS. 4A-4B** in an off-state;

[0017] **FIG. 5B** is a cross-sectional side view of the MEMS switch of **FIG. 5A** in an on-state;

[0018] **FIG. 6** is a graph illustrating resistance reduction using the continuous contact of the MEMS switch of **FIGS. 5-5B**;

[0019] **FIG. 7A** is a diagram of one embodiment of the continuous contact of the MEMS switch of **FIGS. 3A-3B** or **FIGS. 6A-6B** of a first length;

[0020] **FIG. 7B** is another embodiment of the continuous contact of the MEMS switch of **FIGS. 2A-2B** of a second length greater than the first length;

[0021] **FIG. 7C** is another embodiment of the continuous contact of the MEMS switch of **FIGS. 2A-2B** with a narrow middle;

[0022] **FIG. 7D** is another embodiment of the continuous contact of the MEMS switch of **FIGS. 2A-2B** defining a central aperture;

[0023] **FIG. 8** is a schematic top view of a switch cell containing a number of MEMS switches.

Detailed Description

[0024] The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

[0025] It should be understood that, although the terms first, second, etc., may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element without departing from the scope of the present disclosure. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0026] It should also be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element, or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

[0027] It should be understood that, although the terms "upper," "lower," "bottom," "intermediate," "middle," "top," and the like may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed an "upper" element, and, similarly, a second element could be termed an "upper" element depending on the relative orientations of these elements, without departing from the scope of the present disclosure.

[0028] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0029] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having meanings that are consistent with their meanings in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0030] MEMS technology is currently one of the best available options for the implementation of very high-performance relays that operate from DC up to radio frequency and mm-Wave spectrum range. The most important figure of merit for such devices is generated from on-state resistance (Ron) and off-state capacitance (Coff). The product of these two quantities (Ron*Coff), measured in seconds, is an indicator of the intrinsic capability. A smaller Ron*Coff is desired to allow the design of relays that provide low loss when the electrical path is

closed (on-state) while maintaining high levels of isolation when the electrical path is open (off state).

[0031] **FIGS. 1A-1B** are diagrams of a microelectromechanical system (MEMS) switch **100** with a pull-up electrode **102** and a pull-down electrode **104** between terminal electrodes **106, 108**. In particular, terminal electrodes **106, 108** include an input terminal electrode **106** (may also be referred to as a first terminal electrode, input electrode, first RF electrode, etc.), and an output terminal electrode **108** (may also be referred to as a second terminal electrode, output electrode, second RF electrode, etc.). For the sake of completeness, the MEMS switch **100** is connected to a power source **110** coupled to the first terminal electrode **106** (via a power source circuit), a voltage up (Vup) coupling **112** coupled to a pull-up electrode **102**, and a voltage down (Vdn) coupling **114** coupled to the pull-down electrode **104**.

[0032] The MEMS switch **100** (may also be referred to herein as a MEMS relay, MEMS ohmic switch, etc.) further includes a moveable beam **116** (may also be referred to as a floating beam) mechanically anchored at both ends by flexible anchors **117** (e.g., springs). In this way, the moveable beam **116** is configured to move between a first position (off-state) and a second position (on-state) for up and down electrostatic actuation. The moveable beam **116** is connected to a ground connection **118**. The moveable beam **116** further includes a body **119**, an input contact **120A** proximate the input electrode **106**, and an output contact **120B** proximate the output electrode **108**. In certain embodiments, the moveable beam **116** is coupled to an RF node.

[0033] Referring to **FIG. 1A**, the MEMS switch **100** is in the off-state (may also be referred to as a pull-up state) where the moveable beam **116** of the MEMS switch **100** is pulled up (by electrostatic forces) toward the pull-up electrode **102**. In the first position, the moveable beam **116** is disposed adjacent to the pull-up electrode **102** and spaced from the pull-down electrode **104**, the input terminal electrode **106**, and the output terminal electrode **108**. This spacing thus provides an infinite resistance between the moveable beam **116** and each of the input terminal electrode **106** and the output terminal electrode **108**.

[0034] Referring to **FIG. 1B**, the MEMS switch **100** is in the on-state (may also be referred to as a pull-down state), where the movable beam **116** of the MEMS switch **100** is pulled down (by electrostatic forces) towards the pull-down electrode **104**. In the second position, the moveable beam **116** is disposed adjacent to the pull-down electrode **104**, the input terminal electrode **106**, and the output terminal electrode **108** and spaced from the pull-up electrode **102**. In particular, electrical current flows from the input terminal electrode **106**, through the input contact **120A**, through the moveable beam **116**, through the output contact **120B**, to the output terminal electrode **108**. The contacts **120A, 120B** have a higher conductivity (i.e., lower resistance) than the body **119** of the moveable beam **116**. In other words, the electrical flow path includes a parasitic resistance **R** (e.g., 15-45 Ohms) formed from the electrical current flowing from the input contact **120A** to the output contact **120B** through the body **119**. In certain embodiments, the contact-resistance between the input contact **120A** and the input terminal electrode **106** and between the output contact **120B** and the output terminal electrode **106** is about 15-45 Ohms. Contact resistances are limited by total contact area, roughness of contact surfaces, applied contact forces, etc. It is noted that if the contact-resistance and parasitic resistance **R** are each about 15-45 Ohms, then operating many switches in parallel may provide a total switch-array resistance of 0.5 Ohms.

[0035] In certain embodiments, the MEMS switch **100** further includes an up isolation circuit **121** between the pull-up electrode **102** and the Vup coupling **112** (may also be referred to as Vup connection, Vup source, etc.), a second isolation circuit **122** disposed between the moveable beam **116** and electrical ground connection **118**, and a down isolation circuit **124** between the pull-down electrode **104** and the Vdn coupling **114** (may also be referred to as Vdn connection, Vdn source, etc.). The isolation circuits **121**, **122**, **124** isolate the MEMS switch **100** to prevent RF leakage (e.g., through the Vup coupling **112**, the Vdn coupling **114**, and/or the ground connection **118**) by adding electrical impedance at RF leakage points. In certain embodiments, each of the isolation circuits **121**, **122**, **124** (may be referred to as Ziso) includes at least one resistor. The source impedance

connected to the MEMS switch **100** is represented by Zsrc **126,** and the load impedance connected to the MEMS switch **100** is represented by Zload **128**. Additionally, the isolation circuits **121, 124** are utilized to isolate the control voltage sources, such as the Vup coupling **112** and Vdn coupling **114**.

[0036] The isolation circuits **121, 122, 124** provide several benefits. The isolation circuits **121, 122, 124** bias the direct current potential to allow for electrostatic actuation and further provide a path for transient currents during switching. The components of each of the isolation circuits **121, 122, 124** are chosen such that the resistance levels limit RF leakage while enabling the MEMS switch **100** to function as intended (e.g., movement speed of moveable beam **116**, maintain electric potential at the pull-up electrode **102** and pull-down electrode **104** during the switching transients), among other advantages (e.g., accurate engineering of actuation waveforms). In particular, the isolation circuits **121, 122, 124** help maintain RF performance such as voltage handling, insertion loss, isolation, and linearity.

[0037] In certain embodiments, each MEMS switch **100** has an on-resistance of 10's of Ohm and a very low off-state capacitance Coff, resulting in a Ron*Coff of 25-30fs. A low on-resistance is achieved by operating many of these small MEMS RF-switch elements in parallel in an array. In this way, an on-resistance of 0.5 Ohm with an off-state capacitance of 50-60fF can be achieved. However, further reductions can enable even lower loss and/or higher operating frequency as telecommunication bands move increasingly toward higher frequencies.

[0038] **FIGS. 2A-2B** are diagrams of a MEMS switch **200** with a single continuous contact **120'** extending between the input terminal electrode **106** and the output terminal electrode **108**. The MEMS switch **200** includes similar features as those discussed above with reference to **FIGS. 1A-1B** unless otherwise noted. In particular, the MEMS switch **200** includes an input terminal electrode **106** and an output terminal electrode **108**, a pull-up electrode **102**, a pull-down electrode **104** positioned between the input terminal electrode **106** and the output terminal electrode **108,** and a movable beam **116**. The pull-up electrode **102** is configured to electrically bias the movable beam **116** toward the

off-state. In certain embodiments, the pull-up electrode **102** and/or pull-down electrode **104** includes a plurality of pull-up electrodes **102** and/or a plurality of pull-down electrodes **104**. In certain embodiments, the moveable beam **116** further includes a stiffness (e.g., mechanical spring constant) to bias the moveable beam **116** to the off-state away from the input electrode **106**, output electrode **108**, and pull-down electrode **104**. In other words, the moveable beam **116** is mechanically biased toward the off-state.

[0039] In certain embodiments, the pull-down electrode **104** is respectively coupled to a down isolation circuit **124** to isolate a lower voltage source from the plurality of pull-down electrodes **104**. In certain embodiments, a second isolation circuit **122** is positioned between the movable beam **116** and an electrical common ground connection **118**. In certain embodiments, the pull-up electrode **102** is coupled to an up isolation circuit **121** to isolate an upper voltage source from the pull-up electrode **102**.

[0040] The movable beam **116** is configured to move between an on-state adjacent to the plurality of pull-down electrodes **104A, 104B** to electrically couple the input terminal electrode **106** and the output terminal electrode **108** to the movable beam **116**, and an off-state away from the plurality of pull-down electrodes **104A, 104B** to electrically isolate the input terminal electrode **106** and the output terminal electrode **108** from the movable beam **116**.

[0041] Instead of using multiple contacts, the MEMS switch **200** utilizes one continuous contact **120'** that continuously extends between the input terminal electrode **106** and the output terminal electrode **108**. The moveable beam **116** includes a body **119** and a contact **120'** positioned toward a bottom of the body **119** extending between the input terminal electrode **106** and the output terminal electrode **108**. In certain embodiments, the contact **120'** is embedded within the body **119**. In certain embodiments, portions of the contact **120'** are exposed, and portions of the contact **120'** are covered (e.g., by a dielectric film).

[0042] Electrical current flows from the input terminal electrode **106** through the contact **120'** to the output terminal electrode **108**. The contact **120'** has a higher conductivity (i.e., lower resistance) than the body **119** of the moveable

beam **116**. In other words, the electrical flow path includes a resistance **R'** formed from the electrical current flowing through the contact **120'**. However, resistance **R'** of the contact **120'** is less than resistance **R** of the body **119**. In certain embodiments, the contact-resistance between the contact **120'** and each of the input terminal electrode **106** and the output terminal electrode **108** is about 15-45 Ohms. In certain embodiments, the on-state resistance reduces from 0.5 Ohms to 0.35 Ohm, resulting in a 30% improvement. Accordingly, the contact **120'** has reduced the parasitic resistance **R'** without increasing any contact resistance.

[0043] It is also noted that electrical current may also flow through the body **119**, but that the electrical current through the body **119** is in parallel with the electrical current through the contact **120'**. The contact **120'** of the moveable beam **116** provides higher conductivity (i.e., lower resistance) than the body **119** but may also be stiffer than the body **119**. A thickness **t** of the contact **120'** can be adjusted based on the mechanical and/or electrical requirements of the MEMS switch **200**. In certain embodiments, the thickness **t** is between about 30 to 80 nm. Further, the body **119** may be altered to compensate for the additional stiffness and/or weight of the larger surface area of the contact **120'**. For example, the body **119** may require adjusted stress levels applied during deposition to straighten out the body **119** to compensate for the contact **120'** and prevent any mechanical deflection or bowing.

[0044] The contact **120'** further decreases the on-resistance of the MEMS switch by 25-30% without sacrificing the off-state capacitance, thus providing further reduction of the Ron*Coff.

[0045] Although described above as a single switch, other arrangements may be utilized. Multiple relays may be included together into one arrangement. In some non-limiting embodiments, four relays may be provided.

[0046] Accordingly, disclosed herein is a MEMS switch with a movable beam **116** positioned proximate to the input terminal electrode **106** and the output terminal electrode **108**. **T**he movable beam **116** includes a body **119** having a first conductivity and first stiffness, and a contact **120'** having a second

conductivity and a second stiffness more than the first conductivity and the first stiffness. The contact **120'** proximate to and continuously extending between the input terminal electrode **106** and the output terminal electrode **108** limits on-state resistance therebetween. The movable beam **116** is configured to move between an on-state and an off-state. In the on-state, the movable beam **116** electrically couples the contact **120'** of the movable beam **116** with the input terminal electrode **106** and the output terminal electrode **108**. In the off-state, the movable beam **116** electrically isolates the contact **120'** of the movable beam **116** from the input terminal electrode **106** and the output terminal electrode **108**.

[0047] **FIGS. 3A-3B** are views of one embodiment of the MEMS switch **200** of **FIGS. 2A-2C**. The MEMS ohmic switch **300** includes an input terminal electrode **106**, an output terminal electrode **108**, a pull-up electrode **102**, a pull-down electrode **104** positioned between the input terminal electrode **106** and the output terminal electrode **108**, a movable beam **116**, and anchor electrodes **302A, 302B**. The MEMS switch **300** further includes a substrate **304** with the input terminal electrode **106**, output terminal electrode **108**, a pull-down electrode **104**, and anchor electrodes **302A, 302B** mounted on the substrate **304**.

[0048] The pull-down electrode **104** is covered with a dielectric layer **306** to avoid a short-circuit between the movable beam **116** and the pull-down electrode **104** in the on-state. Suitable materials for the dielectric layer **306** include silicon-based materials including silicon-oxide, silicon-dioxide, silicon-nitride, and silicon-oxynitride. The thickness of the dielectric layer **306** is typically in the range of 50nm to 150nm to limit the electric field in the dielectric layer **306**.

[0049] On top of the input terminal electrode **106** is the input terminal contact **308** (may also be referred to as an input RF contact), and on top of the output terminal electrode **108** is the output terminal contact **310** (may also be referred to as an output RF contact). The movable beam **116** forms an ohmic contact with the input terminal electrode **106** and the output terminal electrode **108** in the pulled-down state. In particular, the moveable beam **116** includes a body **119** with a contact **120'** continuously extending between the input terminal electrode **106** and the output terminal electrode **108**.

[0050] On top of the anchor electrodes **302A, 302B** are anchor contacts **312A, 312B,** to which the movable beam **116** is anchored. Suitable materials used for the contacts **120', 308, 310, 312A, 312B** include Ti, TiN, TiAl, TiAlN, AlN, Al, W, Pt, Ir, Rh, Ru, RuO_2, ITO, and Mo and combinations thereof.

[0051] In certain embodiments, the MEMS switch **300** includes a center stopper **314** (e.g., positioned on the dielectric layer **306**). In certain embodiments, suitable materials that may be used for the stopper **314** include Ti, TiN, TiAl, TiAlN, AlN, Al, W, Pt, Ir, Rh, Ru, RuO_2, ITO, Mo, and/or silicon-based dielectric materials such as silicon oxide, silicon-dioxide, silicon-nitride, and silicon-oxynitride and combinations thereof.

[0052] The movable beam **116** (may also be referred to as a switching element, MEMS bridge, etc.) includes lower conductive layer **316** and upper conductive layer **318,** which are joined together using an array of vias **320**. Opposing ends of the upper layer **318** are anchored to opposing ends of the lower layer **316** by vias **322A, 322B**. Opposing ends of the lower conductive layer **316** of the moveable beam **116** are anchored to the anchor contacts **312A, 312B** by vias **324A, 324B**, which provide low compliance to permit operating voltages (e.g., 25V to 40V) to pull the moveable beam **116** in contact with the terminal contacts **308, 310** and center stopper **314**. This allows for a cheap integration of the CMOS (complementary metal-oxide-semiconductor) controller with a charge-pump to generate the voltages to drive the MEMS switch **300**. In other words, ends of the movable beam **116** are mounted to the substrate **304** such that the movable beam **116** is suspended above the input terminal electrode **106**, output terminal electrode **108**, and pull-down electrode **104** in the off state.

[0053] The lower conductive layer **316** includes the contact **120'** embedded within the body **119** at a bottom thereof. The contact **120'** includes exposed input portions **326** aligned with the input terminal electrode **106,** exposed output portions **328** aligned with the output terminal electrode **108**, and covered portion **330** therebetween.

[0054] The body **119** of the moveable beam **116** is configured for mechanical

properties that allow for stable mechanical operation over many cycle-events (and avoid suffering from mechanical fatigue or creep). For example, in certain embodiments, the body **119** of the moveable beam **116** includes TiAl and/or TiAlN, etc.

[0055] The contact **120'** of the moveable beam **116** includes a corrosion-resistant metal that provides good electrical contact resistance. For example, in certain embodiments, the contact **120'** of the moveable beam **116** includes Ruthenium, Ruthenium-oxide, platinum, and/or gold, etc.

[0056] **FIG. 3A** illustrates the MEMS switch **300** in an off-state with the pull-up electrode **102** drawing the moveable beam **116** upward toward the pull-up electrode **102** and away from the pull-down electrode **104,** input electrode **106**, and output electrode **108**. **FIG. 3B** illustrates the MEMS switch **300** in an on-state with the pull-down electrode **104** drawing the moveable beam **116** downward toward the pull-down electrode **104** and away from the pull-up electrode **102**. Current injected from the input terminal contact **308** into the moveable beam **116** when the MEMS switch **300** is actuated down flows out through the moveable beam **116** and output terminal contact **310**. The thicknesses of terminal contacts **308, 310** and center stopper **314** is set such that the center stopper **314** is engaged first upon pull-down actuation.

[0057] In certain embodiments, the MEMS switch **300** includes a cover **332** mounted to the substrate **304** and defines a cavity **334** between the cover **332** and the substrate **304**. The movable beam **116** is positioned within the cavity **332**.

[0058] **FIGS. 4A-4B** illustrate a MEMS switch **400** including pull-down electrodes **104** between the terminal electrodes **106, 108** and is devoid of a pull-up electrode **102**. MEMS switch **400** is similar to the MEMS switch **200** of **FIGS. 2A-2C** except where otherwise noted. The moveable beam **116** includes a stiffness (e.g., mechanical spring constant) to bias the moveable beam **116** to the off-state away from the input electrode **106**, output electrode **108**, and pull-down electrode **104** (without use of a pull-up electrode). Accordingly, in the on-state, the moveable beam **116** bends toward the pull-down electrode **104**, and when

voltage from Vdn coupling **114** is cut off, the moveable beam **116** mechanically returns to the off-state. In other words, the moveable beam **116** is mechanically biased toward the off-state.

[0059] **FIGS. 5A-5B** are cross-sectional side views of one embodiment of the MEMS switch **400** of **FIGS. 4A-4B** in an off-state and on-state, respectively. The MEMS switch **500** is similar to the MEMS switch **300** of **FIGS. 3A-3B** except where otherwise noted. As similarly noted in **FIGS. 4A-4B**, the MEMS switch **500** is devoid of a pull-up electrode **102**. The moveable beam **116** includes a stiffness to bias the moveable beam **116** to the off-state away from the input electrode **106**, output electrode **108**, and pull-down electrode **104**.

[0060] **FIG. 6** is a graph illustrating resistance reduction using the continuous contact of the MEMS switch of **FIGS. 5A-5B**. As illustrated, in certain embodiments, use of the continuous contact reduces the on-switch resistance compared to a beam without the continuous contact (R0) by 0.1 to 0.15 Ohms. A typical beam-contact layer thickness of 30 to 80nm is used. The effect of an increased thickness of the beam-contact layer is shown for three different thicknesses (R1-R3). The thicker the layer is, the more the on-resistance is reduced (e.g., resulting in a Ron improvement of 0.1-0.15 Ohm). The added benefit of the lower parasitic resistance is that less power will be dissipated inside the moveable beam **116**, resulting in less temperature rise, which in turn results in a more stable mechanical performance. Moreover, lower dissipated power and better thermal conductivity of the moveable beam **116** can have positive impact on the linearity of the ON-state switch, lowering intermodulation and harmonic distortion levels.

[0061] **FIGS. 7A-7D** are diagrams illustrating different embodiments of the contact **120',** which may be used depending on electrical and/or mechanical requirements. The MEMS switch includes a plurality of input terminal electrodes **106(1), 106(2)** (referred to generally as input terminal electrodes **106**) and a plurality of output terminal electrodes **108(1), 108(2)** (referred to generally as output terminal electrodes **108**). The input terminal electrodes **106** and the output terminal electrodes **108** are positioned in a grid to stabilize the moveable beam

116 upon contact with the input terminal electrodes **106** and the output terminal electrodes **108**. In other words, the input terminal electrodes **106** are aligned along a width W0, and the output terminal electrodes **108** are aligned along the width W0. Of course, fewer or more input terminal electrodes **106** and/or output terminal electrodes **108** may be used.

[0062] Referring to **FIG. 7A**, the contact **120'(1)** is of a generally rectangular shape of a first length L1. The contact **120'(1)** continuously extends over each of the plurality of input terminal electrodes **106** and the plurality of output terminal electrodes **108**.

[0063] Referring to **FIG. 7B**, the contact **120'(2)** is of a generally rectangular shape of a second length L2. The contact **120'(2)** continuously extends over each of the plurality of input terminal electrodes **106** and the plurality of output terminal electrodes **108**. However, the contact **120'(2)** extends farther past the input terminal electrodes **106** and the output terminal electrodes **108**. In certain embodiments, the length L2 of the contact **120'(2)** is 1-50% (e.g., 10-50%, 20-40%, 20-30%, etc.) more than the length L0 between the set of input terminal electrodes **106** and the set of output terminal electrodes **108**. In this way, the length of the contact **120'(2)** can be adjusted depending on the stiffness requirements of the moveable beam **116**. In particular, a longer contact **120'(2)** would result in a stiffer moveable beam **116** (assuming constant thickness).

[0064] Referring to **FIG. 7C**, the contact **120'(3)** includes end portions **700A, 700B** that are wider at a first width W1 than a middle portion **702** of the contact **120'(3)** at a second width W2. Narrowing the middle portion **702** provides a continuous electrical path between the input terminal electrodes **106** and the output terminal electrodes **108** while also reducing a stiffness and/or weight of the contact **120'(3)**. In certain embodiments, the width W1 of the end portions **700A, 700B** is 1-100% (e.g., 1-50%, 10-50%, 20-80%, 30-60%, etc.) more than the width W2 of the middle portion **702**.

[0065] Referring to **FIG. 7D**, the contact **120'(4)** defines a central aperture **704**. Similar to embodiments discussed above, such a configuration provides a continuous electrical path between the input terminal electrodes **106** and the

output terminal electrodes **108** while also reducing a stiffness and/or weight of the contact **120'(4)**. In certain embodiments, the width W1' of the contact **120'(4)** is 1-100% (e.g., 1-50%, 10-50%, 20-80%, 30-60%, etc.) more than the width W2' of the central aperture **704**. Further, In certain embodiments, the length L1' of the contact **120'(4)** is 1-100% (e.g., 1-50%, 10-50%, 20-80%, 30-60%, etc.) more than the length L2' of the central aperture **704**.

[0066] **FIG. 8** is a schematic top view of a switch cell **800** containing a number of MEMS switches **300**. All MEMS switches **300** in the cell **800** are turned on simultaneously by applying a sufficiently high voltage to the pull-down electrodes **104**. Although MEMS switch **300** is illustrated, a similar configuration could be used for any of the MEMS switches disclosed herein.

[0067] Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

CLAIMS

1. A microelectromechanical system (MEMS) switch, comprising:

an input terminal electrode;

an output terminal electrode;

a pull-down electrode positioned between the input terminal electrode and the output terminal electrode; and

a movable beam positioned proximate the input terminal electrode and the output terminal electrode, the movable beam comprising:

a body comprising a first conductivity and first stiffness; and

a contact comprising a second conductivity and a second stiffness more than the first conductivity and the first stiffness, the contact proximate to and continuously extending between the input terminal electrode and the output terminal electrode to limit on-state resistance therebetween.

the movable beam configured to move between:

an on-state electrically coupling the contact of the movable beam with the input terminal electrode and the output terminal electrode; and

an off-state electrically isolating the contact of the movable beam from the input terminal electrode and the output terminal electrode.

2. The MEMS switch of claim 1, wherein the input terminal electrode comprises an input RF electrode, and the output terminal electrode comprises an output RF electrode.

3. The MEMS switch of claim 1 or 2, wherein the movable beam is coupled to an RF node.

4. The MEMS switch of any one of the preceding claims, wherein the body comprises at least one of TiAl or TiAlN.

5. The MEMS switch of any one of the preceding claims, wherein the contact comprises at least one of ruthenium, ruthenium oxide, platinum, or gold.

6. The MEMS switch of any one of the preceding claims, wherein the contact has a thickness between about 30 to 80 nm.

7. The MEMS switch of any one of the preceding claims, wherein a length of the contact is between 1% to 50% longer than a length between the input terminal electrode and the output terminal electrode.

8. The MEMS switch of any one of the preceding claims, wherein end portions of the contact are wider than a middle portion of the contact.

9. The MEMS switch of any one of the preceding claims, wherein the contact defines an aperture.

10. The MEMS switch of any one of the preceding claims, wherein:

the input terminal electrode comprises a plurality of input terminal electrodes;

the output terminal electrode comprises a plurality of output terminal electrodes; and

the contact continuously extends over each of the plurality of input terminal electrodes and the plurality of output terminal electrodes.

11. The MEMS switch of any one of the preceding claims, wherein the movable beam is mechanically biased toward the off-state.

12. The MEMS switch of any one of the preceding claims, further comprising a pull-up electrode configured to electrically bias the movable beam toward the off-state.

13. The MEMS switch of any one of the preceding claims,

further comprising a substrate;

wherein the input terminal electrode, output terminal electrode, and pull-down electrode are mounted on the substrate;

wherein ends of the movable beam are mounted to the substrate such that the movable beam is suspended above the input terminal electrode, output terminal electrode, and the pull-down electrode in the off-state.

14. The MEMS switch of claim 13,

further comprising a cover mounted to the substrate and defining a cavity between the cover and the substrate;

wherein the movable beam is positioned within the cavity.

15. A microelectromechanical system (MEMS), comprising:

a plurality of MEMS switches, each switch comprising:

an input terminal electrode;

an output terminal electrode;

a pull-down electrode positioned between the input terminal electrode and the output terminal electrode; and

a movable beam positioned proximate the input terminal electrode and the output terminal electrode, the movable beam comprising:

a body comprising a first conductivity and a first stiffness; and

a contact comprising a second conductivity and a second stiffness more than the first conductivity and the first stiffness, the contact proximate to and extending between the input terminal electrode and the output terminal electrode to limit on-state resistance therebetween;

the movable beam configured to move between:

an on-state electrically coupling the contact of the movable beam with the input terminal electrode and the output terminal

electrode; and

an off-state electrically isolating the contact of the movable beam from the input terminal electrode and the output terminal electrode.

16. The MEMS device of claim 15, wherein for each MEMS switch, the body comprises at least one of TiAl or TiAlN, and the contact comprises at least one of ruthenium, ruthenium oxide, platinum, or gold.

17. The MEMS device of claim 15 or 16, wherein for each MEMS switch, the contact has a thickness between about 30 to 80 nm.

18. The MEMS device of any one of claims 15 to 17, wherein for each MEMS switch, a length of the contact is between 1% to 50% longer than a length between the input terminal electrode and the output terminal electrode.

19. The MEMS device of any one of claims 15 to 18, wherein for each MEMS switch, end portions of the contact are wider than a middle portion of the contact.

20. The MEMS device of any one of claims 15 to 19, wherein for each MEMS switch, the contact defines an aperture.