WETTING FINGER LATCHING PIEZOELECTRIC RELAY

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to the following co-pending U.S. Patent Applications, being identified by the below enumerated identifiers and arranged in alphanumerical order, which have the same ownership as the present application and to that extent are related to the present application and which are hereby incorporated by reference:

Application 10010448-1, titled "Piezoelectrically Actuated Liquid Metal Switch", filed May 2, 2002 and identified by Serial Number 10/137,691;

Application 10010529-1, "Bending Mode Latching Relay", and having the same filing date as the present application;

Application 10010531-1, "High Frequency Bending Mode Latching Relay", and having the same filing date as the present application;

Application 10010570-1, titled "Piezoelectrically Actuated Liquid Metal Switch", filed May 2, 2002 and identified by Serial Number 10/142,076;

Application 10010571-1, "High-frequency, Liquid Metal, Latching Relay with Face Contact", and having the same filing date as the present application;

Application 10010572-1, "Liquid Metal, Latching Relay with Face Contact", and having the same filing date as the present application;

Application 10010573-1, "Insertion Type Liquid Metal Latching Relay", and having the same filing date as the present application;

Application 10010617-1, "High-frequency, Liquid Metal, Latching Relay Array", and having the same filing date as the present application;

Application 10010618-1, "Insertion Type Liquid Metal Latching Relay Array", and having the same filing date as the present application;

Application 10010634-1, "Liquid Metal Optical Relay", and having the same filing date as the present application;

Application 10010640-1, titled "A Longitudinal Piezoelectric Optical Latching Relay", filed October 31, 2001 and identified by Serial Number 09/999,590;

Application 10010643-1, "Shear Mode Liquid Metal Switch", and having the same filing date as the present application;

Application 10010644-1, "Bending Mode Liquid Metal Switch", and having the same filing date as the present application;

Application 10010656-1, titled "A Longitudinal Mode Optical Latching Relay", and having the same filing date as the present application;

Application 10010663-1, "Method and Structure for a Pusher-Mode Piezoelectrically Actuated Liquid Metal Switch", and having the same filing date as the present application;

Application 10010664-1, "Method and Structure for a Pusher-Mode Piezoelectrically Actuated Liquid Metal Optical Switch", and having the same filing date as the present application;

Application 10010790-1, titled "Switch and Production Thereof", filed December 12, 2002 and identified by Serial Number 10/317,597;

Application 10011055-1, "High Frequency Latching Relay with Bending Switch Bar", and having the same filing date as the present application;

Application 10011056-1, "Latching Relay with Switch Bar", and having the same filing date as the present application;

Application 10011064-1, "High Frequency Push-mode Latching Relay", and having the same filing date as the present application;

Application 10011065-1, "Push-mode Latching Relay", and having the same filing date as the present application;

Application 10011121-1, "Closed Loop Piezoelectric Pump", and having the same filing date as the present application;

Application 10011329-1, titled "Solid Slug Longitudinal Piezoelectric Latching Relay", filed May 2, 2002 and identified by Serial Number 10/137,692;

Application 10011344-1, "Method and Structure for a Slug Pusher-Mode Piezoelectrically Actuated Liquid Metal Switch", and having the same filing date as the present application;

Application 10011345-1, "Method and Structure for a Slug Assisted Longitudinal Piezoelectrically Actuated Liquid Metal Optical Switch", and having the same filing date as the present application;

Application 10011397-1, "Method and Structure for a Slug Assisted Pusher-Mode Piezoelectrically Actuated Liquid Metal Optical Switch", and having the same filing date as the present application;

Application 10011398-1, "Polymeric Liquid Metal Switch", and having the same filing date as the present application;

Application 10011410-1, "Polymeric Liquid Metal Optical Switch", and having the same filing date as the present application;

Application 10011436-1, "Longitudinal Electromagnetic Latching Optical Relay", and having the same filing date as the present application;

Application 10011437-1, "Longitudinal Electromagnetic Latching Relay", and having the same filing date as the present application;

Application 10011458-1, "Damped Longitudinal Mode Optical Latching Relay", and having the same filing date as the present application;

Application 10011459-1, "Damped Longitudinal Mode Latching Relay", and having the same filing date as the present application;

Application 10020013-1, titled "Switch and Method for Producing the Same", filed December 12, 2002 and identified by Serial Number 10/317,963;

Application 10020027-1, titled "Piezoelectric Optical Relay", filed March 28, 2002 and identified by Serial Number 10/109,309;

Application 10020071-1, titled "Electrically Isolated Liquid Metal Micro-Switches for Integrally Shielded Microcircuits", filed October 8, 2002 and identified by Serial Number 10/266,872;

Application 10020073-1, titled "Piezoelectric Optical Demultiplexing Switch", filed April 10, 2002 and identified by Serial Number 10/119,503;

Application 10020162-1, titled "Volume Adjustment Apparatus and Method for Use", filed December 12, 2002 and identified by Serial Number 10/317,293;

Application 10020241-1, "Method and Apparatus for Maintaining a Liquid Metal Switch in a Ready-to-Switch Condition", and having the same filing date as the present application;

Application 10020242-1, titled "A Longitudinal Mode Solid Slug Optical Latching Relay",, and having the same filing date as the present application;

Application 10020473-1, titled "Reflecting Wedge Optical Wavelength Multiplexer/Demultiplexer", and having the same filing date as the present application;

Application 10020540-1, "Method and Structure for a Solid Slug Caterpillar Piezoelectric Relay", and having the same filing date as the present application;

Application 10020541-1, titled "Method and Structure for a Solid Slug Caterpillar Piezoelectric Optical Relay", and having the same filing date as the present application;

Application 10030438-1, "Inserting-finger Liquid Metal Relay", and having the same filing date as the present application;

Application 10030521-1, "Pressure Actuated Optical Latching Relay", and having the same filing date as the present application;

Application 10030522-1, "Pressure Actuated Solid Slug Optical Latching Relay", and having the same filing date as the present application; and

Application 10030546-1, "Method and Structure for a Slug Caterpillar Piezoelectric Reflective Optical Relay", and having the same filing date as the present application.

FIELD OF THE INVENTION

The invention relates to the field of micro-electromechanical systems (MEMS) for electrical switching, and in particular to a piezoelectrically actuated liquid metal relay.

BACKGROUND

Liquid metals, such as mercury, have been used in electrical switches to provide an electrical path between two conductors. An example is a mercury thermostat switch, in which a bimetal strip coil reacts to temperature and alters the angle of an elongated cavity containing mercury. The mercury in the cavity forms a single droplet due to high surface tension. Gravity moves the mercury droplet to the end of the cavity containing electrical contacts or to the other end, depending upon the angle of the cavity. In a manual liquid metal switch, a permanent magnet is used to move a mercury droplet in a cavity.

Liquid metal is also used in relays. A liquid metal droplet can be moved by a variety of techniques, including electrostatic forces, variable geometry due to thermal expansion/contraction and magneto-hydrodynamic forces.

Rapid switching of high currents is used in a large variety of devices, but provides a problem for solid-contact based relays because of arcing when current flow is disrupted. The arcing causes damage to the contacts and degrades their conductivity due to pitting of the electrode surfaces.

Conventional piezoelectric relays either do not latch or use residual charges in the piezoelectric material to latch or else activate a switch that uses a latching mechanism.

Micro-switches have been developed that use liquid metal as the switching element and the expansion of a gas when heated to move the liquid metal and actuate the switching function. Liquid metal has some advantages over other micro-machined technologies, such as the ability to switch relatively high powers (about 100mW) using metal-to-metal contacts without micro-welding or overheating the switch mechanism. However, the use of heated gas has several disadvantages. It requires a relatively large amount of energy to change the state of the switch, and the heat generated by switching must be dissipated effectively if the switching duty cycle is high. In addition, the actuation rate is relatively slow, the maximum rate being limited to a few hundred Hertz.

FIG. 9 is a top view of a relay in an opening state in accordance with certain embodiments of the present invention.

FIG. 10 is a top view of a circuit substrate of a relay in accordance with certain embodiments of the present invention.

FIG. 11 is a side view of a circuit substrate of a relay in accordance with certain embodiments of the present invention.

FIG. 12 is a top view of a relay in an open state in accordance with certain embodiments of the present invention.

FIG. 13 is a sectional view of a relay in accordance with certain embodiments of the present invention.

FIG. 14 is a top view of a relay in a closing state in accordance with certain embodiments of the present invention.

FIG. 15 is a top view of a relay in a closed and latched state in accordance with certain embodiments of the present invention.

FIG. 16 is a top view of a relay in an opening state in accordance with certain embodiments of the present invention.

FIG. 17 is a top view of a circuit substrate of a relay in accordance with certain embodiments of the present invention.

DETAILED DESCRIPTION

While this invention is susceptible of embodiment in many different forms, there is shown in the drawings and will herein be described in detail one or more specific embodiments, with the understanding that the present disclosure is to be considered as exemplary of the principles of the invention and not intended to limit the invention to the specific embodiments shown and described. In the description below, like reference numerals are used to describe the same, similar or corresponding parts in the several views of the drawings.

The present invention relates to an electrical relay in which the formation of a conducting liquid bridge between two fixed contacts is facilitated by action of a conducting, wettable finger. The conducting liquid may be a liquid metal, such as mercury or a gallium alloy. The finger is attached to one end of a beam, the other end of the beam is fixed to the substrate of the relay. The beam and the attached finger are moved by the action of one or more piezoelectric elements acting on the beam. The piezoelectric elements may operated to bend or deflect the beam.

FIG. 1 is a side view of an exemplary embodiment of a relay of the present invention. The relay has three layers: a cap layer 102, a piezoelectric layer 104 and a substrate layer 106. The substrate layer 106 supports electrical connections 108 to the switch, electrical connections 110 to the piezoelectric actuator and the associated circuitry. These three layers form a relay housing.

FIG. 2 is a top view of the relay in **FIG. 1**. The broken lines indicate hidden structure including the moveable beam 112 and the switch finger 114 that is attached

to the free end of the beam 112. These elements are positioned within a switching cavity 116 in the piezoelectric layer of the relay. Also shown are two electrical contacts 118 and 120 that have wettable surfaces supporting droplets of conducting liquid. The sections 3-3 and 4-4 will be described below with reference to **FIG. 3** and **FIG. 4** respectively.

FIG. 3 is a sectional view through the section 3-3 in **FIG. 2**. The moveable beam 112 is fixed at one end to the substrate of the piezoelectric layer 104. The free end of the beam supports the switch finger 114. These elements are positioned within the switching cavity 116. The contact 120 is attached via a non-wettable pad 124 to the substrate 106. The other contact (118 in **FIG. 2**) is attached via a non-wettable pad 122 to the substrate 106. The electrical contacts are positioned within a recess in the switching cavity. The contacts have a wettable surface that supports a volume of conducting liquid 126. The volume of the conducting liquid is chosen such that, without the presence of the wettable finger, the liquid forms a separate droplet on each contact. The contacts are electrically connected to the connectors 108 that allow a signal to be routed through the relay. The beam 112 is moved by action of a piezoelectric actuator. Control signals are coupled to the actuator via connectors 110 that are electrically coupled to contact pads 128 in the switching cavity.

FIG. 4 is a sectional view through the section 4-4 in **FIG. 2**. The switch finger 114 is attached to the free end of the moveable beam 112 and is positioned in proximity to the electrical contacts and the supported liquid droplets 126. The conducting liquid 126 does not wet the non-wettable pad 124. In this embodiment,

the beam 112 is moved by action of a piezoelectric element 130 attached to the side of the beam and operable to bend the beam.

FIG. 5 is a top view of a relay with the cap layer 102 removed. The switch is in an open state, since the liquid metal does not bridge the gap between the electrical contacts. In this embodiment, the moveable beam 112 is acted upon by piezoelectric elements 130 and 132 attached to the sides of the beam. Extension of the piezoelectric element 130 along the length of the beam or contraction of the piezoelectric element 132 along the length of the beam will cause the beam to bend such that the free end of the beam, and the attached switch finger, moves in the direction indicated by the arrow 134. The piezoelectric elements may be used alone or in concert. Control signals to the piezoelectric elements are provided via contact pads 128.

FIG. 6 is a top view of a relay with the cap layer 102 removed. The switch is in a closing state. The beam 112 has been bent by action of the piezoelectric elements 130 and 132, causing the switch finger 114 to touch the conducting liquid volumes 126. The conducting liquid 126 wets the surface of the wettable finger and forms a conducting bridge between the two fixed electrical contacts. This completes the electrical connection between the two electrical contacts and closes the circuit. The switch finger may be non-conductive, but a conductive switch finger reduces the electrical resistance through the connection.

FIG. 7 is sectional view through the section 7-7 in **FIG. 6**. The free end of the beam 112 has been displaced vertically in the figure relative to its position in **FIG. 4**.

The switch finger 114 has been inserted into the conducting liquid volume 126, causing the two volumes to coalesce and complete the electrical connection.

FIG. 8 is a top view of a relay in a closed and latched state with the cap layer 102 removed. Once the switch finger has completed the conducting liquid connection, the piezoelectric elements 130 and 132 are de-energized and the beam 112 returns to its non-deflected position. However, surface tension in the conducting liquid 126 maintains the liquid bridge between the electrical contacts and the wettable switch finger. The electrical connection between the two electrical contacts is maintained and the switch is latched in the closed state.

In order to open the switch, the wettable switch finger is moved farther away from the electrical contacts. This is shown in **FIG. 9**, which is a top view of a relay in an opening state with the cap layer 102 removed. Referring to **FIG. 9**, the piezoelectric elements 130 and 132 are energized with a reverse polarity so that element 130 contracts and element 132 is extended to bend the beam and moves its free end 112 in a direction indicated by the arrow 134. The switch finger is moved away from the electrical connections and the surface tension bond maintaining the liquid bridge is broken. The conducting liquid breaks into two volumes 126 and the electrical circuit is broken. Surface tension in the liquid retains the liquid on the two contacts, even in the presence of body forces such as those due to motion of the whole relay. Thus, the relay is latched in the open position.

FIG. 10 is a top view of a substrate layer 106 of a relay. Two electrical contacts 118 and 120 are fixed to non-wettable pads that are in turn fixed to the substrate 106. Electrical pads 128 provide electrical connections to the piezoelectric

elements. The pads and contacts may be formed on the substrate using known micro-machining techniques.

A side view of the circuit substrate is shown in **FIG. 11**. The electrical contacts 118 and 120 are fixed to non-wettable pads 122 and 124, respectively, which are in turn fixed to the substrate 106. The electrical contacts 118 and 120 are electrically coupled to connectors 108 on the external surface of the substrate. Alternatively, the electrical connectors may be connected, via traces on the top of the substrate, to connectors on the edge of the substrate. The electrical pads 128 provide electrical connections to the piezoelectric elements and are electrically coupled to the connectors 110 on the external surface of the substrate.

FIG. 12 is a top view of an alternative embodiment of the relay with the cap layer 102 removed. The switch is in an open state. In this embodiment, the moveable beam 112 is acted upon by a piezoelectric actuator 140 attached to a side of the switching channel 116. Extension of the piezoelectric element 140 in the plane of the layer and perpendicular to the beam moves the beam in the direction indicated by the arrow 134. In this embodiment, the piezoelectric actuator is positioned closer to the fixed end of the beam than to the free end so that the beam amplifies the motion of the piezoelectric element, thereby producing a larger displacement of the switch finger 114. Other forms of mechanical amplification may be used. Control signals are supplied to the piezoelectric element via the pads 128 and the contacts 142 and 144. The piezoelectric actuator 140 may comprise a single piezoelectric element or a stack of piezoelectric elements.

FIG. 13 is a sectional view through the section 13-13 in **FIG. 13**. The piezoelectric element 140 is coupled via the contact 142 to the substrate 104, and via the contact 144 to the beam 112. When a voltage is applied across the piezoelectric element it deforms in an extensional mode (the vertical direction in the figure) and acts laterally on the beam 112. This, in turn, moves the switch finger 114.

FIG. 14 is a top view of the relay in **FIG. 12** showing the switch in a closing state. The piezoelectric element 140 has been energized and displaces the beam 112 laterally. This has moved the switch finger 114 to touch volume of conducting fluid 126, causing it to wet between the switch finger 114 and the two electrical contacts. This completes the electrical circuit between the electrical contacts.

FIG. 15 is a top view of a relay in a closed and latched state with the cap layer 102 removed. Once the switch finger has completed the conducting liquid connection, the piezoelectric element 140 is de-energized and the beam 112 returns to its non-deflected position. However, surface tension in the conducting liquid 126 maintains the liquid bridge between the electrical contacts and the wettable switch finger. The electrical connection between the two electrical contacts is maintained and the switch is latched in the closed state.

In order to open the switch, the wettable switch finger is moved farther away from the electrical contacts. This is shown in **FIG. 16**, which is a top view of a relay in an opening state with the cap layer 102 removed. Referring to **FIG. 16**, the piezoelectric element 140 is energized with a reverse polarity so that the element contracts and pulls the beam in a lateral direction. This moves the free end of the beam 112 in the direction indicated by the arrow 134. The switch finger is moved

away from the electrical connections and the surface tension bond maintaining the liquid bridge is broken. The conducting liquid breaks into two volumes 126 and the electrical circuit is broken. Surface tension in the liquid retains the liquid on the two contacts, even in the presence of body forces such as those due to motion of the whole relay. Thus, the relay is latched in the open position.

FIG. 17 is a top view of a substrate layer 106 of the relay shown in **FIGs. 10 - 16**. Two electrical contacts 118 and 120 are fixed to non-wettable pads that are in turn fixed to the substrate 106. Electrical pads 128 provide electrical connections to the two ends of the piezoelectric element. The pads and contacts may be formed on the substrate using known micro-machining techniques.

While the invention has been described in conjunction with specific embodiments, it is evident that many alternatives, modifications, permutations and variations will become apparent to those of ordinary skill in the art in light of the foregoing description. Accordingly, the present invention is intended to embrace all such alternatives, modifications and variations as fall within the scope of the appended claims.

What is claimed is:

1. An electrical relay comprising:

a relay housing enclosing a switching cavity (116);

a first electrical contact (118) in the switching cavity (116), having a wettable surface;

a second electrical contact (120) in the switching cavity (116) spaced from the first electrical contact (118) and having a wettable surface;

a conducting liquid (126) in wetted contact with the first (118) and second (120) electrical contacts;

a beam (112) having a fixed end attached to the relay housing within the switching cavity (116) and a free end;

a wettable switch finger (114), attached to the free end of the beam (112) and moveable to touch the conducting liquid (126); and

a piezoelectric actuator (130, 132 or 140) operable to move the beam (112) in a lateral direction to cause the switching finger (114) to move from a non-deflected position to a first position, where the conducting liquid (126) wets between the first and second contacts and the switch finger and completes an electrical circuit between the first and second contacts, and to a second position where the conducting liquid (126) cannot wet between first and second contacts and the switch finger and the electrical circuit between the first and second contacts is broken.

2. An electrical relay in accordance with claim 1, wherein the non-deflected position of the switch finger (114) and the volume of the conducting liquid (126) are such that

movement of the switch finger (114) from the first position to the non-deflected position does not break the electrical circuit completed by the conducting liquid (126).

3. An electrical relay in accordance with claim 1, wherein the non-deflected position of the switch finger (114) and the volume of the conducting liquid (126) are such that movement of the switch finger (114) from the first position to the second first position breaks the electrical circuit completed by the conducting liquid (126).

4. An electrical relay in accordance with claim 1, wherein the piezoelectric actuator comprises a first piezoelectric element (130 or 132) attached to a first side of the beam (112), the first piezoelectric element (130 or 132) operable to deform in a longitudinal mode parallel to the beam (112) and thereby bend the beam.

5. An electrical relay in accordance with claim 1, wherein the piezoelectric actuator comprises a piezoelectric element (140) acting between a wall of the switching cavity (116) and a region of the beam (112) between the free end and the fixed end, the piezoelectric element (140) operable to deform in a longitudinal mode substantially perpendicular to the beam (112) and thereby deflect the beam.

6. An electrical relay in accordance with claim 1, wherein the conducting liquid (126) is a liquid metal.

7. An electrical relay in accordance with claim 1, wherein the wettable finger (114) is electrically conductive.

8. An electrical relay in accordance with claim 1, wherein the relay housing comprises:

a substrate layer (106) supporting electrical connections (108) to the first (118) and second (120) electrical contacts and electrical connections (110) to the piezoelectric actuator (130, 132 or 140);

a cap layer (102); and

a piezoelectric layer (104) positioned between the substrate layer (106) and the cap layer (102) and having the switching cavity (116) formed therein.

9. A method for switching an electrical circuit in an electrical relay between a first contact (118) and a second contact (120), the first and second contacts being wetted by a first conducting liquid (126) method comprising:

if the circuit is to completed:

energizing an actuator (130, 132 or 140) to move a wettable finger (114) to a first position where the wettable finger (114) touches the conducting liquid (126) and causes it to wet between the first (118) and second (120) contacts and the wettable finger (114); and

if the circuit is to broken:

energizing the actuator (130, 132 or 140) to move a wettable finger (114) to a second position where conducting liquid (126) cannot wet between the first (118) and second (120) contacts and the wettable finger (140).

10. A method in accordance with claim 9, further comprising:

if the circuit is to completed:

de-energizing the actuator (130, 132 or 140) after the wettable finger (114) has moved to the first position; and

if the circuit is to broken:

de-energizing the actuator (130, 132 or 140) after the wettable finger (114) has moved to the second position.