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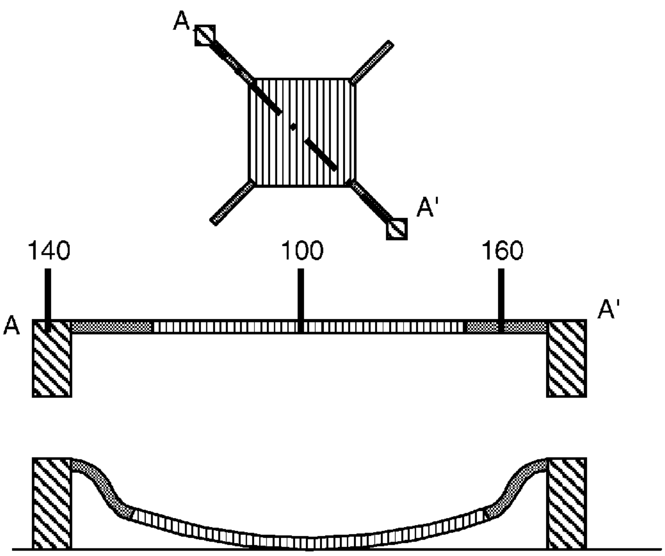

FIG. 1

(57) Abstract: The present invention relates to a MEMS switch and a method of operating a MEMS switch, in order to reduce impact stress. Several MEMS suffer from a so-called zipping effect. This zipping effect can take place in MEMS switches consisting of spring-suspended membranes, cantilevers or double-clamped beams which are actuated electrostatically and operated at pull-in. A capacitive MEMS switch consists of a free hanging upper electrode suspended by one or more springs above a fixed lower electrode. The device is switched between a state of low capacitance to a state of high capacitance by applying e.g. a DC potential between the two electrodes. This DC potential pulls the upper electrode towards the bottom electrode, leaving a thin separation determined by an isolation layer that is present on top of the lower electrode.

WO 2010/049865 A1

MEMS SWITCH WITH REDUCED IMPACT STRESS

FIELD OF THE INVENTION

The present invention relates to a MEMS switch and a method of operating a MEMS switch, in order to reduce impact stress.

BACKGROUND OF THE INVENTION

Microelectromechanical systems (MEMS) are the technology of the very small, and merge at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micromachines (in Japan), or Micro Systems Technology - MST (in Europe). MEMS are separate and distinct from a hypothetical vision of Molecular nanotechnology or Molecular Electronics. MEMS are made up of components between 1 to 100 µm in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from a 20 µm to a millimeter. They usually consist of a central unit that processes data, the microprocessor, and several components that interact with the outside such as microsensors. At these size scales, the standard constructs of classical physics do not always hold true. Due to MEMS' large surface area to volume ratio, surface effects such as electrostatics and wetting dominate volume effects such as inertia or thermal mass.

Several MEMS suffer from a so-called zipping effect, which will be explained in the remainder of this application. This zipping effect can take place in MEMS switches consisting of spring-suspended membranes, cantilevers or double-clamped beams which are actuated electrostatically and operated at pull-in.

A capacitive MEMS switch consists of a free hanging upper electrode suspended by one or more springs above a fixed lower or bottom electrode. In a MEMS upper and lower electrode may be interchanged. The device is switched between a state of low capacitance to a state of high capacitance by applying e.g. a

DC potential between the two electrodes. This DC potential pulls the upper electrode towards the bottom electrode, leaving a thin separation determined by an isolation layer that is present on top of the lower electrode.

The transition of the switch from an open to a closed state (and vice versa) is governed by:

An electrostatic force caused by a potential difference between the upper and lower electrode. This force increases with the inverse of the squared distance that remains between the two electrodes. Just before contact, the remaining distance to the lower electrode is small, and hence the electrostatic force is large.

A stiffness of springs with which the upper electrode is suspended. The springs generate a vertical restoring force that increases linearly with their displacement.

A flexibility of the upper electrode (or membrane). Due to a finite rigidity of the membrane, not only the springs are deformed, but also the membrane becomes slightly bent.

And the interplay of these above effects.

In many practical MEMS switch layouts, the springs are connected at the corners of the membrane, as shown in figure 1. In Fig. 1, also the deformed shape at first contact (in the middle of the membrane) is schematically illustrated.

The zipping effect of the membrane, and the corresponding high acceleration of the membrane corners and spring ends, generates unwanted vibrations in the springs, as measured with an interferometric setup (see Fig. 2). These vibrations may result in plastic deformation or fatigue, reducing the reliability of the device.

Thus, prior art MEMS suffer from a variety of unwanted and undesired effects, as is described above, resulting in the problems as described.

The present invention is aimed at solving one or more of the above mentioned problems, and specifically to reduce the excessive vertical acceleration of the membrane near the springs of the upper membrane.

SUMMARY OF THE INVENTION

The present invention relates to a capacitive MEMS switch layout for reduced impact stress comprising an upper electrode having a zipping motion, one or more anchors, one or more springs having a first attachment to the upper electrode and a second attachment to an anchor, and a fixed lower electrode, characterized in that the zipping motion is characterized by at least one vector which at least one vector has substantially no component directed towards and ending close to or at any first attachment, and to a method of reducing impact stress, specifically in MEMS switches such as the capacitive MEMS switch according to the invention, by time varying actuation voltage applied to a first electrode involving at least two voltage levels, preferably cyclic time varying, wherein after the switch has commenced closure by applying a first voltage level that is higher than the static pull in voltage of the switch and before complete closure of the switch the actuation voltage is lowered by applying at least one second voltage level that is at closure higher than the static pull out voltage of the switch.

Thereby, excessive vertical acceleration of the upper electrode, such as a membrane, near the springs of the upper electrode is reduced, as well as plastic deformation and/or fatigue is reduced, and reliability and lifetime of the device are improved.

It has been found after intensive research that the position of attachment of the springs at the membrane also governs the transition of the switch from open to closed state. The springs not only exert a vertical spring force on the membrane, but also a bending moment which has an effect because the membrane is not perfectly rigid.

Further, squeeze film damping between the upper and lower electrode plays a role in this respect.

Typically the present capacitive switch is characterized in that the net torsion of the one or more springs during operation is substantially equal to zero.

DETAILED DESCRIPTION OF THE INVENTION

In a first aspect the present invention relates to a capacitive MEMS switch layout for reduced impact stress comprising an upper electrode having a zipping motion, one or more anchors, one or more springs having a first attachment to the upper electrode and a second attachment to an anchor, and a fixed lower electrode, characterized in that the zipping motion is characterized by at least one vector which at least one vector has substantially no component directed towards and ending close to or at any first attachment.

The term MEMS may in principal also refer to NEMS.

Although the present invention is thus in general applicable for electrostatically actuated MEMS devices such as galvanic and capacitive switches, the present invention is explained on the basis of an electrostatically actuated suspended membrane capacitive switch, because this is a likely case under which a pronounced zipping effect can take place. In the context of the invention the term “capacitive MEMS switch” is meant to comprise also any other electrostatically actuated suspended membrane device, but preferably a capacitive MEMS switch.

An advantage of the present invention is that the capacitive MEMS switch will have a longer life time, because the springs do not deform plastically and/or crack as quickly as in a conventional design according to the prior art.

A zipping motion relates to an effect present in a capacitive MEMS switch; when such a switch is close a first electrode contacts a second electrode. However, due to the construction of the MEMS switch, such contacting typically starts at what can be identified as one or more first points of contacts, e.g. in the middle of the switch, at one or more borders of the switch etc. Then, comparable to a zipper, at least a part of the remaining first electrode not being in contact yet with the second electrode comes into contact with said second electrode. Even more complex, such contacting can start at a first position, propagate to one or more second position on the first and second electrode, and even further, e.g. when reaching an edge of the first electrode, propagate in a further direction, not necessarily being the same as a first direction of propagation. Thus, this effect is referred to as zipping motion.

A zipping motion is therefore typically characterized by at least one vector, indicating an origin or first point of contact of the zipping motion, and pointing towards an endpoint of the zipping motion, i.e. last point of contact. As indicated above, an upper electrode may have more than one vector characterizing the zipping motion, e.g. one starting in a lower left corner, and one starting in a lower right corner of the upper electrode. It has now been found that the origin of the zipping motion vector is relatively less important. Further, it has been found that in order to reduce the zipping mode, any vector characterizing the zipping motion should not end substantially at a first attachment, between a spring and the upper electrode. Such a vector, should end at a location relatively far away from any first attachment, e.g. in the middle between two first attachments. Alternatively, such a vector may end in the middle of an upper electrode, such as at a mirror plane. Even further, any vector should not point to, i.e. have substantially no component directed to, a first attachment, between a spring and the upper electrode, and at the same time substantially ending at the first attachment. Thus, a vector pointing towards a location in between two first neighboring attachments is allowed, even preferably, a vector substantially parallel between a virtual line connecting said two attachments, reduces the zipping motion substantially. Even further, it is preferred that any vector is physically cancelled by any second vector, i.e. if a first vector is pointing in a first direction, it is preferred that a second vector points in substantially the opposite direction. It is noted that typically vectors lie ion the plane of the membrane.

Further it is noted that symmetrical solutions wherein the upper and lower electrode are interchanged are also envisaged.

Typically the spring is made of a resilient material. Preferably such a material is used in a process of manufacturing the MEMS.

The anchors are typically attached to a body, comprising the MEMS. Springs are attached to an anchor at one end and to an electrode at an other end.

In a preferred embodiment the present invention relates to a capacitive MEMS switch, wherein the geometry of the switch is further characterized by at least one mirror plane, preferably by two mirror planes.

An advantage thereof is that unwanted forces caused by zipping motion can cancel each other out, reducing the need to take other measures to reduce the impact stress.

In a preferred embodiment the present invention relates to a capacitive MEMS switch, wherein the upper electrode is formed from a flexible material and/or further comprising an isolation on top of the lower electrode. Such isolation may cover part of a surface of the upper electrode, or may cover it fully. Such isolation is typically formed of a dielectric material, such as silicon oxide, silicon nitride, high k dielectric material etc. And advantage thereof of is that the zipping mode can further be optimized, and further, other characteristics of the MEMS switch can be tuned and optimized.

An advantage thereof is that a membrane made from a flexible material will ensure that the membrane does not land as a rigid plate. In the rigid case, all of the impact energy will be transferred to the springs. For a flexible membrane, part(s) of the membrane will touch sooner than others. The resulting roll-off or zipping behavior can be used to minimize impact stress (directed) at the springs.

In a preferred embodiment the present invention relates to a capacitive MEMS switch, wherein the upper electrode and/or lower electrode comprises one or more sections with high density and/or one or more sections with low density. Low density relates to e.g. a reduction of conducting material, such as one or more holes, a dielectric material, a bridge being at a larger distance from the counter electrode, a reduction of conductivity (e.g. silicon has a reduced conductivity versus copper), a relatively low doped material, and combinations thereof. High density relates to e.g. a good conducting material, etc. As such, the performance of the present switch may be further optimized and tuned, e.g. with respect to the zipping mode.

An advantage thereof is that it gives a designer of the device freedom to tune dynamics and forces at precisely chosen locations to reduce the zipping effect precisely where it occurs. Further it makes it possible to further reduce impact stress by minimizing the zipping effect.

In a preferred embodiment the present invention relates to a capacitive MEMS switch, wherein the lower electrode has sections, in order to reduce electrostatic force near the location of the first attachment to the one or more springs. Such reduction of electrostatic forces may further improve the performance of the present switch.

An advantage thereof is that it gives a designer of the device freedom to tune dynamics and forces at precisely chosen locations to reduce the zipping effect precisely where it occurs. Further it makes it possible to further reduce impact stress by minimizing the zipping effect.

In a preferred embodiment the present invention relates to a capacitive MEMS switch, wherein the upper electrode is attached to two or more springs, preferably to four or more springs, which springs are attached to two or more anchors, wherein optionally two springs are attached to one anchor.

An advantage thereof is that the use of two or more springs enables the design of a switch which has limited initial deflection or initial curvature so that a well-defined gap results. In a preferred embodiment the present invention relates to a capacitive MEMS switch, wherein the upper and/or lower electrode comprises one or more sections with high density close to the attached spring and one or more sections with low density far away from the attached spring, or vice versa.

An advantage thereof is that it gives a designer of the device freedom to tune dynamics and forces at precisely chosen locations to reduce the zipping effect precisely where it occurs. Further it makes it possible to further reduce impact stress by minimizing the zipping effect.

In a preferred embodiment the present invention relates to a capacitive MEMS switch wherein the physical sum of the vectors is substantially zero.

An advantage thereof is that the zipping motion is self-cancelling.

In a preferred embodiment the present invention relates to a capacitive MEMS switch, selected form the group consisting of:

MEMS switches having two * j anchors, further comprising two * j or four * j first attachments, wherein j = 1, 2, 3, 4, 5, etc, wherein the upper electrode and/or lower electrode comprises one or more sections with high density and/or one or more sections with low density, such one section with high density, and n by m sections with low density, wherein n is chosen from 1-25, such as 2-10, such as 3-8, such as 4-6, and wherein m is chosen from 1-10, such as 2-8, such as 3-7, such as 4-6, and combinations thereof, such as wherein n and m are even, or wherein n and m are odd, or wherein n is odd and m is even, or wherein n is even and m is odd, such as n=4 and m=8, n=8 and m=8, n=3 and m=9, and n=3 and m=8.

Further preferred are MEMS switches having four anchors, further comprising four first attachments, wherein the upper electrode and/or lower electrode comprises one or more sections with high density and/or one or more sections with low density, such one section with high density, and n by m sections with low density, wherein n is chosen from 1-25, such as 2-10, such as 3-8, such as 4-6, and wherein m is chosen from 1-10, such as 2-8, such as 3-7, such as 4-6, and combinations thereof, such as wherein n and m are even, or wherein n and m are odd, or wherein n is odd and m is even, or wherein n is even and m is odd, such as n=4 and m=8, n=8 and m=8, n=3 and m=9, and n=3 and m=8. With respect to two anchors, switches having four anchors are somewhat more stable.

The combination of the above parameters, such as density, number of holes, gives a designer of the device freedom to tune dynamics and forces at precisely chosen locations to reduce the zipping effect precisely where it occurs. Further it makes it possible to further reduce impact stress by minimizing the zipping effect. Small variations in various effects according to the present invention may as such be obtained, by varying the parameters mentioned.

As such, the above preferred embodiments, and combinations thereof, provide an advantage in that the performance of the present switch may be further optimized and tuned, e.g. with respect to the zipping mode.

In a second aspect the invention relates to a method of reducing impact stress, specifically in MEMS switches such as the capacitive MEMS switch according to the invention by time varying actuation voltage applied to a first electrode involving at least two voltage levels, preferably cyclic time varying, wherein after the switch has commenced closure by applying a first voltage level that is higher than the static pull in voltage of the switch and before complete closure of the switch the actuation voltage is lowered by applying at least one second voltage level that is at closure higher than the static pull out voltage of the switch.

An advantage thereof is that it makes it possible to reduce the impact stress in any electrostatically actuated MEMS device, regardless of its layout because the suggested solution is pure electronic and can be tuned to happen exactly at the moment that the high stresses in the device occur.

In a preferred embodiment the present method comprises a step, wherein the applied voltage is driven by the outcome of a measurement to determine a current through the switch, or wherein the cycle is permanently fixed during operation.

An advantage thereof is that it this preferred embodiment functions even better than that of claim 10, as it now works independently of small variations in device dimensions or environmental conditions: it relates to a feedback method that makes tuning automatic.

In a preferred embodiment the present method comprises a step, wherein time varying actuation voltage is applied to the first electrode as a whole or to one or more segments of the first electrode.

An advantage thereof is that precise control of movement and associated forces in the device become possible. This makes it possible to further reduce the zipping effect while sacrificing only the least possible in closing time.

In a preferred embodiment the present method comprises a step wherein one or more time varying actuation voltages are applied to the one ore more segments of the first electrode, preferably one ore more different time varying actuation voltages.

An advantage thereof is that it provides even better control than the above embodiment.

In a third aspect the invention relates to a use of a capacitive MEMS switch according to the invention for reduced impact stress.

The present invention is further elucidated by the following figures and examples, which are not intended to limit the scope of the invention. The person skilled in the art will understand that various embodiments may be combined.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a typical MEMS switch layout in which the springs are connected to the membrane corners. In the lower graph, the schematic deformed shape at initial contact is shown.

Fig. 2 shows vertical displacement as a function of time of the ends of two separate springs.

Fig. 3 shows a schematic representation of a 2D model of a flexible switch membrane suspended by springs.

Fig. 4 shows vertical displacement, velocity and acceleration of two points of the switch of figure 3.

Fig. 5 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 6 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 7 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 8 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 9 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 10 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 11 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 12 shows examples of possible actuation voltage cycles to reduce the impact velocity at the springs.

Fig. 13 shows an interferometric image of a MEMS capacitive switch.

Fig. 14 shows a division of the lower electrode into segments with different shaped actuation cycles.

Fig. 15 shows a spring displacement at its center and end position as a function of time, extracted through image processing of the interferometric images for a standard actuation pulse and shaped actuation pulse of the top left of Fig. 12.

DETAILED DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a typical MEMS switch layout in which the springs (160) are connected to the membrane (100) or upper electrode corners. In the lower graph, a force is applied to the membrane and the schematic deformed shape at initial contact is shown. A cross section A-A' is given. Two anchors (140) are further visible. The membrane is typically formed of a conducting material, such as silicon, or doped silicon. The springs may be formed of the same material as the membrane, i.e. silicon, or from a different material. Anchors are typically formed from a non-conducting material, such as a dielectric material, such as silicon oxide, silicon nitride etc.

The portion of the membrane that is not yet in contact exhibits a high electrostatic force due to the small residual gap. Therefore, this portion of the membrane shows a high acceleration downward, until contact occurs. The result is a zipping motion of the membrane, directed from its centre towards its corners where the springs are attached. At the end of the closing motion, the membrane corners are the last to make contact with a relatively high impact velocity.

The zipping effect and the high acceleration and contact velocity of the membrane corners are measured with a laser vibrometer.

Fig. 2 shows the vertical displacement of the end of two separate springs (at the place where they are connected to the membrane) as a function of time. At t= 80 μs, the acceleration of the spring ends (or membrane corners) is clearly visible.

This behavior is also demonstrated in simple 2D simulations. In these simulations, the structure of Fig. 3 is regarded.

Fig. 3 shows a schematic representation of a 2D model of a flexible switch membrane (300) suspended by springs (360). A top electrode (300) attached with springs (360) to anchors (340). Further visible are a dielectric layer (310), typically silicon oxide or silicon nitride, and a lower electrode (320), typically formed of a conducting material, such as silicon, metal, or doped silicon.

The 2D model is a discretized version of a beam (with width W out of plane), taking into account elastic forces, electrostatic forces, squeeze film damping, and contact. The structure is divided into a number of elements and nodes (small circles). Without further detail, we will now focus on the simulation results of the closing motion of the switch at a certain voltage pulse, starting at t=0.

Fig. 4 shows vertical displacement, velocity and acceleration of two points of the switch of Fig. 3.

In Fig. 4, the vertical displacement, velocity and acceleration of two points on the switch are shown. The blue curves show the results for the end of the switch (where the springs are attached), the green curves show the results at the middle of the switch.

It is clearly shown that the middle of the switch makes contact first at t=7 μs. At that moment, the end of the switch exhibits a high (negative) acceleration, leading to a high impact velocity.

The zipping effect of the membrane, and the corresponding high acceleration of the membrane corners and spring ends, generates unwanted vibrations in the springs. These vibrations may result in plastic deformation or fatigue, reducing the reliability of the device.

Fig. 5 shows an example according to the invention of a geometry of the electrode (500) in combination with the position and shape of the springs (560) being attached to anchors (540). In a preferred embodiment he geometry of the MEMS is further characterized by one or two mirror planes. A first mirror plane (591) and a second mirror plan (590) are indicated.

In Fig. 5 the geometry of the electrode in combination with the position and shape of the springs ensures that the short edges of the top electrode (top and bottom in the figure above) land first. The main reason for this is the bending moment exerted by the springs on the membrane. This causes the short edges to bend down. The zipping effect therefore propagates from the edges towards the centre. This has two advantages. First the spring attachments do not experience the maximum acceleration because that happens in the centre. Second, any lateral or torsional motion related to the zipping effect comes from two opposite directions and cancels out in the centre.

Fig. 5a shows the sipping effect of the top electrode, seen from aside, parallel to line 591. The arrows indicate the force exerted on the electrode.

Fig. 5b shows a configuration with springs attached to the electrode according to the invention (left) and a prior art configuration (right). The present configuration is characterized in that the net torsion of the one or more springs during operation is substantially equal to zero, whereas the prior art configuration suffers from a net torsion during operation, with all the negative effects described.

Fig. 6 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 6 shows an alternative. Here the bending moment in the springs is minimized, thus reducing the torsional vibration along the axis A of the springs.

Moreover, the design can be tuned such that the corners of the upper electrode touch the lower electrode first. The zipping effect thus arrives at the springs from two opposing directions simultaneously. This ensures that the spring does not bend axially around axis B. Further 3D calculations may be performed to further optimize the layout for all required specifications.

Fig. 6a shows the force on the electrode along C-C' when the electrode is in a down position.

Figs. 7-11 and 14 show a bottom right quadrant of a top electrode.

Fig. 7 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Etch holes in the upper electrode are typically circular, equally sized and distributed equally over the membrane as shown in the figure below. Each figure shows only one quadrant of a capacitive switch. A square geometry is assumed in the figures, but the principle equally applies to other geometries. The centre of the device shown in the figures is in the upper left corner, and the spring attachment is in the lower right corner.

By increasing the hole sizes or hole density near the spring attachments, the electrostatic force near the spring attachments is less, and thus the acceleration is less. At the same time two other effects play a role in the behaviour of this modified layout.

First the stiffness of the membrane decreases near the spring attachments because more and/or larger holes are present. This is predicted to increase the zipping effect because it increases the bending of the membrane near the corners. Second the presence of larger and/or more holes decreases the air damping near the corners. This is also predicted to increase the zipping effect.

It is at present clear that the dynamic behaviour of the device is governed by an intricate combination of these three effects. An optimal configuration of hole sizes and positions can be found.

As an illustration, two possible configurations of hole sizes are illustrated below.

Fig. 8 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 9 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

A third method consists of patterning the lower electrode. In the conventional design the lower electrode is a continuous sheet of conductive material. The following alternatives are presented.

A first alternative is to etch small holes in the lower electrode. The density of the holes and/or their sizes can be made dependent on the location (i.e. relatively more hole area near the spring attachments, locally reducing the effective electrode area). If the holes are made small with respect to the size of the gap, the electrostatic force in the open state is hardly influenced because of fringing effects. In the closed state (and when almost closed) the force is dependent on the local effective electrode area. By tailoring the hole density, the zipping effect can be reduced.

A disadvantage of this solution is that the ratio between the open and close capacitance is smaller than in the conventional design. A large ratio between the two is desired for the application of the capacitive switch. The reason is that the effective electrode area is always smaller than without the small holes and that this reduces the capacitance in the closed state but hardly influences the capacitance in the open state (because of the fringing effects at larger distances).

Fig. 10 shows an example of a geometry of the electrode in combination with the position and shape of the springs.

Fig. 11 shows an example of a geometry of the electrode in combination with the position and shape of the springs, comprising various segments, e.g. (1191)-(1193) as well as a small segment at the lower right corner. Segments may be spherical or polygonal. The number of segments can be from 1 to any number, in principle, such as 3 or 4, or the segments can form a substantially continuous geometry.

A segment can e.g. be given different timing of the actuation pulses or different voltage amplitudes or both (see also below). For example, segment 3 could be given a slightly higher voltage to ensure that the upper electrode lands first at the springs. Alternatively, segment 3 could be given a lower voltage to reduce the zipping effect. The shape of the segments is only schematically shown. Variations on the shape are possible.

A time varying actuation voltage is provided such that the zipping effect and the impact velocity at the springs are reduced. The actuation voltage cycle can be either permanently fixed or can be controlled actively by measuring an operation parameter (for example the switch's state by measuring the current through the switch). The actuation voltage cycle involves at least two voltage levels. After the switch has commenced closure by applying a voltage level that is higher than the static pull-in voltage, the voltage is reduced before complete closure of the switch in one of the following steps to a lower level to reduce electrostatic forces and the zipping effect. The voltage level to hold down the switch in the closed state at the end of the cycle has to be higher than the static pull-out voltage. The transition between the levels is done during the traversal from open to closed state, either before or after initial contact at the center of the membrane, but always before contact is made at the spring ends. A number of examples of possible actuation voltage cycles are given in Fig. 12.

Fig. 12 shows examples of possible actuation voltage cycles to reduce the impact velocity at the springs.

Active control of the actuation voltage could, for example, be used to vary the transition time between the levels and / or the voltage levels themselves. In one example, the current through the switch is sensed. Upon detection of a current above a certain level, settable by the user, the actuation voltage is switched between a preset high and low value (top left of Fig. 12).

Fig. 13 shows an interferometric image of a MEMS capacitive switch.

To illustrate the working principle and the benefits from this invention, the following measurement is carried out. In a stroboscopic interferometric setup, the transient behavior of a reference device is measured, after which the captured images are analyzed with image processing software. An example of such a captured interferometric image of the device is given in Fig. 13.

In the main idea, the shaped actuation pulse is applied to the lower electrode as a whole. In another idea, the lower electrode is divided into segments which can be subject to different shaped actuation cycles (see figure 14, in which only a quarter symmetry of the device is shown).

Fig. 14 shows a division of the lower electrode into segments (1491)-(1493) with different shaped actuation cycles.

Next, two different actuation profiles are applied. The first one is a constant voltage of 54 V at t = 0. The second one consists of two voltage levels (top left Fig. 5). The high level, starting at t = 0, is equal to 49 V, the low level is set to 29 V. The transition between the high and low level is tuned manually to coincide with the moment at which first contact is made in the middle of the membrane (here at 6 us). After the images have been processed, we look at the displacement of one of the springs (horizontal bottom right one in Fig. 7) at two points (in the middle and at the end where it is connected to the membrane) as a function of time. The results are shown in Fig. 15.

Fig. 15 shows a spring displacement at its center and end position as a function of time, extracted through image processing of the interferometric images.

We can clearly distinguish the oscillations in the spring at the normal actuation pulse at the moment when zipping occurs (6 μs). These oscillations are reduced when the shaped pulse is employed, although the total closing time is increased. This is, however, not a problem since the opening time is usually much longer than the closing time of a switch, even in the new situation with the shaped pulse. The opening time of a MEMS switch is, therefore, the limiting factor.

CLAIMS:

1. Capacitive MEMS switch layout for reduced impact stress comprising an upper electrode having a zipping motion, one or more anchors, one or more springs having a first attachment to the upper electrode and a second attachment to an anchor, and a fixed lower electrode, characterized in that the zipping motion is characterized by at least one vector which at least one vector has substantially no component directed towards and ending close to or at any first attachment.

2. Capacitive MEMS switch according to claim 1, wherein the geometry of the switch is further characterized by at least one mirror plane, preferably by two mirror planes.

3. Capacitive MEMS switch according to any of claims 1-2, wherein the upper electrode is formed from a flexible material and/or further comprising an isolation on top of the lower electrode.

4. Capacitive MEMS switch according to any of claims 1-3, wherein the upper electrode and/or lower electrode comprises one or more sections with high density and/or one or more sections with low density.

5. Capacitive MEMS switch according to any of claims 1-4, wherein the lower electrode has sections, in order to reduce electrostatic force near the location of the first attachment to the one or more springs.

6. Capacitive MEMS switch according to any of claims 1-5, wherein the upper electrode is attached to two or more springs, preferably to four or more springs, which springs are attached to two or more anchors, wherein optionally two springs are attached to one anchor.

7. Capacitive MEMS switch according to any of claims 1-6, wherein the upper and/or lower electrode comprises one or more sections with high density close to the attached spring and one or more sections with low density far away from the attached spring, or vice versa.

8. Capacitive MEMS switch according to any of claims 1-7, wherein the physical sum of the vectors is substantially zero.

9. Capacitive MEMS switch according to any of claims 1-8, selected form the group consisting of:

- MEMS switches having two * j anchors, further comprising two *j or four * j first attachments, wherein j = 1, 2, 3, 4, 5, etc, wherein the upper electrode and/or lower electrode comprises one or more sections with high density and/or one or more sections with low density, such one section with high density, and n by m sections with low density, wherein n is chosen from 1-25, such as 2-10, such as 3-8, such as 4-6, and wherein m is chosen from 1-10, such as 2-8, such as 3-7, such as 4-6, and combinations thereof, such as wherein n and m are even, or wherein n and m are odd, or wherein n is odd and m is even, or wherein n is even and m is odd, such as n=4 and m=8, n=8 and m=8, n=3 and m=9, and n=3 and m=8.

10. Method of reducing impact stress, specifically in MEMS switches such as the capacitive MEMS switch according to any of claims 1-9 , by time varying actuation voltage applied to a first electrode involving at least two voltage levels, preferably cyclic time varying, wherein after the switch has commenced closure by applying a first voltage level that is higher than the static pull in voltage of the switch and before complete closure of the switch the actuation voltage is lowered by applying at least one second voltage level that is at closure higher than the static pull out voltage of the switch.

11. Method according to claim 10, wherein the applied voltage is driven by the outcome of a measurement to determine a current through the switch, or wherein the cycle is permanently fixed during operation.

12. Method according to any of claims 10-11, wherein time varying actuation voltage is applied to the first electrode as a whole or to one or more segments of the first electrode.

13. Method according to any of claims 10-12, wherein one or more time varying actuation voltages are applied to the one or more segments of the first electrode, preferably one or more different time varying actuation voltages.

14. Use of a capacitive MEMS switch according to any of claims 1-9 for reduced impact stress.

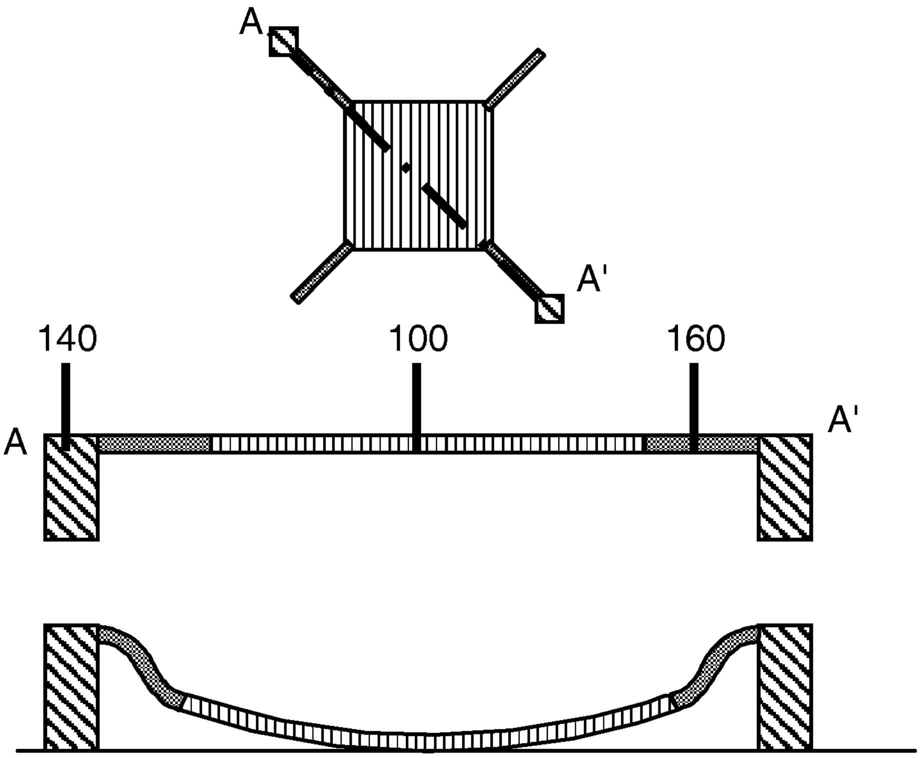
A
A'
140
100
160
A
A'

FIG. 1

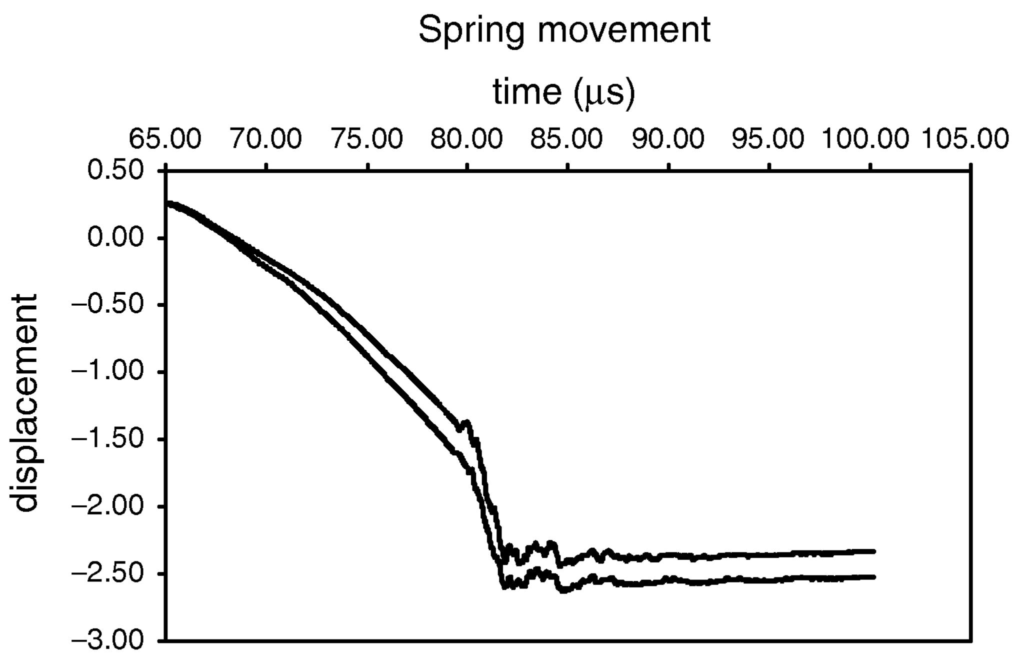
Spring movement
time (μs)
65.00
70.00
75.00
80.00
85.00
90.00
95.00
100.00
105.00
0.50
0.00
−0.50
−1.00
−1.50
−2.00
−2.50
−3.00
displacement

FIG. 2

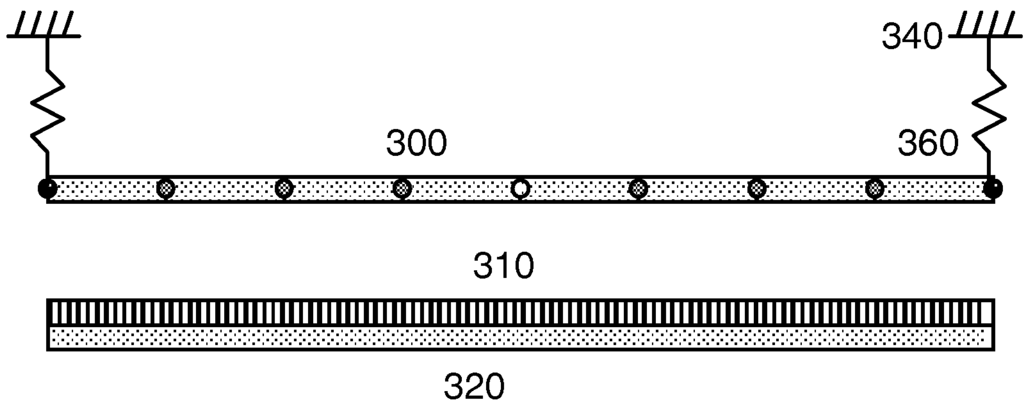
340
300
360
310
320

FIG. 3

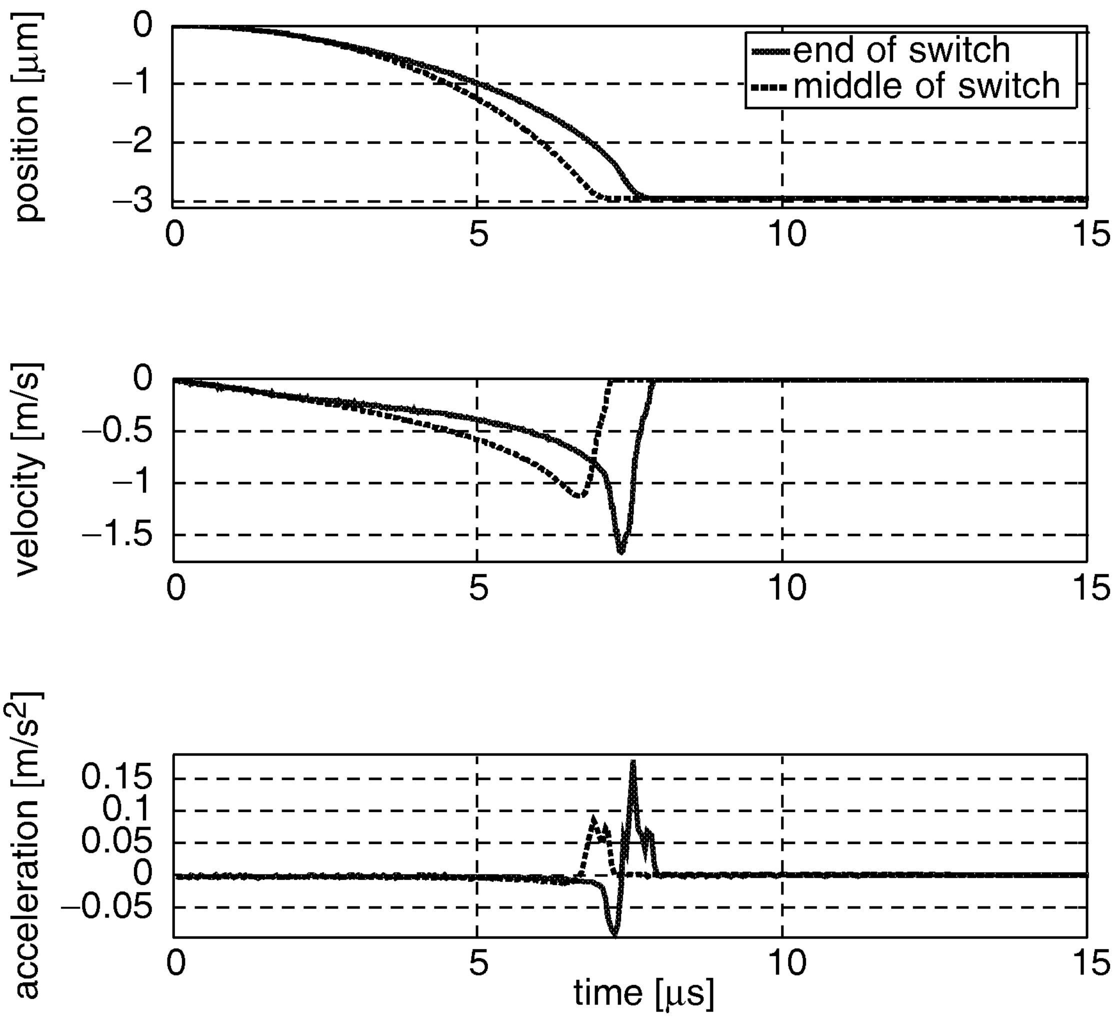
position [µm]
0
–1
–2
–3
end of switch
middle of switch
velocity [m/s]
0
–0.5
–1
–1.5
acceleration [m/s2]
0.15
0.1
0.05
0
–0.05
0
5
10
15
time [µs]

FIG. 4

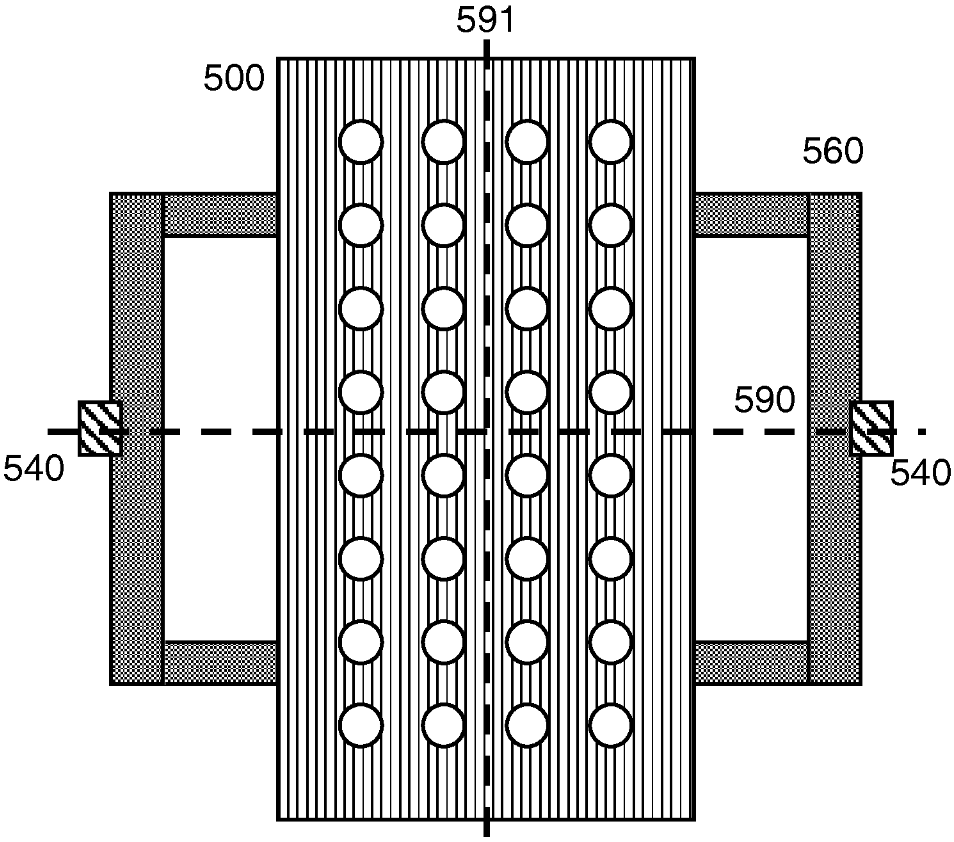

FIG. 5

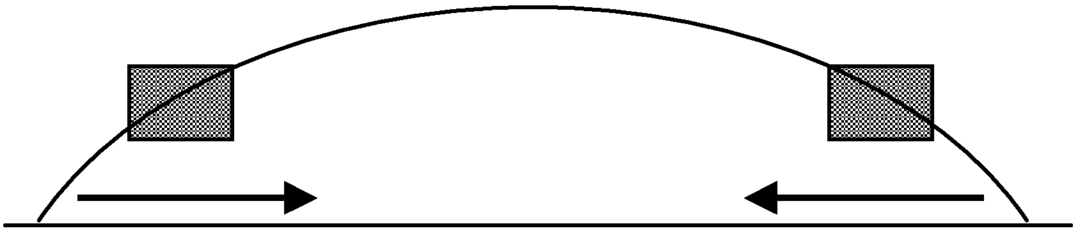

FIG. 5A

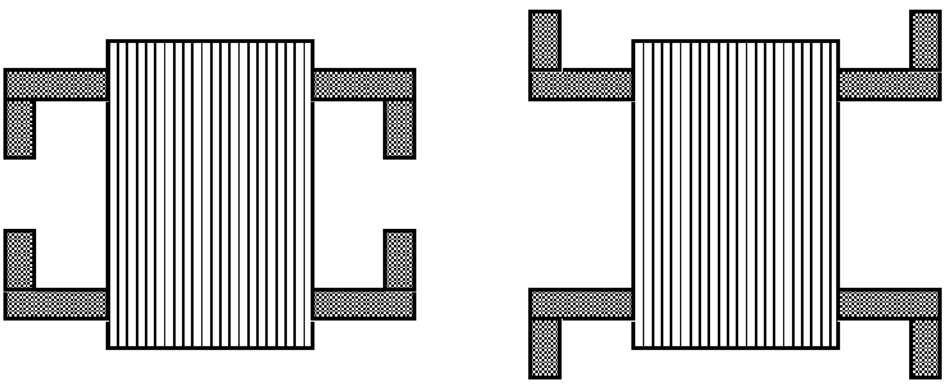

FIG. 5B

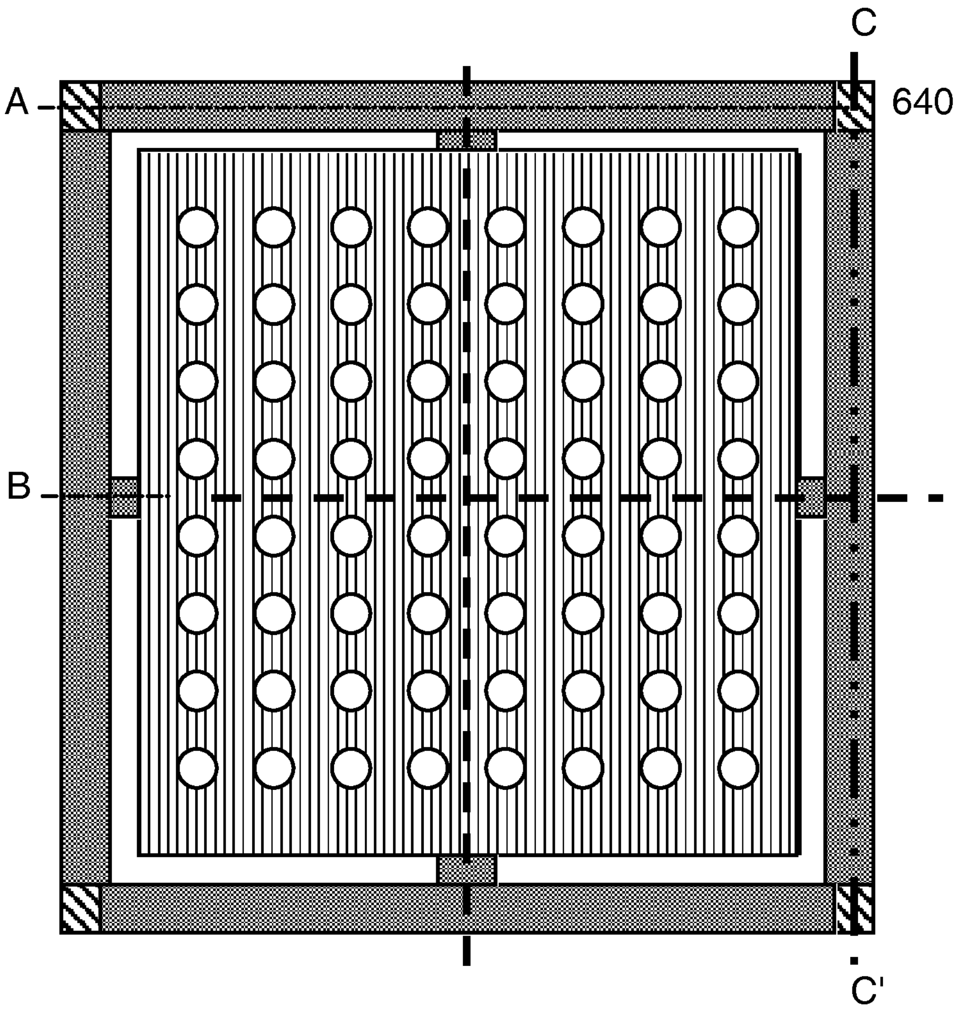

FIG. 6

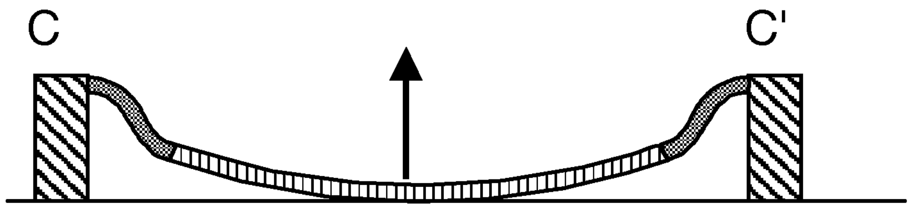

FIG. 6A

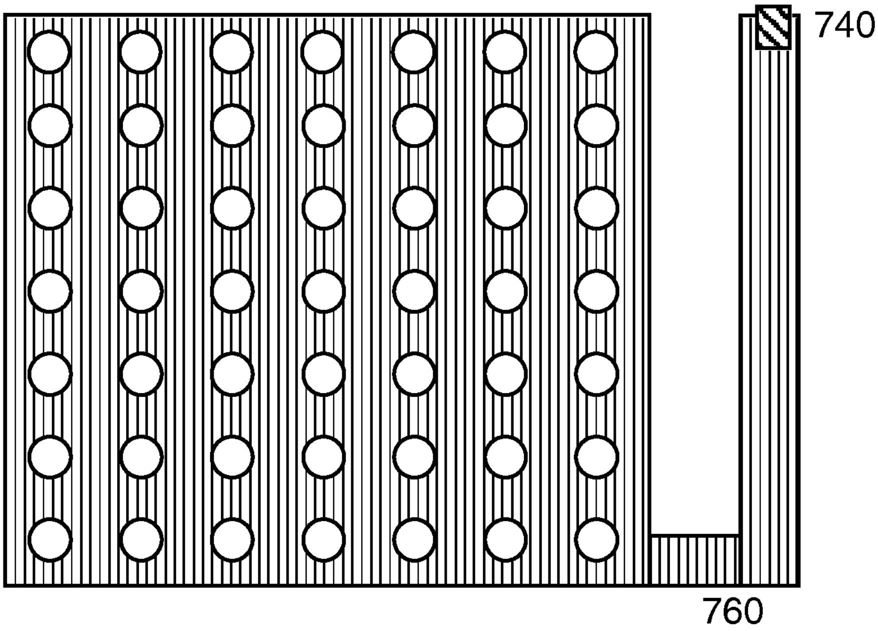

FIG. 7

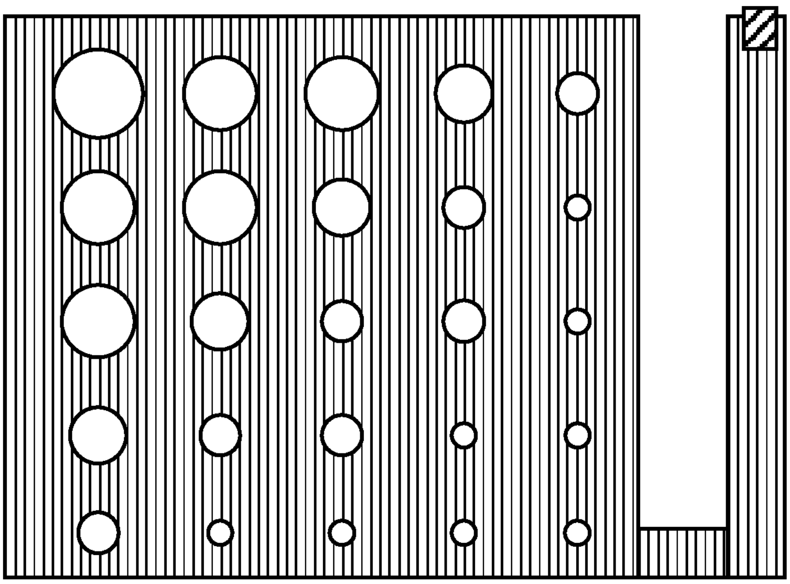

FIG. 8

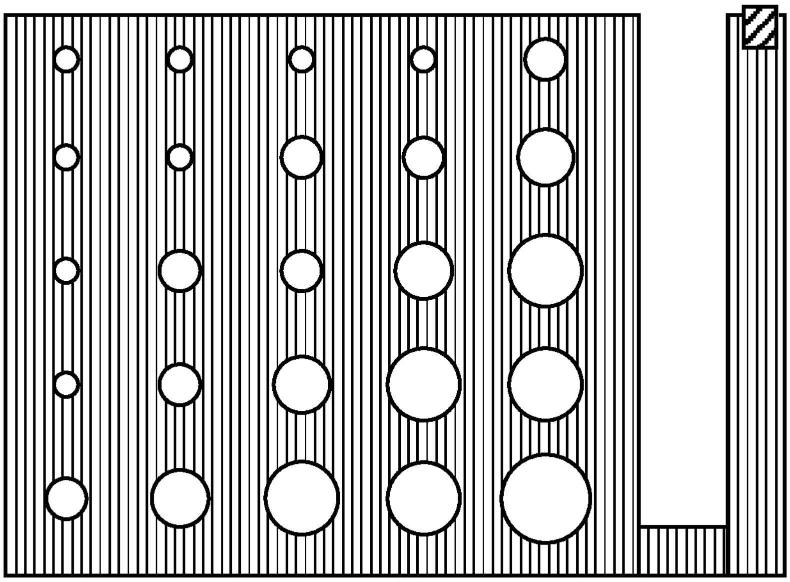

FIG. 9

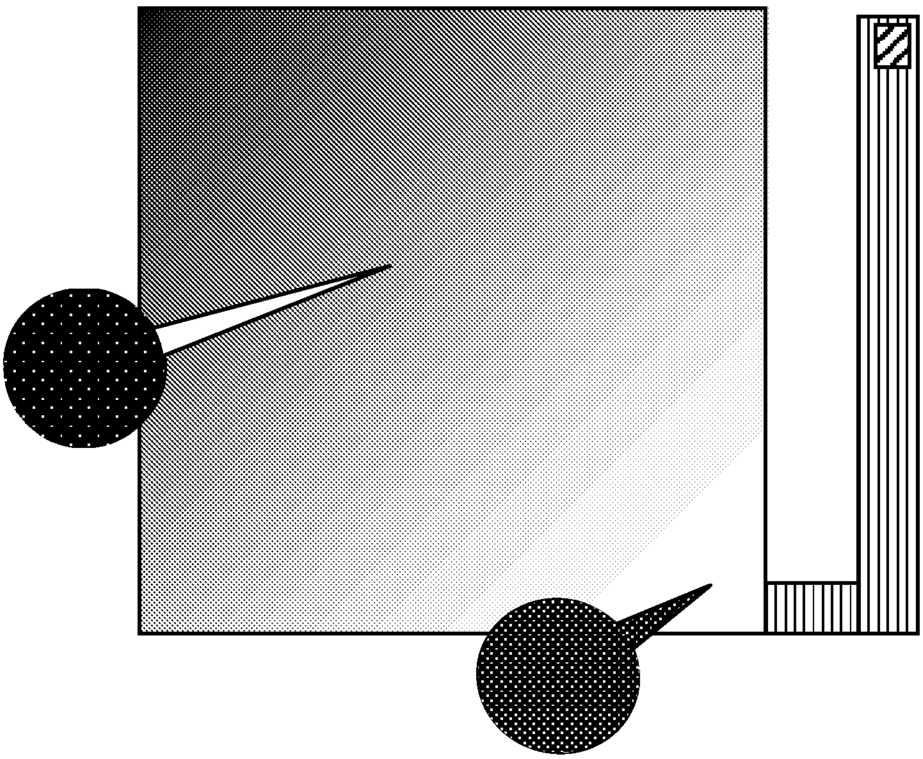

FIG. 10

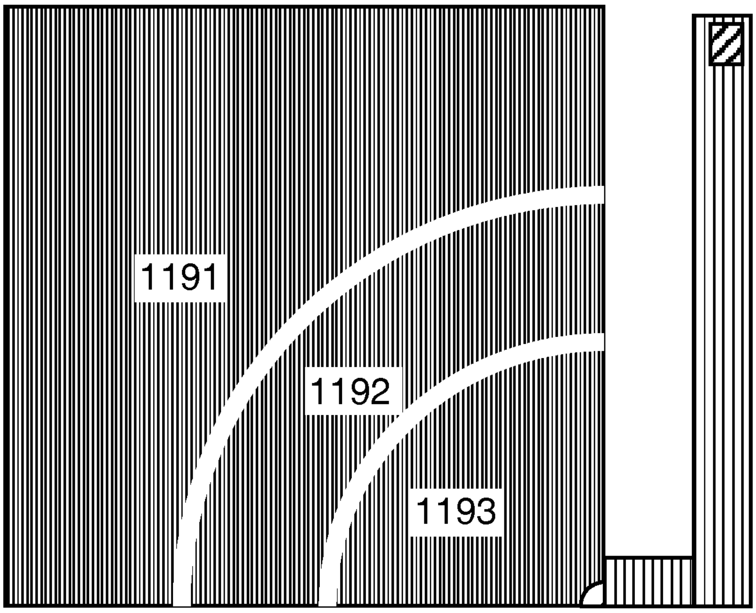
1191
1192
1193

FIG. 11

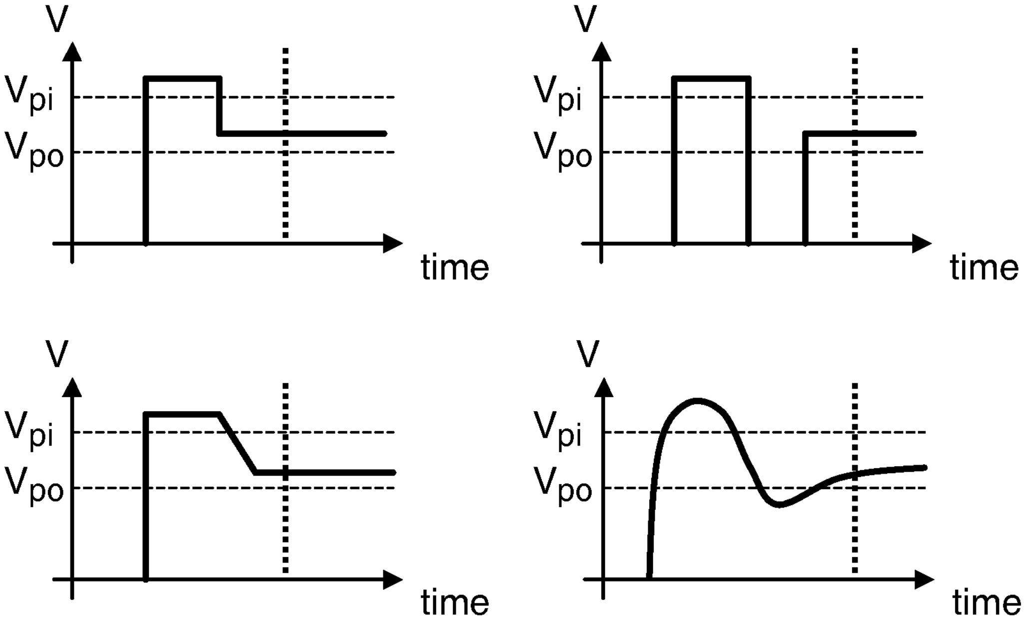
V
Vpi
Vpo
time
V
Vpi
Vpo
time
V
Vpi
Vpo
time
V
Vpi
Vpo
time

FIG. 12

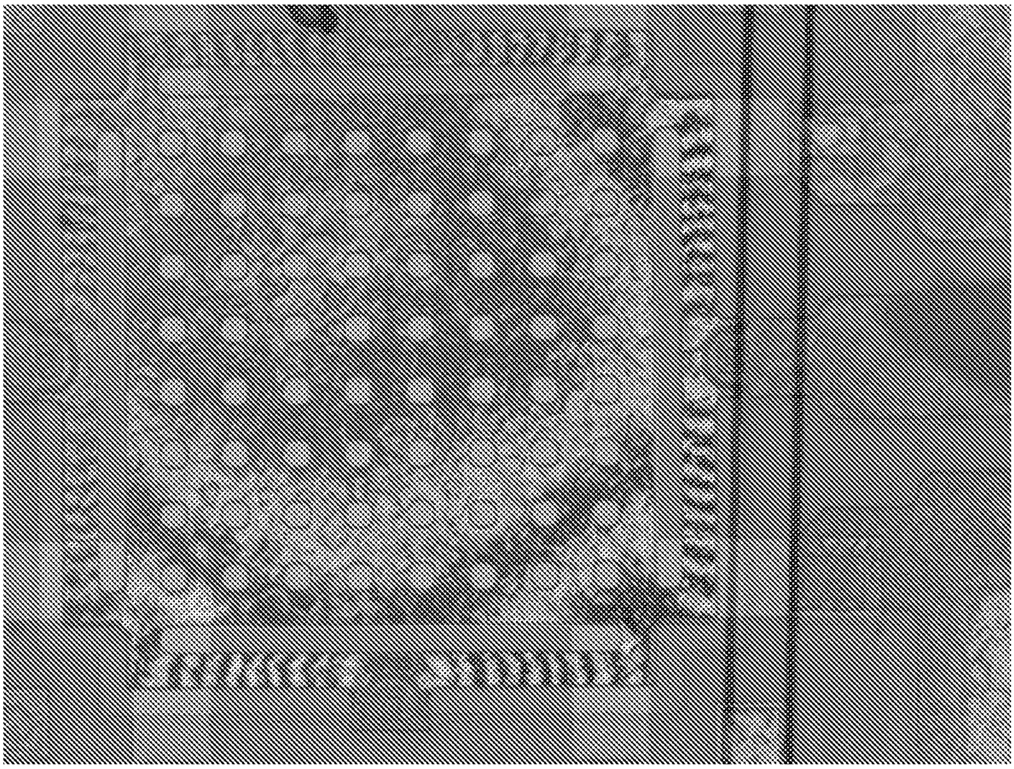

FIG. 13

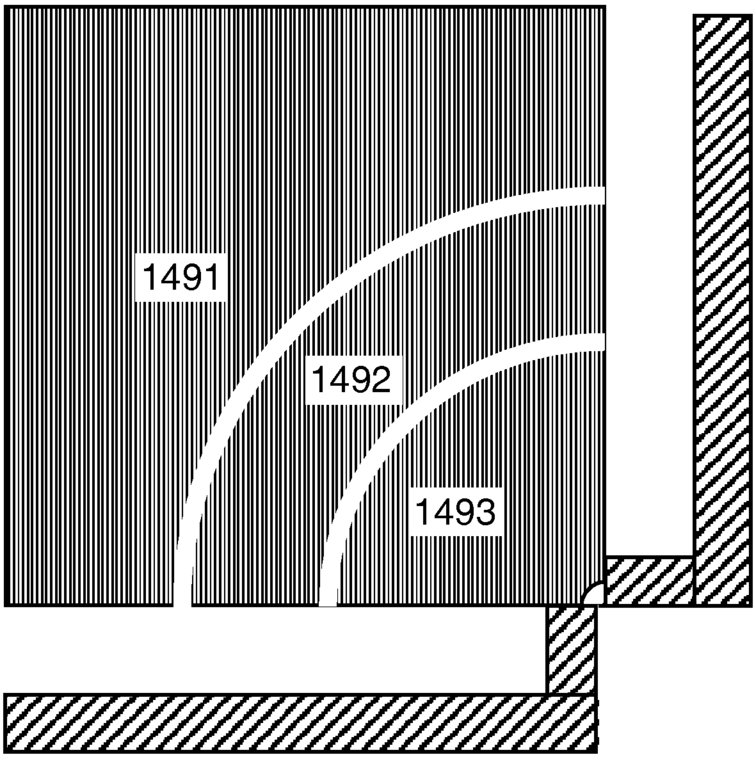

FIG. 14

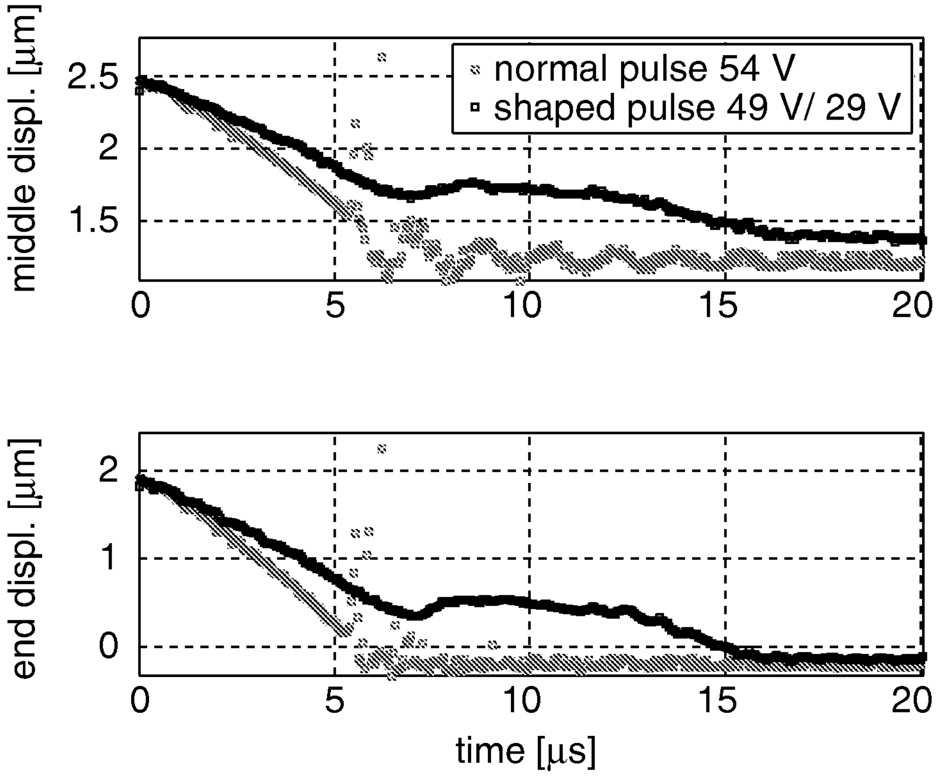
middle displ. [μm]
2.5
2
1.5
normal pulse 54 V
shaped pulse 49 V/ 29 V
0
5
10
15
20
end displ. [μm]
2
1
0
0
5
10
15
20
time [μs]

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/054707

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01H59/00 B81B3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B81B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 635 750 A (SCHLAAK HELMUT [DE] ET AL) 3 June 1997 (1997-06-03)	1-4,14
Y	column 2, line 64 - column 5, line 36; figures 1-10	5-8
Y	DE 42 05 029 C1 ((SIEI) SIEMENS AG) 11 February 1993 (1993-02-11) column 2, line 23 - column 6, line 53; figures 1-8F	5-8
A	HESSE S K ET AL: "DIMENSIONIERUNG ELETROSTATISCHER MIKRORELAIS-ANTRIEBE" F & M FEINWERKTECHNIK MIKROTECHNIK MIKROELEKTRONIK, HANSER, MUNCHEN, DE, vol. 106, no. 7/08, 1 July 1998 (1998-07-01), pages 546-548, XP000847007 ISSN: 1437-9503 the whole document	1

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 February 2010	18/02/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Nieto, José Miguel

International application No.
PCT/IB2009/054707

INTERNATIONAL SEARCH REPORT

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 9-13
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 9-13

Claim 9 is not clear as it discloses too many alternatives and is not supported by the description. The skilled person would be unable, on the basis of the information given in the application as filed (the wording of claim 9 is also included in the description, but no embodiments are disclosed) to extend the particular teaching of the description to the whole of the field claimed by using routine methods of experimentation or analysis. Claims 10-13 are not clear and not supported by the description as following expressions attempt to define the subject-matter in terms of the result to be achieved, which merely amounts to a statement of the underlying problem, without providing the technical features necessary for achieving this result: - "after the switch has commenced closure by applying a first voltage level that is higher than the static pull in voltage of the switch and before complete closure of the switch" (no monitoring means are disclosed that could implement the claimed voltage modulation as a voltage/time dependence and a time value that corresponds to "before complete closure" is also not defined in the application) - "second voltage level that is at closure higher than the static pull out voltage of the switch" (the expression "at closure" appears to be related with another actuation time that is whether measurable with any disclosed means nor defined in the application).

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2009/054707

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5635750	A	03-06-1997	DE	4437260 C1	19-10-1995
			EP	0710972 A1	08-05-1996
			JP	8227647 A	03-09-1996
DE 4205029	C1	11-02-1993	NONE		