A micromachined magnetostatic relay or switch includes a springing beam on which a magnetic actuation plate is formed. The springing beam also includes an electrically conductive contact. In the presence of a magnetic field, the magnetic material causes the springing beam to bend, moving the electrically conductive contact either toward or away from another contact, and thus creating either an electrical short-circuit or an electrical open-circuit. The switch is fabricated from silicon substrates and is particularly useful in forming a MEMs commutation and control circuit for a miniaturized DC motor.
FIG. 5A

FIG. 5B

FIG. 5C
FIG. 6
FIG. 7
become dominated by the commutation and control electronics. This is particularly noticeable in a highly miniaturized motor, such as a commercially available 3-mm diameter motor, the size of the motor, not the size of the commutation electronics, is most critical in space constrained applications. The magnetostatic switch requires no biasing current or voltage and is useful in directly switching loads.

In one aspect, the invention features a magnetostatic switch having at least one substrate formed from a nonconductive or semiconductive material and a springing beam, such as a cantilever beam or a torsional beam, formed on the substrate. Two electrically conductive contacts define at least two switching states: (1) an open state in which the conductive contacts are physically separated from each other, and (2) a closed state in which the conductive contacts physically contact each other. One of the conductive contacts is formed on the springing beam. The springing beam includes a magnetic material which, in the presence of a magnetic field, creates an actuation force that causes the conductive contacts to switch from one of the switching states to another of the switching states.

In some embodiments, the springing beam includes a layer of material deposited onto the substrate. In other embodiments, the springing beam is formed from a portion of the substrate and is surrounded by a void left after etching away a portion of the substrate.

In some cases, one of the conductive contacts is formed on the substrate. In other cases, this conductive contact is formed on another substrate. In alternative embodiments, the magnetic beam is formed substantially from the magnetic material or from a nonconductive material or semiconductive material.

In other embodiments, the magnetic material is formed on a surface of the springing beam, and one of the conductive contacts is formed on an opposing surface of the springing beam or on a surface of the magnetic material. Both normally open and normally closed versions of the switch are useful.

In another aspect, the invention involves the fabrication of a magnetostatic switch. A temporary layer of removable material is formed over a portion of a rigid substrate. A springing beam then is formed by depositing a layer of material over a portion of the temporary layer and over at least some portion of the substrate that is not covered by the temporary layer. The temporary layer then is removed to form a gap between the substrate and a portion of the springing beam.

In some embodiments, an electrically conductive contact layer is formed over at least a portion of the springing beam. Other embodiments include forming an electrically conductive contact layer over at least a portion of another rigid substrate, forming a patterned layer of material over a portion of the other substrate to serve as a spacing layer, and bending the two substrates to position the springing beam and the contact layer between the substrates.

Some embodiments include forming a layer of magnetic material, such as permalloy, on the springing beam. In other embodiments, the springing beam itself is formed from the magnetic material. In some of these embodiments, the
electrically conductive material includes a metal, such as silver or gold, with good contact properties.

Still other embodiments include forming at least two electrically conductive areas, electrically isolated from each other, on a third substrate. The third substrate then is bonded to the other two substrates so that one of the conductive areas connects electrically to the springing beam and another of the conductive areas connects electrically to the contact layer. Electrically conductive pegs extend from the conductive areas on the third substrate and bond electrically to the other substrates.

Other embodiments and advantages will become apparent from the following description and from the claims.

DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B are simplified diagrams of a normally-open magnetostatic switch.

FIGS. 2A and 2B are simplified diagrams of a normally-closed magnetostatic switch.

FIGS. 3A, 3B, and 3C are diagrams illustrating, in cross-section, the fabrication of a magnetostatic switch micromachined from two substrates.

FIGS. 4A, 4B, 4C, 4D, and 4E are perspective views of similar structure. The cantilever beam in this alternative design for the normally closed switch resembles the normally open switch of FIG. 1A, except that the cantilever beam is formed such that residual stress imparts curvature to the beam, holding the tip of the beam against the lower electrical contact when the switch is inactive. Applying a magnetic field to the magnetic actuator plate causes the beam to bend away from the substrate, thus separating the contacts when the switch is open, pulling the contacts apart.

Several design parameters are considered when designing micromachined magnetostatic switches like these. For a normally-open switch, these parameters include load voltage, maximum current through the switch, operating force (i.e., the force between the contacts when the switch is closed), contact closing time, and lifetime operations. Table 1 shows typical values for these parameters in three types of switches: conventional electrostatic microswitches, conventional electromagnetic microswitches, and the micromachined magnetostatic switch described here. This table shows, among other things, that the micromachined magnetostatic switch produces much larger contact forces than the conventional microswitches produce, which reduces contact resistance and thus supports much larger operating currents.

In most situations, the micromachined magnetostatic switches and the systems in which they are used are designed to produce large actuation forces, which leads to several additional benefits. Larger actuation forces are present allow a stiffer cantilever beam, which leads to shorter switching time, higher g-force tolerance, and greater contact breaking force. Greater contact breaking force in turns leads to increased switching lifetime. Large actuation forces also provide the large contact forces, typically between 100 μN and 1 mN, required to yield an acceptable contact resistance when common contact materials, such as silver and gold, are used. The presence of large actuation forces also allows the switches to be designed with large gap distances between contacts, which increases device breakdown voltage.

The force generated at the free end of the cantilever beam is represented by the equation:
where \( T \) = the thickness of the magnetic actuation plate \( W \) = the width of the plate \( L \) = the length of the plate \( \beta \) = the deflection angle of the beam \( H \) = the magnitude of the external magnetic field, and \( M_s \) = the saturation magnetization of the magnetic material. This equation shows that the bending force is greatest when the values of \( M_s, W, T, \) and \( L \) are large and the deflection angle (\( \beta \)) is small. In a DC motor, the magnitude of magnetic field (\( H \)) is determined by the motor itself, and the deflection angle is determined by the desired gap distance between the contacts in the switch. In most embodiments, the gap distance between contacts and the rotation of the beam are very small, so \( \beta = 0 \).

A soft magnetic material such as permalloy has a high saturation magnetization (\( M_s \) greater than 0.8 Tesla), has thick plating capability, and automatically magnetizes with the desired magnetization orientation when actuated. Therefore, materials such as permalloy can be advantageous for constructing the magnetic actuation plate. Forces in excess of 5 mN are easily obtained with a permalloy actuation plate having a width of 3 mm and a thickness of 10 \( \mu \)m, DC field strengths that produce a magnetic field strength of approximately 2500 gauss.

FIGS. 3A, 3B, and 3C show a magnetostatic switch micromachined from two rigid substrates 300, 305, each of which is made from a material such as silicon. The first substrate 300 (FIG. 3A) includes a magnetic actuation plate 310 formed on a surface 315 of the substrate 300. The size of the plate 310 and the materials used to form the plate 310 are determined by the factors discussed above. The plate 310 is formed over a sacrificial spacing layer (not shown here) that is deposited on a portion of the surface 315 of the substrate 300, as discussed in more detail below. After the spacing layer is removed, the plate 310 forms a cantilevered beam, a portion of which contacts the substrate 300, and the rest of which is separated from the substrate 300 by the void left by the spacing layer. An optional contact layer 320 appears on the cantilever portion of the plate 310.

The second substrate 305 (FIG. 3C) includes a contact layer 325. A permanent spacing layer 330 is deposited and patterned over a portion of the contact layer 325. Alternatively, the spacing layer 330 is formed directly on the contact layer 330. The height of this spacing layer 330 is determined by the desired gap distance between the contact layers 320, 325. As shown in FIG. 3C, the substrates 300, 305 are bonded or clipped together to form a switch. One or more bond wires 335, 340 are connected to the magnetic actuation plate 310 on the first substrate 300 and to the contact layer 325 on the second substrate 305.

FIGS. 4A through 4E show one technique for creating the magnetic actuation plate on a substrate 400. First, a sacrificial spacing layer 405 is deposited onto the substrate 400. The magnetic actuation plate 420 is formed from an etchable material, such as photoresist. In highly miniaturized switches, the spacing layer 405 typically has a thickness between 2 \( \mu \)m and 20 \( \mu \)m. The spacing layer 405 is patterned to form anchor holes 410, which allow the magnetic material forming the actuation plate to bond with the substrate 400 as described above. In many switches, a very thin electropolishing seed layer is deposited over the spacing layer to facilitate formation of the magnetic actuation plate.

A photoresist plating, mold cavity 420 then is deposited over the spacing layer 405 and patterned to form a mold cavity 420 (FIG. 4B). The mold cavity 420 exposes most of the spacing layer 405, including the anchor holes 410. A magnetic material 425, such as permalloy, is deposited onto the spacing layer 405, filling the mold cavity 420 (FIG. 4C). The magnetic material 425 also fills the anchor holes 410 in the spacing layer 405, forming anchors (discussed below) that contact the substrate 400 directly. The magnetic material 425 is deposited to a thickness of between 10 \( \mu \)m and 20 \( \mu \)m in many highly miniaturized switches.

A layer of contact material 435 then is deposited over the layer of magnetic material 425 (FIG. 4D). The contact material 435 is selected from a wide range of materials with good electrical contact properties, including evaporated metals such as gold and silver. A typical thickness for the contact layer 435 is between 0.1 \( \mu \)m and 10 \( \mu \)m.

An etchant then is used to remove the photoresist mold layer 415 and spacing layer 405 from the substrate 400, leaving a magnetic actuation plate 440 mounted to the substrate 400 by anchors 445. The magnetic actuation plate 440, which includes the layers of magnetic material 425 and contact material 435, is spaced above the substrate 400 by the thickness of the stripped spacing layer 405.

Fabrication of the second substrate is carried out as shown in FIG. 3B. A layer of contact material is deposited onto a rigid substrate. A permanent spacing layer then is deposited over the contact material and patterned to avoid inhibiting the operation of the magnetic actuation plate. A wide variety of materials, such as photoresist, glass, plated metals, and plastic, are used to form the permanent spacing layer. A typical thickness for this layer is between 10 \( \mu \)m and 200 \( \mu \)m, depending on the desired operating characteristics of the switch. The two substrates then are bonded together to form an operational switch.

In other embodiments, the magnetic material is deposited onto a cantilevered beam formed in the silicon substrate. One fabrication technique uses an anisotropic silicon etchant to produce a cavity in a silicon substrate frame. Etching stops just short of the opposing surface of the substrate, creating a thin silicon membrane at the bottom of the cavity. A photoresist layer then is deposited onto the membrane and patterned to form the shape of the cantilevered beam. The substrate undergoes an etching process, such as reactive ion etching (RIE), to remove all exposed portions of the membrane, leaving only a cantilevered beam connected to the substrate frame, similar to that shown in FIG. 5A and discussed below. In some cases, the cantilever beam is formed into complex shapes. For example, in one implementation the plate is attached to the substrate via torsional beams. In another implementation, one end of the plate is shaped into multiple independent fingers, as shown in FIG. 5A. The magnetic material is deposited onto the cantilevered beam using standard techniques, such as permalloy electroplating. This process allows single crystal silicon to serve as the mechanical spring material. Single crystal silicon has strength properties similar to steel without the plastic deformation limitations.

FIGS. 5A through 5C show the components of a switch fabricated from three substrates. The first substrate 500 (FIG. 5A) includes the magnetic actuation plate 515, which is formed on the surface of or as a cantilevered beam 520 in the substrate 500. Electrical contacts 525 are molded at the free end of the cantilevered beam 520. At least a portion of the substrate 500 includes a conductive layer 535 that allows electrical connection between the contact points at the end of the magnetic actuation plate 515 and at least a portion of the surrounding frame. In many switches, this conductive layer 535 is the magnetic plate itself. Alternatively, the conductive layer 535 is formed by depositing an electrical contact material, such as silver or gold, over the surface of the substrate 500. Holes or recesses 530a-d are formed in the
substrate 500, including in the conductive area 535, to allow alignment and, in some cases, electrical contact with the other substrates.

The second substrate 505 (FIG. 5B) includes a conductive contact plate 540 that connects electrically to the magnetic actuation plate 515 only when the switch is active. The contact plate 540 often is formed from the same material as the electrical contacts 525 on the magnetic actuation plate 515, but other contact materials also are used. The second substrate 505 also includes spacers 545, 550a-d that provide the required physical separation between the magnetic actuation plate 515 and the contact plate 540. The spacers 545, 550a-d can be formed in place from nearly any material, either conductive or insulative. The spacers may also be placed manually, if desired. One approach uses a low-resistance conductive material, such as copper, that is electrodeposited onto the surface of the substrate 505 through a mold. In this implementation, at least one spacer 545 connects electrically to the contact plate 540. The remaining spacers 550a-d may or may not connect electrically to the magnetic actuation plate 515. Each spacer 545 that connects to the contact plate 540 is isolated electrically from the spacers that connect to the magnetic actuation plate 515. Holes 555a-c, 560a-d in the spacers allow alignment and, in some cases, electrical connectivity with the other substrates.

The third substrate 510 (FIG. 5C) serves as an output and protective layer for the switch. This substrate 510 includes two conductive areas 565, 570a-b that are electrically isolated from each other. One of these areas 570a-b connects electrically to the magnetic actuation plate 515. The other area 565 connects to the spacer 545, which is connected to the contact plate 540. The two areas 565, 570a-b connect electrically to each other only when the switch is active, i.e., only when the magnetic actuation plate 515 and the contact plate 540 are in contact. The conductive areas 565, 570a-b terminate in conductive pads 575a-b, 580a-b that allow the switch to connect to outside circuitry.

Several alignment pegs 585a-c, 590a-d extend from the conductive areas 565, 570a-b on this substrate 505. These pegs allow alignment with the other substrates and, in some cases, are electrically conductive to ensure electrical connectivity with the other substrates. The first substrate 500 rests directly on the third substrate, with four of the pegs 590a-d protruding through the holes 530a-d in the first substrate 500. In some cases, the pegs bond to the conductive surface 535 of the substrate 500 through a conductive bonding mate, such as solder, thus connecting the magnetic actuation plate 515 to the corresponding conductive area 570a-b of the third substrate 510. In other applications, an insulative adhesive, such as epoxy, is used.

The second substrate 505 sits directly over the first substrate 500. One set of pegs 585a-c protrudes into the holes 555a-c in the spacer 545 that connects to the contact plate 540, thus bonding the contact plate 540 to the corresponding conductive area 565 on the third substrate 510. The other set of pegs 590a-d protrudes into the holes 560a-d in the other spacers 550a-d. The pegs and the spacers usually are bonded using a conductive bonding material, such as solder. The first substrate 500 and the second substrate 505 are oriented so that the magnetic actuation plate 515 touches the contact plate 540 when the switch is active.

FIG. 6 shows a DC motor 650 having a commutation circuit that includes micromachined magnetic actuation relays 602, 604, 606 like those described above. In this example, the motor 600 is a four-pole, three-phase brushless motor having three pairs of primary and secondary windings A-A’, B-B’, C-C’. The windings in each pair are positioned on opposite sides of the motor housing 608 and are separated by a magnetic rotor having four poles. The relays 602, 604, 606 here shown in relative positions in which they are spaced by angles of 120° and are placed in close proximity to stator poles. Absolute positioning of the relays 602, 604, 606, and even the number of relays, depends on the particular motor and wiring implementation with which they are used. More complex commutation techniques involving microactuated relays may include H-bridge circuits, zener diode shunts, and other electronics. The particular commutation circuit used depends on the desired performance and lifetime characteristics for the motor in a particular application.

FIG. 7 is a schematic diagram showing the windings of the DC motor of FIG. 6 wired into a common “Y” or “star” configuration. The circuit 700 includes three branches 702, 704, 706 extending from a common node 708. Each of the branches includes one of the pairs of primary and secondary windings A-A’, B-B’, C-C’, connected in series between the common node 708 and one of three power nodes 710, 712, 714. The common node 708 connects to ground. Each of the power nodes 710, 712, 714 connects to a power supply line (PWL) through one of the magnetostatic relays 602, 604, 606. The magnetostatic relays 602, 604, 606 close, and therefore apply power to the corresponding branches 702, 704, 706 of the circuit 700, each time the magnetic rotor 610 induces a magnetic field in the relays.

Other embodiments are within the scope of the following claims. For example, some embodiments of the micromachined magnetostatic switch are produced using a single-substrate fabrication technique, instead of the two-substrate and three-substrate techniques described above. Also, in many applications the switch is formed from magnetic and electrically conductive materials having properties different than the properties of those materials described above. For example, magnetic materials other than permalloy are used in applications requiring higher or lower values for the saturation magnetization of the material. Also, the magnetic material itself may be used instead of a traditional contact material to form the electrical contact when the switch is closed. In some embodiments, a springing element such as a torsional beam or a helical spring is used instead of or in addition to the cantilever beam.

The micromachined magnetostatic switch is suitable for a wide range of applications other than commutation of DC motors, including virtually any application for which traditional relays and switches are used. Examples include telecommunication switching, household electronics and appliances, computers, and handheld electronics. The magnetostatic switch also is useful as a magnetic field sensor. An array of these switches designed to respond to magnetic fields of varying strengths provides very sensitive magnetic field measurements. As a result, these switches also are useful in applications previously reserved for traditional magnetic devices, such as Hall Effect sensors. The switches are useful as rotational and linear encoders, as well as in applications previously requiring reed relays.

What is claimed is:

1. A magnetostatic switch comprising:
   at least one substrate formed from a nonconductive or semiconductive material;
   a springing beam formed on the substrate; and
   two electrically conductive elements, one formed on the springing beam, and at least two switching states, including an operating state in which the conductive elements are physically separated from each other, and a closed state in which the conductive elements physically contact each other;
wherein the springing beam includes a magnetic material which, based on a magnetic field, creates an actuation force that causes the electrically conductive elements to switch from the closed state when the actuation force is not present in which the electrically conductive elements touch one another, and are in the open state when the actuation force is present, in which the electrically conductive elements do not touch one another.

2. A magnetostatic switch comprising:

- at least one substrate formed from a nonconductive or semiconductive material;
- a springing beam formed on the substrate; and
- two electrically conductive elements, one formed on the springing beam, that together define at least two switching states, including an open state in which the conductive elements are physically separated from each other, and a closed state in which the conductive elements physically contact each other;
- wherein the springing beam includes a magnetic material which, based on a magnetic field, creates an actuation force that causes the electrically conductive elements to switch from one of the switching states to another of the switching states; and
- wherein the conductive elements are held in the closed state by residual stress in the springing beam; and
- wherein the electrically conductive elements are in the closed state when the actuation force is not present.

3. A method of fabricating a magnetostatic switch, the method comprising:

- forming a temporary layer of removable material over a portion of a rigid substrate;
- forming a springing beam by depositing a layer of magnetic material over at least a portion of the temporary layer and over at least some portion of the substrate that is not covered by the temporary layer; and
- removing the temporary layer to form a gap between the substrate and a portion of the springing beam.

4. The method of claim 3, further comprising forming an electrically conductive contact layer over at least a portion of the springing beam.

5. The method of claim 3, further comprising:

- forming an electrically conductive contact layer over at least a portion of another rigid substrate;
- forming a patterned layer of material over a portion of the other substrate to serve as a spacing layer; and
- bonding the two substrates so that the springing beam and the contact layer are positioned between the substrates and are held separate from each other by the spacing layer.

6. The method of claim 5, further comprising selecting the electrically conductive material to minimize the electrical resistance between the springing beam and the contact layer.

7. The method of claim 5, wherein the electrically conductive material that forms the contact layer comprises a metal.

8. The method of claim 7, wherein the electrically conductive material comprises silver.

9. The method of claim 7, wherein the electrically conductive material comprises gold.

10. The method of claim 5, wherein the material that forms the spacing layer is electrically conductive.

11. The method of claim 10, wherein the material that forms the spacing layer comprises copper.

12. The method of claim 5, further comprising:

- forming at least two electrically conductive areas, electrically isolated from each other, on a third substrate; bonding the third substrate to the other two substrates so that one of the conductive areas connects electrically to the springing beam and another of the conductive areas connects electrically to the contact layer.

13. The method of claim 12, further comprising forming electrically conductive pegs that extend from the conductive areas on the third substrate and bond electrically to the other substrates.

14. The method of claim 3, wherein the springing beam normally touches the contact layer, and bends to release its contact to the contact layer.

15. The method of claim 3, further comprising selecting the magnetic material so that the springing beam bends to touch the contact layer in the presence of a magnetic field.

16. The method of claim 3, further comprising selecting the magnetic material to maximize saturation magnetization.

17. The method of claim 14, wherein the magnetic material comprises permalloy.