US006713908B1

(12) **United States Patent**
Tai et al.

(10) **Patent No.: US 6,713,908 B1**
(45) **Date of Patent: Mar. 30, 2004**

(54) **USING A MICROMACHINED MAGNETOSTATIC RELAY IN COMMUTATING A DC MOTOR**

(75) Inventors: **Yu-Chong Tai**, Pasadena, CA (US); **John A. Wright**, Pasadena, CA (US); **Gerald Lilienthal**, Pasadena, CA (US)

(73) Assignee: **California Institute of Technology**, Pasadena, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/281,831**

(22) Filed: **Mar. 30, 1999**

Related U.S. Application Data

(60) Provisional application No. 60/080,063, filed on Mar. 31, 1998.

(51) **Int. Cl.**[7] **H02K 1/00**; H02K 3/00

(52) **U.S. Cl.** .... **310/68 R**; 310/68 B; 310/179; 310/180; 310/40 MM; 310/DIG. 6; 318/138; 318/251

(58) **Field of Search** .... 310/68 B, 68 R, 310/40 MM, DIG. 6, 173, 179–180; 318/138, 251; 335/78, 80, 38, 205, 154

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,626,222 A * 12/1971 Dischler 310/96
3,900,780 A * 8/1975 Tanikoshi 318/254
4,475,068 A * 10/1984 Brailsford 318/254
5,293,523 A * 3/1994 Posey 335/205
5,605,614 A * 2/1997 Bornand 205/50
5,629,918 A * 5/1997 Ho et al. 369/112
6,094,116 A * 7/2000 Tai et al. 335/78

OTHER PUBLICATIONS

Hiroshi Hosaka, et al.; Electromagnetic Microrelays: Concepts and Fundamental Characteristics; 1993; IEEE.

Joe Drake, et al.; An Electrostatically Actuated Micro–Relay; 1995; Proc. Transducers '95, Stockholm, Sweden, vol. 2, pp. 380–383.

John Wright, et al.; Magnetostatic MEMS Relays for the Miniaturization of Brushless DC Motor Controllers; Jan. 1999; MEMS '99 Conference.

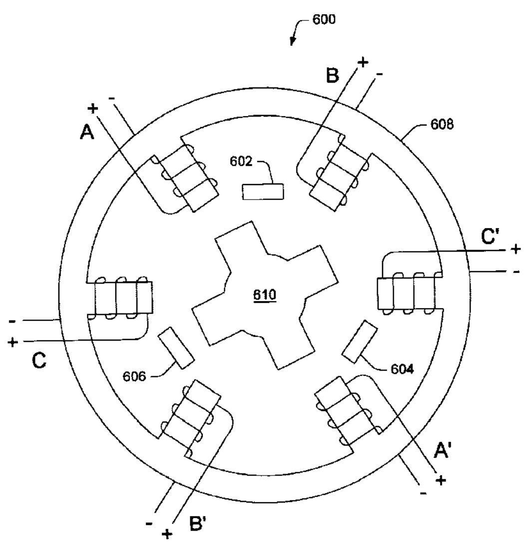
* cited by examiner

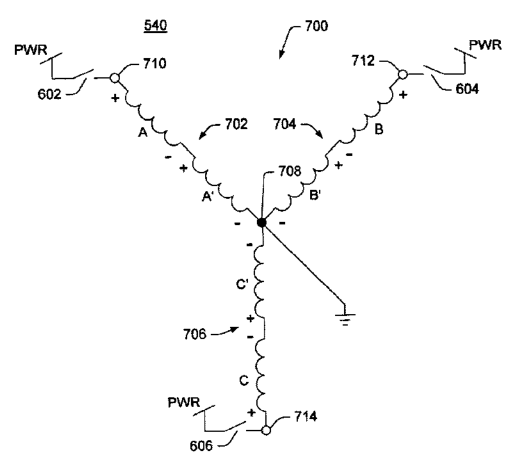
Primary Examiner—Karl Tamai
Assistant Examiner—J. Aguirrechea
(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

(57) **ABSTRACT**

A DC motor is commutated by rotating a magnetic rotor to induce a magnetic field in at least one magnetostatic relay in the motor. Each relay is activated in response to the magnetic field to deliver power to at least one corresponding winding connected to the relay. In some cases, each relay delivers power first through a corresponding primary winding and then through a corresponding secondary winding to a common node. Specific examples include a four-pole, three-phase motor in which each relay is activated four times during one rotation of the magnetic rotor.

14 Claims, 6 Drawing Sheets





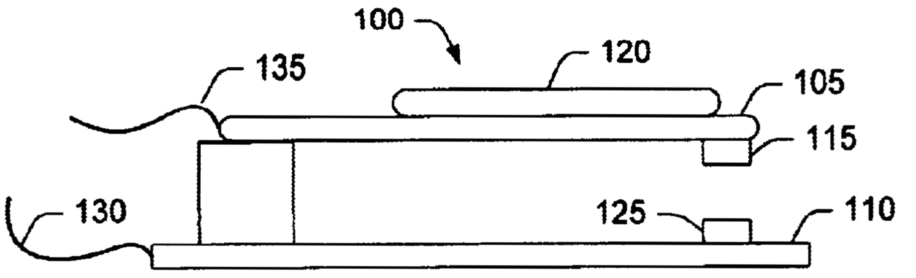


FIG. 1A

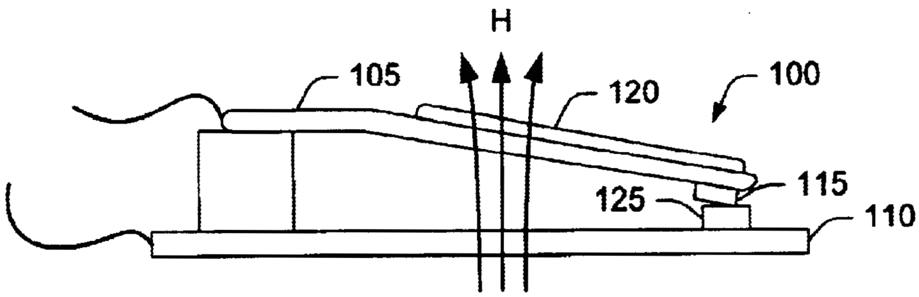


FIG. 1B

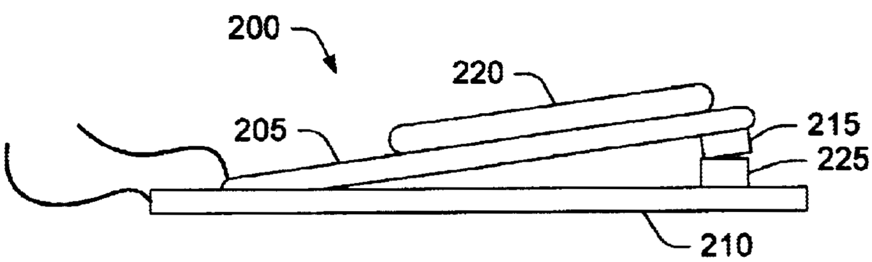


FIG. 2A

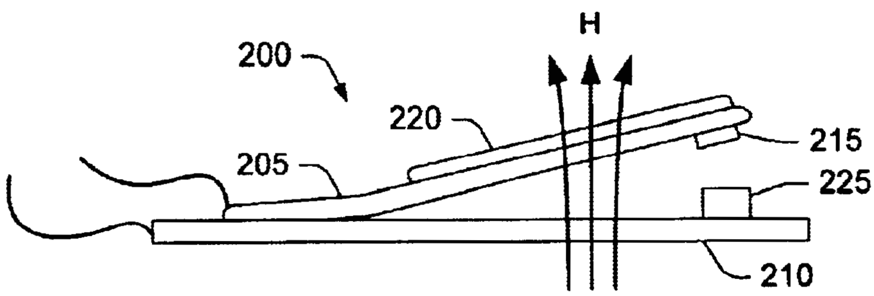


FIG. 2B

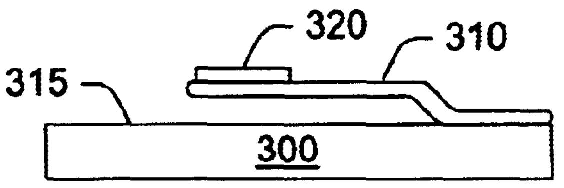


FIG. 3A

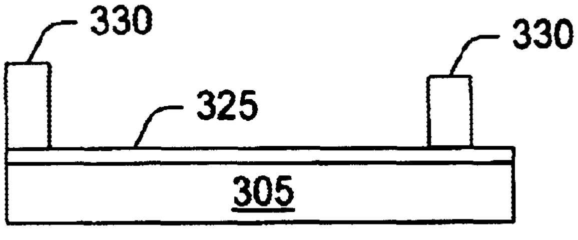


FIG. 3B

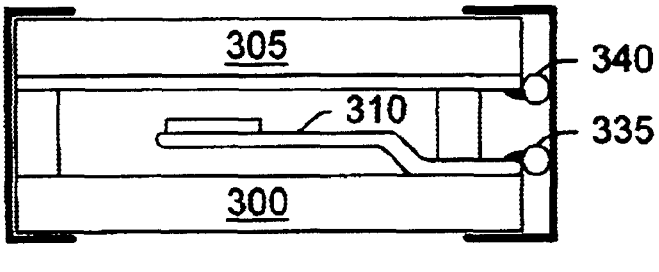


FIG. 3C

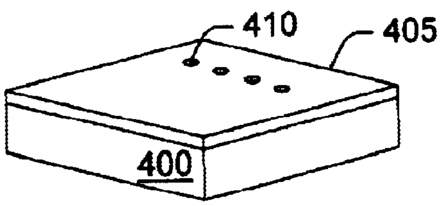


FIG. 4A

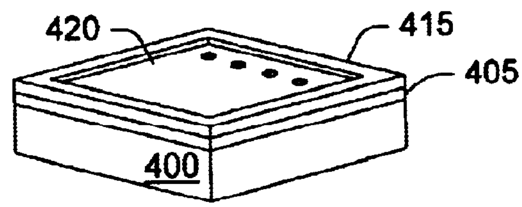


FIG. 4B

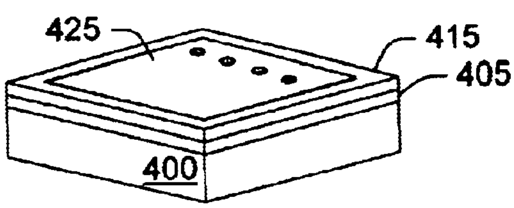


FIG. 4C

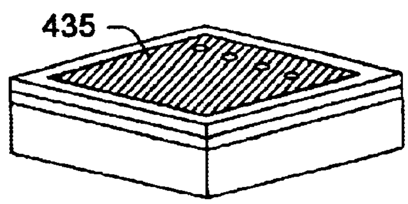


FIG. 4D

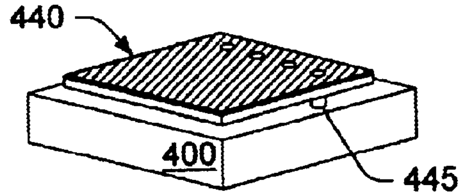


FIG. 4E

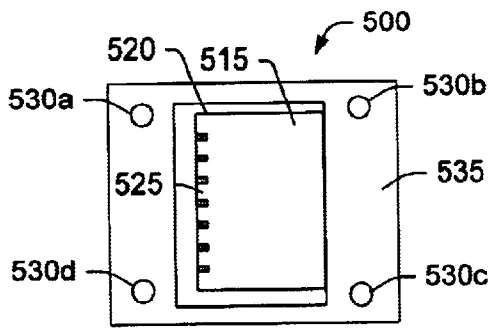


FIG. 5A

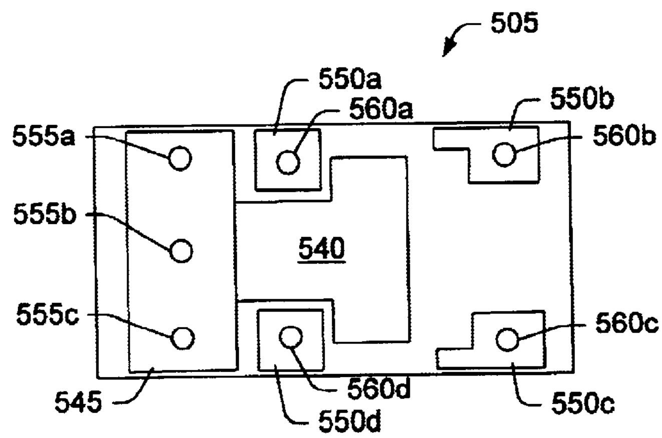


FIG. 5B

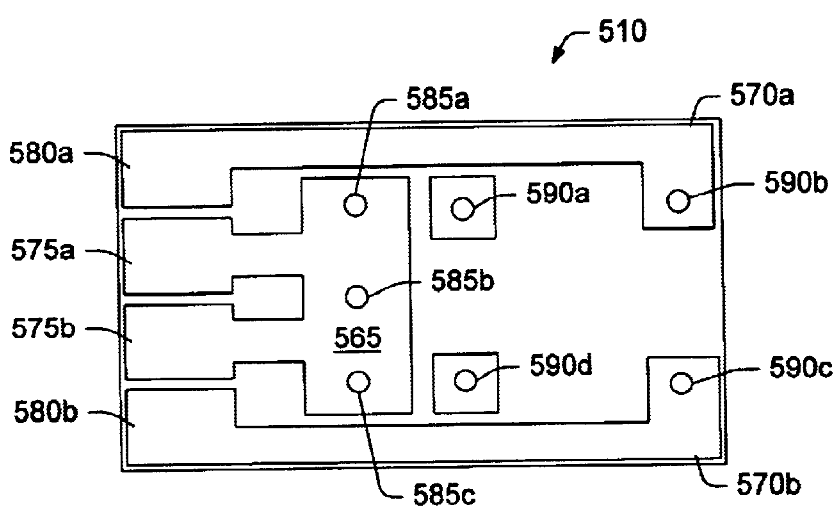


FIG. 5C

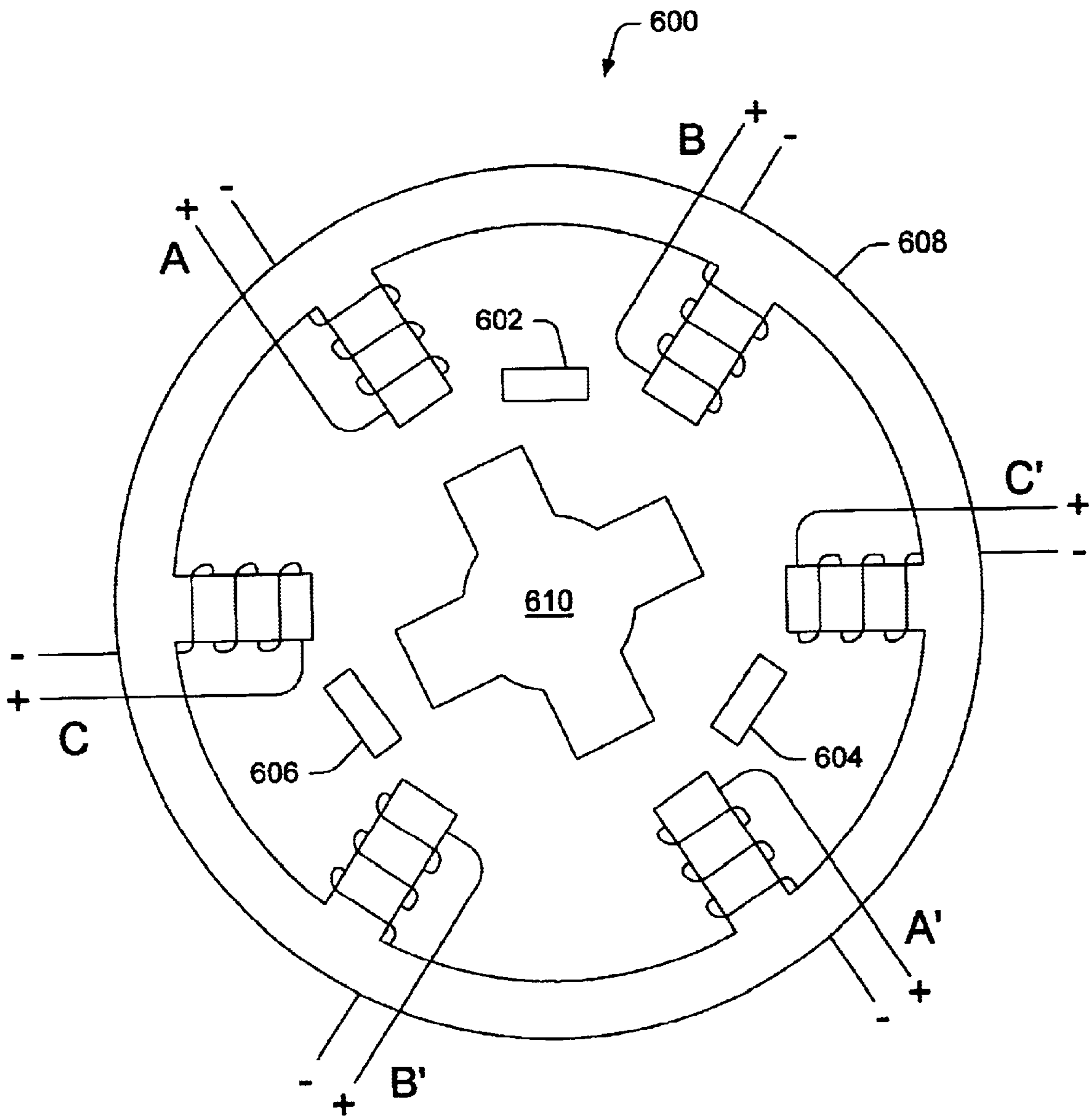


FIG. 6

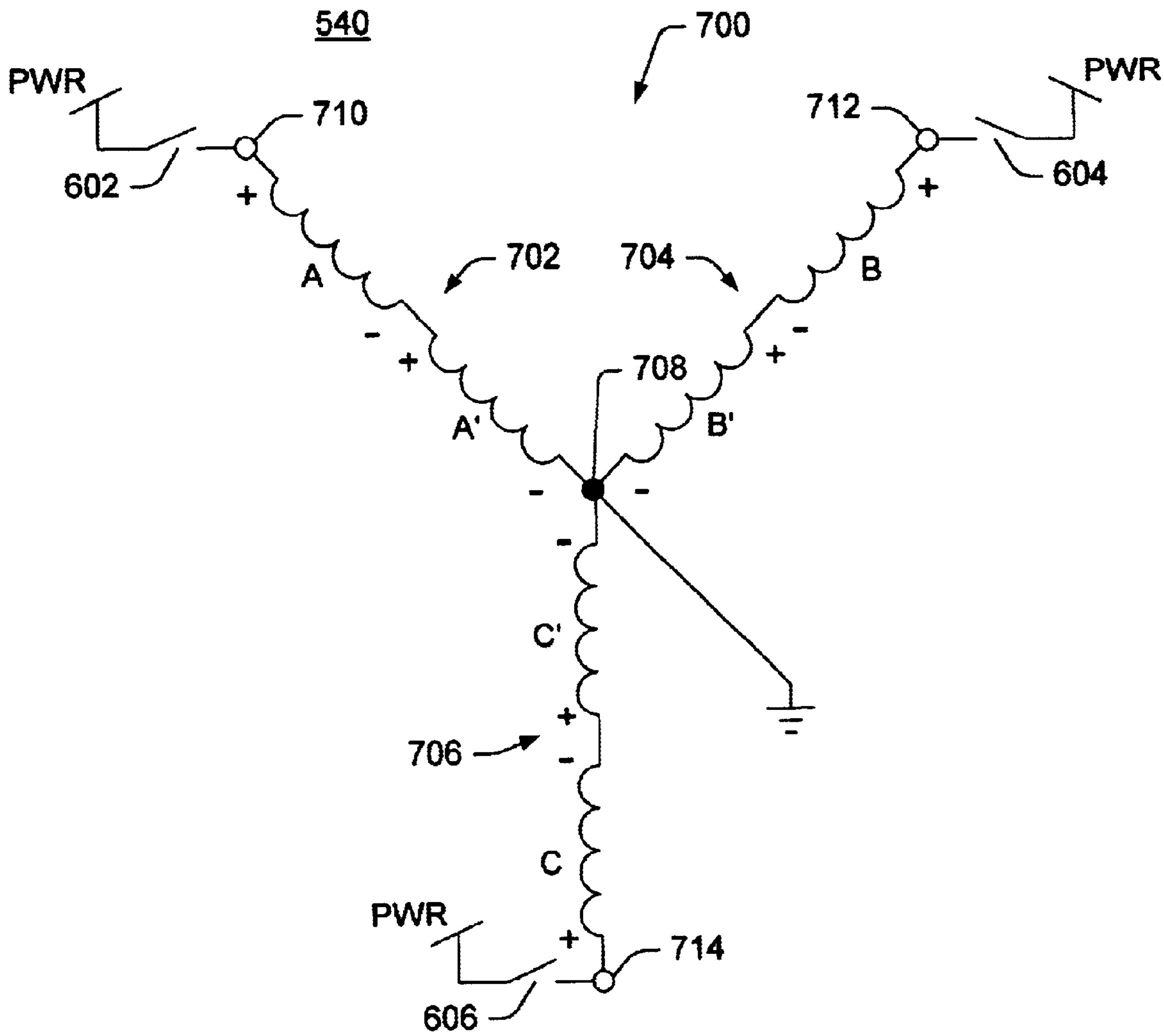

540
700
PWR
710
602
+
A
702
-
+
A'
-
708
704
712
PWR
604
+
B
-
+
B'
-
-
C'
+
706
-
C
PWR
+
714
606

FIG. 7

USING A MICROMACHINED MAGNETOSTATIC RELAY IN COMMUTATING A DC MOTOR

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/080,063, filed on Mar. 31, 1998.

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

TECHNOLOGICAL FIELD

The invention relates to miniaturization of electronic components and, in particular, to using a micromachined magnetostatic relay in commutating a DC motor.

BACKGROUND

Manufacturers and users of electrical and electronic components strive to reduce the size and increase the reliability of these components and the systems in which they are used. Miniaturization of components leads to more compact and lightweight systems, which increases the range of uses for these systems and decreases the costs associated with transporting and using these systems. Improving component reliability lengthens the lifespan and enhances the performance of systems in which the components are used.

Miniaturization and reliability improvements are particularly important in areas such as space exploration and satellite communications. The cost of launching equipment from the Earth's surface is directly related to the size and weight of the equipment, and even modest reductions in equipment size produce large reductions in cost. Likewise, improving the reliability of components used in spaceborne systems extends and improves the performance of these systems, thus reducing the associated costs. In general, each newly developed generation of space oriented components and systems must meet or exceed the performance and cost standards set by previous generations.

One example of commonly used components for which size and reliability are particularly important is DC electric motors. DC motors are used widely as motive devices for linear and rotary drives in spaceborne applications. As gains have been made in the miniaturization of DC motors, the size, weight, and complexity of DC motor systems have become dominated by the commutation and control electronics that drive the motors. The disparity between the size of the motor and the size of its control electronics is particularly noticeable in a highly miniaturized motor, such as a commercially available 3-mm diameter motor, the commutation and control electronics of which are more than ten times larger than the motor itself. Even modest reductions in the power budget, complexity, mass, and volume of components such as these produce tremendous gains in the cost and reliability of spaceborne systems.

SUMMARY

In recognition of the above, the inventors have developed micromachined magnetostatic relays or switches that are highly miniaturized and highly reliable. The switches are made very small using micromachining fabrication techniques, and the materials are carefully selected to provide high reliability. The switches are useful in a wide variety of microelectronic mechanical system (MEMS) applications, particularly in the miniaturization of DC electric motors. For example, in one embodiment of the invention, the switches are used as relays in a MEMS circuit that replaces the conventional commutation and control electronics in a DC motor. This MEMS circuit is much smaller than the DC motor itself, so 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 DC motor having a plurality of windings and at least one magnetostatic relay positioned to activate in the presence of a magnetic field. Each relay is connected electrically to at least one corresponding winding and to power. The motor also includes a magnetic rotor having at least one pole positioned to induce a magnetic field in each magnetostatic relay when passing by the relay.

In some embodiments, the windings are arranged in pairs of primary and secondary windings, and each relay connects to a corresponding one of the pairs of windings. In some cases the secondary windings all connect to a common node, and each of the primary windings connects to the corresponding relay. In one implementation, the motor is a four-pole, three-phase motor that includes three relays separated from each other by approximately 120°.

In another aspect, the invention features a DC motor having a plurality of windings and at least one magnetostatic relay connected electrically to at least one of the windings and to power. Each relay has at least one substrate formed from a non-conductive or semiconductive material, a springing beam formed on the substrate, and two electrically conductive elements, one of which is formed on the springing beam. The electrically conductive-elements 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. The springing beam includes a magnetic material which, in the presence of a magnetic field, creates an actuation force that causes the electrically conductive elements to apply power to or remove power from at least one of the windings by switching from one of the switching states to another of the switching states. The motor also includes a magnetic rotor having at least one pole positioned to induce a magnetic field in each magnetostatic relay when passing by the relay.

In another aspect, the invention features a method for use in commutating a DC motor. The method includes rotating a magnetic rotor to induce a magnetic field in at least one magnetostatic relay in the motor. Each relay is activated in response to the magnetic field to deliver power to at least one winding in the motor.

In some embodiments, each relay first delivers power through a corresponding primary winding and then through a corresponding secondary winding to a common node. Other embodiments include activating each relay four times during one rotation of the magnetic rotor.

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 a substrate at several steps of a two-substrate switch fabrication process.

FIGS. 5A, 5B, and 5C are plan views of substrates in a three-substrate switch fabrication process.

FIG. 6 is a plan view of a DC motor having a MEMS commutation circuit that uses micromachined magnetostatic switches.

FIG. 7 is a schematic diagram of the motor windings for the DC motor of FIG. 6.

DETAILED DESCRIPTION

FIGS. 1A and 1B show a normally-open microelectronic mechanical system (MEMS) relay or switch **100**. The switch **100** includes a cantilever beam **105** mounted on a substrate **110**. For convenience, the substrate **110** is made from a substrate material, such as silicon, that is plentiful and relatively inexpensive. The substrate **110** includes an electrical contact **125** made of an electrically .conductive material, such as gold or silver, with a relatively low contact resistance at modest contact forces. The cantilever beam **105** includes a magnetic actuation plate **120** which, in many embodiments, is made of a soft magnetic material with high permeability, such as permalloy ($Ni_{80}Fe_{20}$). The cantilever beam **105** also includes an electrical contact **115**, which may or may not be made of the same material that forms the contact **125** on the substrate **110**.

As shown in FIG. 1A, the cantilever beam **105** keeps the electrical contacts **115**, **125** separated when the switch **100** is inactive, i.e., when no magnetic field is present. When an external magnetic field H appears, magnetic forces attempt to align the magnetic actuation plate **120** with the magnetic field H, causing the cantilever beam **105** to bend toward the substrate. If the strength of the magnetic field exceeds the design threshold of the switch, the electrical contacts **115**, **125** touch, as shown in FIG. 1B, completing an electrical circuit through bond wires **130**, **135**. The electrical circuit is broken when the magnetic field disappears and the restoring force of the cantilever beam **105** separates the electrical contacts **115**, **125**. In alternative implementations, the cantilever beam **105** is designed to separate the contacts **115**, **125** when the direction or the magnitude of the magnetic field changes.

FIGS. 2A and 2B show a normally-closed MEMS switch **200** of similar structure. The cantilever beam **205** in this switch is mounted on the substrate **210** so that the electrical contacts **215**, **225** of the beam **205** and the substrate **210** are held together when the switch **200** is inactive. Applying a magnetic field to the magnetic actuator plate **220** causes the beam **205** to bend away from the substrate **210**, thus separating the contacts **215**, **225**. The contacts **215**, **225** come together again when the magnetic field disappears or, alternatively, when the direction or the magnitude of the magnetic field changes.

An alternative design for the normally closed switch resembles the normally open switch of FIG. 1A, except that the cantilever beam **105** is formed such that residual stress imparts ID curvature to the beam **105**, holding the tip of the beam **105** against the lower electrical contact **125**. In this embodiment, subjecting the beam **105** to a magnetic field creates a **105** force that opposes the residual stress in the beam **105**, pulling the contacts **115**, **125** 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 I below 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.

TABLE I

Parameter	Unit	Electrostatic Microswitch	Electromagnetic Microswitch	Micromachined Magnetostatic Switch
load voltage	volts	20	20	36
maximum current	mA	0.1	100	>500
operating force	mN	0.001	0.1	>1
contact gap	μm	2	>5	>5
contact closing time	μsec	20	200	<100
lifetime operations	cycle	>10 million	N/A	>100 million

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 s 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:

$$F_{bending}=M_s(WT)H\cos\theta,$$

where T=the thickness of the magnetic actuation plate **120**, W=the width of the plate **120**, L=the length of the plate **120**, θ=the deflection angle of the beam **105** (θ=0 when the switch is inactive), 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 H are large and the deflection angle (θ) 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 $\theta\approx 0$.

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 μm in a DC motor that produces a magnetic field strength of approximately 2500 gauss.

FIGS. **3**A, **3**B, and **3**C show a magnetostatic switch micromachined from two rigid substrates **306**, **305**, each of which is made from a material such as silicon. The first substrate **300** (FIG. **3**A) 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. **3**B) 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 substrate **300**. The height of this spacing layer **330** is determined by the desired gap distance between the contact layers **320**, **325**. As shown in FIG. **3**C, 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. **4**A through **4**E 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** (FIG. **4**A). The spacing layer **405** is formed from an etchable material, such as photoresist. In highly miniaturized switches, the spacing layer **405** typically has a thickness of between 2 μm and 20 μm. 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 below. In many switches, a very thin electroplating seed layer is deposited over the spacing layer to facilitate formation of the magnetic actuation plate.

A photoresist plating mold layer **415** then is deposited over the spacing layer **405** and patterned to form a mold cavity **420** (FIG. **4**B). 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. **4**C). 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 μm and 20 μm in many highly miniaturized switches.

A layer of contact material **435** then is deposited over the layer of magnetic material **425** (FIG. **4**D). 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 μm and 10 μm.

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. **3**B. 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 μm and 200 μm, 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 is 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. **5**A 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. **5**A. 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. **5**A through **5**C show the components of a switch fabricated from three substrates. The first substrate **500** (FIG. **5**A) 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 **530***a–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. **5**B) 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**, **550***a–d* that provide the required physical separation between the magnetic actuation plate **515** and the contact plate **540**. The spacers **545**, **550***a–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 **550***a–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 **555***a–c*, **560***a–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**, **570***a–b* that are electrically isolated from each other. One of these areas **570***a–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**, **570***a–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**, **570***a–b* terminate in conductive pads **575***a–b*, **580***a–b* that allow the switch to connect to outside circuitry.

Several alignment pegs **585***a–c*, **590***a–d* extend from the conductive areas **565**, **570***a–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 **590***a–d* protruding through the holes **530***a–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 material, such as solder, thus connecting the magnetic actuation plate **515** to the corresponding conductive area **570***a–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 **585***a–c* protrudes into the holes **555***a–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 **590***a–d* protrudes into the holes **560***a–d* in the other spacers **550***a–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 **600** having a commutation circuit that includes micromachined magnetostatic 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 are 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 micromachined relays 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 (PWR) 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 DC motor comprising:

a plurality of windings;

at least one microelectronic mechanical system (MEMS) relay positioned in the motor to activate in the presence of a magnetic field, where each relay includes:

a first substrate formed from a nonconductive or semiconductive material;

a magnetic actuation plate micro-machined on said first substrate, said magnetic actuation plate having a first conductive surface, said magnetic actuation plate comprising one or more anchors in direct contact with the first substrate, where said magnetic actuation plate and said one or more anchors are formed of permalloy material; and

a second substrate provided adjacent to said magnetic actuation plate, said second substrate having a nonconductive surface and a second conductive surface,

where said first and second conductive surfaces define at least two switching states, including an open state in which the conductive surfaces are physically separated from each other, and a closed state in which the conductive surfaces physically contact each other,

where said magnetic actuation plate, in the presence of a magnetic field, creates an actuation force that causes the electrically conductive surfaces to switch from one of the switching states to another of the switching states, and

where each relay is connected electrically to at least one corresponding winding and to power; and

a magnetic rotor having at least one pole positioned to induce a magnetic field in each MEMS relay when passing by the relay.

2. The motor of claim **1**, wherein the windings are arranged in pairs of primary and secondary windings and each relay connects to a corresponding one of the pairs of windings.

3. The motor of claim **2**, wherein the secondary windings all connect to a common node and each of the primary windings connects to the corresponding relay.

4. The motor of claim **1**, wherein the motor is a four-pole, three-phase motor.

5. The motor of claim **4**, wherein the motor includes three relays separated from each other by approximately 120°.

6. The motor of claim **1**, wherein the relay is magnetically switched between the first and the second switching states without an electrical biasing current or voltage.

7. A spaceborne system, the spaceborne system comprising a DC motor micromachined mechanical system (MEMs) commutation circuit, the DC motor micromachined mechanical system (MEMs) commutation circuit comprises:

a plurality of windings wired into a star configuration;

a plurality of micromachined mechanical system switches each electrically connected to one part of said windings, wherein each switch is magnetically switched by a magnetic field without an electrical biasing current or biasing voltage to turn electrical power on or off in at least one of the windings; and

a rotating magnetic rotor having at least one pole to direct the magnetic field in at least one of the switches when passing by the switch.

8. The DC motor micromachined mechanical system (MEMs) commutation circuit as in claim **7**, wherein said switch comprises a micromachined magnetostatic switch.

9. The spaceborne system as in claim **7**, wherein the number of switches corresponds to the number of motor phases.

10. The spaceborne system as in claim **7**, wherein said switch is a relay, wherein the relay comprises:

a first and second conductive surface to define at least two switching states, including an open state in which the conductive surfaces are physically separated from each other, and a closed state in which the conductive surfaces physically contact each other to permit a current flow between the two conductive surfaces.

11. A DC motor for spaceborne applications comprising a commutation circuit, the communication circuit comprising:

a plurality of windings, wherein the plurality of windings comprise three pairs of primary and secondary windings wired into a star configuration;

a micromachined mechanical system (MEMs) relay electrically connected to one part of said windings for a motor phase, wherein the relay is actuated in response to a magnetic field and operates without biasing current or biasing voltage, wherein the relay comprises a first and second conductive surface to define at least two switching states, including an open state in which the conductive surfaces are physically separated from each other, and a closed state in which the conductive surfaces physically contact each other to permit a current flow between the two conductive surfaces; and

a rotating magnetic rotor having at least one pole positioned to direct the magnetic field in the relay when passing by the relay.

12. The DC motor as in claim **11**, wherein the number of switches corresponds to the number of motor phases.

13. A method for applying power to a DC motor in spaceborne applications, the method comprising:

actuating a micromachined mechanical system (MEMs) relay in a magnetic field, wherein a rotating magnetic rotor induces the magnetic field, wherein the relay is magnetically actuated without an electrical biasing current or voltage; and

closing the micromachined mechanical system (MEMs) relay to conduct current through a DC motor commutation circuit, wherein the DC motor commutation circuit comprises:

a power source, three pairs of primary and secondary windings, three micromachined mechanical system (MEMs) relays, and a ground terminal.

14. A method for removing power from a DC motor in spaceborne applications, the method comprising:

opening a micromachined mechanical system (MEMs) relay when a magnetic field is removed from the micromachined mechanical system (MEMs) relay; and

terminating current conduction through a DC motor commutation circuit when the micromachined mechanical system (MEMs) relay opens, wherein the DC motor commutation circuit comprises:

a power source, a plurality of windings wired into a star configuration, one semiconductor device, and a ground terminal, wherein the one semiconductor device is a micromachined mechanical system (MEMs) relay.

* * * * *