Integrated Magnetic Microrelays: Normally Open, Normally Closed, and Multi-Pole Devices

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SUMMARY

A fully integrated magnetically actuated micromachined relay has been realized. This particular device uses a single layer coil to actuate a movable upper magnetically responsive platform. The minimum current for actuation was 180 mA, resulting in an actuation power of 33 mW. Devices have been tested which can make and break 1.2 A of current through the relay contacts when the relay is electromagnetically switched. Operational lifetimes in excess of 300,000 operations have been observed. A normally closed relay has also been developed through the addition of permanent magnets to the microrelay. These devices have also been able to electromagnetically switch 1.2 A of current. Multi-pole devices, which contain more than one pair of contacts per coil have also been realized, and possess comparable performance characteristics to single-pole devices.

Keywords: Microrelay Magnetic Actuator Integrated Microrelay

INTRODUCTION

Electromechanical relays remain widely used *for* a number of applications including automotive control circuitry, test equipment, and the switching of high frequency signals. Historically the manufacturing process of electromechanical relays has been serial, i.e., devices are built one at a time, which can result in production bottlenecks and make it difficult to produce large relay arrays. Solid state relays (SSRs) have been one solution to this production problem. SSRs allow *for* devices to be batch fabricated; however, in some cases they may also have higher offset voltage injection, lower maximum off-state resistance, and higher contact power dissipation than their electromagnetic counterparts. Micromachined relays are produced by the application of batch fabrication techniques to electromechanical relays in an attempt to combine the best attributes of both electromechanical relays and SSRs.

Microfabrication techniques have been used *for* the fabrication of electromechanical relays *for* many years. Petersen [1] demonstrated electrostatically actuated microrelays in 1979. Those devices used metallic contact materials to reduce the contact resistance and increase the current carrying capacity. Since that time polysilicon electrostatic microrelays on CMOS have been demonstrated [2-3]. These devices had a relatively low carry current of approximately 10 mA. *Other* versions of electrostatic microrelays have also been demonstrated and have shown lower contact resistance through the use of metallic contact materials {4-7]. One electrostatically actuated device reported lifetimes in excess of 10^8 [5].

Mercury is used in electromechanical relays to improve lifetimes by reducing the contact wear. A microrelay with mercury contacts has been demonstrated by Simon et al. [8]. This device had contact resistance lower than 1 Q, with a maximum carry current of 20 mA.

Low actuation voltages may be desirable in applications such as automotive circuits, where voltages are low, but currents may be high. Magnetically-driven microrelays are very desirable in such an environment as they are compatible with these require ments. Previously reported magnetic microrelays do not have fully integrated coils [9-11]. The schemes presented have used either an external electromagnet [9-10], or an integrated heating element [11]. Previously we reported a fully integrated magnetically actuated micromachined relay [12]. The use of a fully integrated magnetically actuated microrelay design has several advantages. Minimum sized relays may be obtained, and the devices do not require any assembly of a coil to an actuator plate, thus allowing for further advantages of batch fabrication. Our approach has been to use a fully integrated magnetic actuation design to realize integrated microrelays.

DEVICE CONCEPT

In the design of these microrelays a single layer coil was used to reduce fabrication complexity and eliminate the via connections required in a multilayer coil. Figure I shows a schematic view of a double-pole single-throw (DPST) microrelay. A DPST relay is one in which two electrically isolated contact pairs are actuated by the same electromagnet. This is a common commercial relay configuration, and is easily achieved with this microrelay design by patterning multiple contact pairs over a single electromagnet. This may increase the size of the electromagnet depending on the required power rating of the contacts.

In addition to double-pole devices, normally-closed relays have also been investigated. A normally-closed relay is "ON" allowing a current to flow between the two contacts when no current flows through the coil; instead, the magnetic plate is held in contact by a permanent magnet. When a current passes through the coil a sufficient magnetic flux is generated that opposes the magnetic flux provided by the permanent magnet. In this situation, the mechanical restoring force of the suspension arms can pull the upper plate off of the contacts thus discontinuing the flow of current between the contacts and turning the relay "OFF." When the current is discontinued in the coil, the magnetic flux provided by the permanent magnet is sufficient to overcome the mechanical forces of the suspension arms, thus connecting the two contacts and turning the relay "ON" even though no current flows through the coil.

The ability to create normally-open, normally-closed, and multi-pole devices from the same basic microrelay design is advantageous, as it reduces the necessary number of designs a manufacturer would require for these basic relay types.

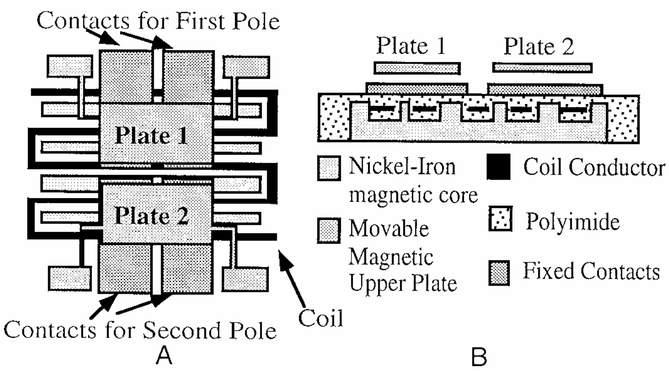

Figure 1: Schematic of the DPST microrelay. A: overhead view showing the coil winding through the side magnetic cores. Two electrically isolated sets of contacts are then fabricated on top of the electromagnet. B: side view across the contacts showing the two independent upper plates and contact sets over one electromagnet.

DEVICE OPERATION

The operation of the normally open device is similar to other electromagnetic relays, with the exception that the flux is distributed rather than additive as is the case with most conventional electromagnetic relays. Figure 2 shows a schematic of the flux patterns and how they add in adjacent side core areas. The device actuates by passing a current of sufficient magnitude through the coil and generating a magnetic flux which is concentrated by the lower and side magnetic cores. The magnetic flux then flows through the magnetic gap (consisting of the air gap between the contacts and the upper movable plate and the distance from the side core to the top of the contacts), and into the upper magnetic plate. The flux then propagates along the upper magnetic plate to the area over the next side core, where the flux again passes through the magnetic gap, and into the adjacent side core on the other side of the coil. The magnetic flux thus generates a force on the upper magnetic plate, which then moves down toward the electromagnet. For single-pole devices, a pair of contacts are positioned between the upper magnetic plate and the electromagnet; for double-pole devices, two pairs of contacts are positioned over the electromagnet, and two upper plates are fabricated over the same coil. In either case, when the upper magnetic plate moves down toward the electromagnet it encounters the two contacts which stop its motion. Since the upper plate is conductive, a current flows from one contact through the upper plate, and into the other contact.

When the current in the coil is discontinued, the mechanical restoring forces of the upper plate suspension arms are sufficient to pull the upper plate off of the contacts. When the plate is pulled off of the contacts the current is discontinued and the relay is again in the "OFF" state.

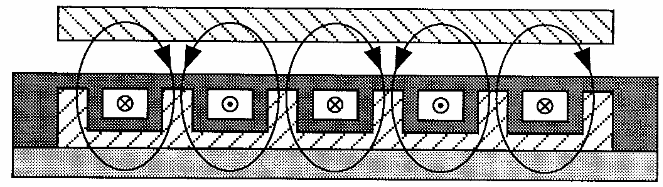

Figure 2: Conceptual view of the flux patterns generated by this microrelay geometry (contacts not shown).

FABRICATION

The microrelay fabrication is based on standard polyimide mold electroplating techniques [13] and consists of an integrated planar meander coil and one or more pairs of relay contacts positioned above the coil. A movable magnetic plate is surface micromachined above the contacts and connects the contacts when coil current is applied to the electromagnet (normally open, or 'Form A', operation).

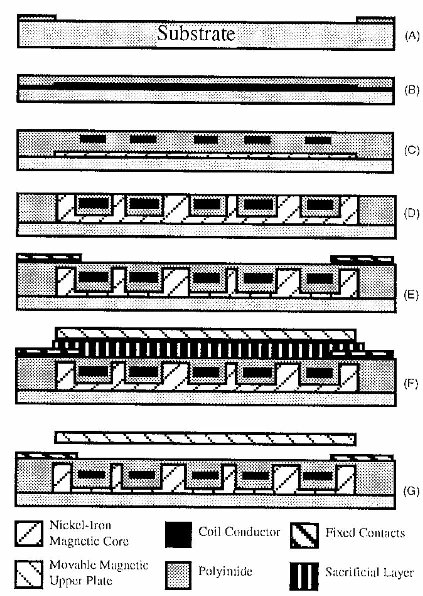

Figure 3: A side view schematic of the fabrication process used to produce microrelays. (A) after lower core polymer mold deposition; (B) insulated lower magnetic core; (C) after coil electroplating and insulation; (D) after side magnetic core electrodeposition; (E) after deposition of contacts over the electromagnet; (F) after plating of the upper movable magnetic plate; (G) the completed microrelay after photoresist sacrificial layer has been removed.

To create a normally closed (Form B) microrelay, a permanent magnet is incorporated in the microrelay on the surface of the substrate or in the relay package. The permanent magnet acts to hold the contacts closed when no current is applied to the coils. When current is applied, flux is generated which acts to open the contacts. The use of the same relay geometry for Form A and Form B operation (the only difference is the presence of the permanent magnet), allows a manufacturing advantage since no relay redesign is needed to move from Form A to Form B operation. Form B relays are of particular interest in designs where the contacts are to be closed over 50% of their operating life. Figure 4 shows a fabricated DPST microrelay on a dime.

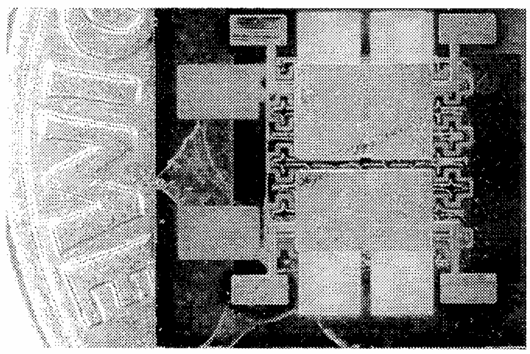

Figure 4: Photomicrograph of a completed Double-Pole, Single-Throw magnetic microrelay, top view. The relay is shown next to a dime for comparison.

RESULTS

Several different relay geometries were tested. These included four-arm, bridge-type upper movable plates, and more flexible two-arm cantilever-type upper plates. In addition, two operating modes of the relay were investigated: one in which the movable plate formed one of the contacts and one or both of the lower contacts formed the second contact, and one in which the movable plate bridged both lower contacts. The first operation mode has lower contact resistance since only one contact to movable plate interface is formed upon relay closure; the second operation mode has higher contact resistance but no current must flow through the movable plate support arms.

All types of suspensions and operating modes produced successfully actuating and functional relays. As expected, the more flexible cantilever-type suspension required lower actuation currents, and the first operation mode had lower contact resistance. For a typical cantilever-type device, with beam dimensions of 200 μm width and 2 mm length, actuation was achieved with a 500 mA coil current. The lowest contact resistance was observed at 600 mA for these devices; the actuation power (i.e., power consumed by the coil) was 320 mW at the 600 mA actuation current. By decreasing the line width of the coils, and increasing the number of coil lines under the upper plate, actuation currents and powers of 180 mA and 33 mW respectively were achieved. Other geometric parameters of the power-minimized device were beam widths of 100 μm and an upper plate that was 1.95 mm by 3.5 mm in length. These power levels are more typical of commercially available reed and miniature armature relays, which are typically rated at 50 mW of coil power.

The coil resistance of the microrelays was typically 1 to 1.5 Ω, depending on coil size and thickness. The microrelay coils have been tested up to in excess of 3.0 A DC continuously for several hours and did not fail. The coil and relay were both still operational after this experiment.

Measurements of the microrelay contact resistance under electromagnetic actuation were performed in air using a DC multimeter. Values of the "ON" resistance as low as 0.85 Ω were measured, with typical values of 2-3 Ω. Similar results were observed on several different relay designs. The "OFF" resistance was infinite; no current flow was observed with voltages in excess of 10 V applied across the contacts.

Testing of the microrelay with an active load being switched across the contacts has also been performed. A cantilever type microrelay, shown in Figure 5, was able to repeatedly switch a 1.2 A DC load, both making and breaking the circuit in the first operational mode (one contact to upper plate interface) by energizing the relay coil. This relay had an upper plate measuring 4 mm x 2.4 mm. The suspension arms were 400 μm wide. The voltage drop across the contacts was measured to be 1.6 V at this current. Thus the contacts were able to successfully operate with 1.92 W of power being dissipated across them without contact failure. No experiments were conducted beyond 1.2 A with electromagnetic actuation.

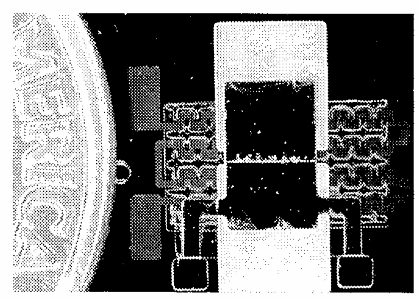

Figure 5: Photomicrograph of a cantilever microrelay shown next to a dime. This type of relay has been able to switch 1.2A by means of electromagnetic actuation of the upper plate using the integrated electromagnet.

A long-term reliability test of the microrelay was performed using a computer-controlled actuation and measurement setup. The current passed through the microrelay contacts during these tests was supplied by a digital multimeter, and was approximately 2.5 mA. The devices tested have shown that operation lifetimes in excess of 311,000 cycles are possible. Tests beyond 310,000+ cycles were not performed, and the termination after 310,000+ cycles was arbitrary, not due to any changes in device performance. Figure 6 shows lifetime test results for a cantilever-type device. The device was tested in an unpackaged state and not protected from dust or other disturbances in the surrounding air.

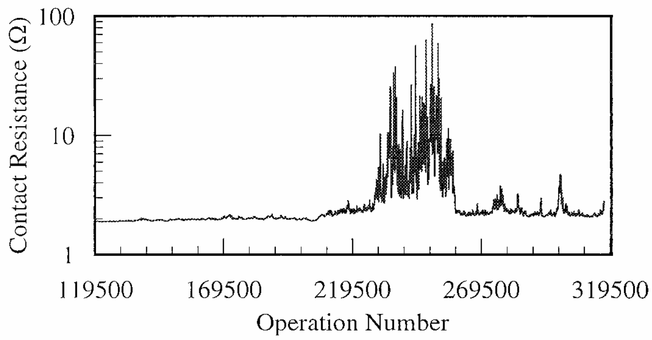

Figure 6: Lifetime results for one pair of contacts of the DPST relay reported here. The device was operated in the normally-open configuration.

Actuation times of the microrelays were typically in the range of 1 to 2.5 msec, with values as large as 5 msec being observed for some of the microrelays. Typical release times were measured to be 2.5 msec.

Testing of the microrelay contacts for their ultimate limits was also performed. The contacts when closed mechanically (non-switching) had a contact resistance of 0.017 Ω and could carry 4.5 A of current for several minutes before failure occurred, and 3 A of current repeatedly without failure.

The Form B (normally closed) microrelay has been tested and shows somewhat higher electromagnetic actuation currents, possibly due to non-optimal magnet placement, and slightly different gap thickness due to fabrication. The permanent magnet is not integrated and thus the placement of the magnet has a large influence on device performance. The contact resistance with no current through the coil (normally closed contact) averaged less than 10 Ω. The contact resistance with actuation current was infinite, as desired. Form B microrelays have been electromagnetically switched over 600 consecutive trials to demonstrate operation. Figure 7 displays the "on" contact resistance over the 600 trials. The "off" state contact resistance was greater then 10^{10} Ω. The contact metallurgy is the same as that used for the Form A devices.

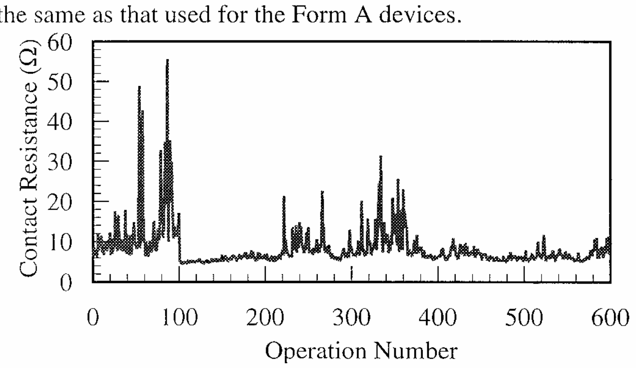

Figure 7: Contact Resistance of a Form B, normally closed microrelay when the coil is in the "off" state. When the coil is "on", the contact resistance was measured to be infinite, or larger than 10^{10} Ω.

Multi-pole microrelays, specifically double-pole devices, were successfully fabricated and tested. These devices had comparable performance to those microrelays described above and were fabricated in the same manner. Both poles operated in the normally-open manner, and were not tested for normally closed behavior.

CONCLUSIONS

Fully integrated magnetically actuated micromachined relays have been realized. Normally-open, normally-closed, and multi-pole microrelays have all been realized through the use of the planar coil electromagnet design. Microrelays have been fabricated which can switch up to 1.2 A electromagnetically without device failure. Lifetime testing of the microrelays has shown devices remain operational after 300,000 operations. Through minimization of the coil design, the power required for switching has been reduced to 33 mW.

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REFERENCES

[1] K. E. Petersen, "Membrane Switches on Silicon," *IBM J. Res. Develop.*, vol. 23, 376-385 (1979).

[2] M. A. Gretillat, P. Thieubaud, N. F. de Rooij, and C. Linder, "Electrostatic Polysilicon Microrelays Integrated with MOSFETs," *Proc. IEEE Microelectromechanical Sys. Conference*, Oiso, Japan, pp. 97-101 (1994).

[3] M. A. Gretillat, P. Thieubaud, C. Linder, and N. F. de Rooij, *J. Micromech. Microeng.*, vol. 5, pp. 156-160 (1995).

[4] S. Roy and M. Mehregany, *Proc. IEEE Microelectromechanical Sys. Conference*, Amsterdam, Netherlands, pp. 353-357 (1995).

[5] J. Drake, H. Jerman, B. Lutze, and M. Stuber, *Proc. Transducers '95*, Stockholm, Sweden, vol. 2, pp. 380-383 (1995).

[6] M. Sakata, *Proc. IEEE MEMS Workshop*, Salt Lake City, pp. 149-151 (1989).

[7] J. J. Yao and M. F. Chang, *Proc. Transducers '95*, Stockholm, Sweden, vol. 2, pp. 384-387 (1995).

[8] J. Simon, S. Saffer, and C.J. Kim, "A Micromechanical Relay with a Thermally-Driven Mercury Micro-Drop," *Proc. IEEE Microelectromechanical Sys. Conference*, San Diego, pp. 515-520 (1996).

[9] H. Hosaka, H. Kuwano, and K. Yanagisawa, *Proc. IEEE Microelectromechanical Sys. Conference*, Ft. Lauderdale, pp. 12-17 (1993).

[10] H. Hosaka, H. Kuwano, and K. Yanagisawa, *Sensors and Actuators A (Physical)*, vol. A40, pp. 41-47, (1994).

[11] E. Hashimoto, H. Tanaka, Y. Suzuki, Y. Uenishi, and A. Watabe, "Thermally Controlled Magnetization Actuator (TCMA) using Thermosensitive Magnetic Materials," *Proc. IEEE Microelectromechanical Sys. Conference*, Oiso, Japan, pp. 108-113 (1994).

[12] W. P. Taylor, M. G. Allen and C. R. Dauwalter, "A Fully Integrated Magnetically Actuated Micromachined Relay," *Proc. 1996 Solid State Sensor and Actuator Workshop*, Hilton Head, pp. 231-234 (1996).

[13] A. B. Frazier, C. H. Ahn, and M. G. Allen, *Sensors and Actuators A (Physical)*, vol.A45, pp. 47-55, (1994).