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MEMS microrelays

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Abstract

There has been significant recent interest in applying microelectromechanical (MEMS) technology to miniaturization of relays for a variety of applications in the telecommunications, test equipment, and automotive fields. Mechanical switches with metal-to-metal contact are still preferred where low insertion loss and high off-isolation are required, particularly in cost-sensitive applications. MEMS technology offers great promise in addressing the need for smaller electromechanical relays, and may bridge the performance and economic gaps between conventional electromechanical technology and solid state devices. In this paper we cover some general MEMS approaches to building a microrelay and the challenges and trade-offs involved. We also discuss specific devices we have explored using a new MEMS thermal actuation. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

Mechanical switches based on metal-to-metal contact are useful in a variety of power management, information processing and communication systems because their on resistance is lower than that of semiconductor switches and their off resistance and transmission frequency are higher. Electromechanical relays (EMRS) make use of such switches and can be found in all manner of electric devices ranging from toys to automobiles, telephone switches to major appliances. A modern automobile is reported to contain as many as 150 electromechanical relays to manage such functions as drive-train control and accessories. In the age of solid state electronics, electromechanical relays may appear to be an anachronism, but it has proven difficult and costly to duplicate the electrical performance of an EMR in solid state devices. Thus

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EMRS continue to be the device of choice in applications requiring less than an ohm of on-resistance, high off-isolation, high current capacity, and low power consumption at modest cost.

Solid-state relay (SSR) devices based on coupling a phototransistor with an LED have made inroads in specific switching applications requiring extreme reliability and/or miniaturization. Typical commercial SSRs can match EMRs with respect to isolation, providing more than 1500 V breakdown strength between load and control circuits. However, SSR falls short in insertion loss and current capacity when compared to an equivalent size EMR. Moreover, the cost of SSR devices is more than three times that of similar EMRs. This drives a significant commercial need for a device which bridges the technical and economic gaps between EMR and SSR devices, particularly to address the need for extreme miniaturization while preserving EMR benefits. This need has motivated a number of groups [1, 2] to apply Microelectromechanical (MEMS) technology in making smaller and more capable microrelays.

2. Application of MEMS

MEMS fabrication allows the coupling of mechanical and electronic functionality in a single micro-scale device. Borrowing from integrated circuit manufacturing, MEMS processes are typically performed on silicon wafers using batch processing techniques. This permits economies of scale, precision, and device matching capabilities that are unparalleled in conventional assembly-based manufacturing. In many respects MEMS technology is ideally suited to miniaturization of a relay. The mechanical functionality required, i.e., closure of a switch contact, is well defined and relatively simple, while the electronic aspects are similarly straightforward, even trivial by IC standards. Combining these functionalities ought not to be a complex merger. However, several important challenges must be met at the outset to design a device suitable for the real world.

First, a MEMS relay having performance capabilities on par with even a low-end EMR must have switch gaps capable of withstanding reasonable load voltages. Conventional EMRs with switching gaps greater than about 250 μm will safely withstand thousands of volts. This presents the first contradiction encountered in using MEMS for making switches: on a MEMS scale, the entire device, let alone the switch gap, may only be a few hundred microns in size. The first compromise that must be made, therefore, is in open-contact withstanding voltage. For realistic MEMS actuators, a switch gap of 10–20 μm (air) can be achieved, providing a withstanding voltage up to about 400 V [3].

A second major challenge in making a MEMS relay lies in achieving sufficient contact force to obtain low and stable contact resistance. Here again, conventional EMRs employ relatively large magnetic coils that generate tens of millinewtons of force on contact closure, thus insuring stable metal-to-metal contact. This magnitude of force is not readily available in the MEMS world, where typical actuators produce forces ranging from a few millinewtons up to a few millinewtons over a range of a few microns. Fortunately, with proper selection of contact metallurgy, good contact closure can be obtained with as low as 1 millinewton [4], and provide contact resistance in the range of one hundred milliOhms. This is higher than conventional EMRs by a factor of 2–3, but much better than typical miniature SSR devices that may impose several tens of ohms of on-resistance.

Another hurdle for a MEMS relay is the need to carry reasonably large currents, of the order of a few hundred milliamps up to 1 amp. For many switching applications, it is the ability to handle large current that drives the use of a relay in the first place. As an extreme example, the starter motor on an automobile must draw current through a relay driven by the ignition switch, rather than the switch itself, which would otherwise melt. On the MEMS scale, conductors and contacts fabricated with silicon IC processing may be smaller in cross-sectional area than 50-gauge wire, imposing severe limits on current carrying capacity and contributing extra series resistance in the device. New processing techniques such as wafer-level electroplating must be combined with silicon processing to achieve practical current capacity. A related limitation is the ability to withstand current surge effects. Owing to their larger mass, conventional EMRs can sustain several times their rated load current for short durations without damage. A MEMS relay might be destroyed by very brief overcurrent conditions due to its small thermal mass.

In spite of these challenges, a number of groups have aggressively pursued MEMS technology for producing commercially viable microrelays. Several groups have demonstrated experimental MEMS relays capable of switching modest electric loads. Initial applications are envisioned in automated test equipment (ATE), telecommunications, and automotive markets for switching relatively small loads (< 1 amp). In ATE and telecommunications, the small size of the relay and the ability to integrate multiple relays in a single package will provide value to the end user [5]. For example, a microrelay may be small enough to place right on the ATE probe card rather than in the tester main frame. This will drastically reduce probe lead lengths and significantly improve tester performance. In the cost-sensitive automotive market, MEMS microrelays may represent a lower cost alternative to conventional EMRs for specific low-current, high-isolation applications.

We report here on our recent efforts to produce a MEMS microrelay and initial performance characteristic we have measured. Over the past year, the MEMS Technology Applications Center at MCNC has undertaken a project to merge a proprietary thermal actuator technology with nickel surface micromachining techniques to produce a series of functional microrelay prototypes. Aspects of device design, modeling, fabrication, and testing are discussed, along with prospects for applying these devices in specific commercial applications.

3. MEMS actuators for microrelays

At the heart of any mechanical relay lies the actuator used to close (or open) the switch contacts. Conventional EMRs use a magnetic field set up by passing current through coil windings. Magnetic actuators are well suited to contact actuation by virtue of their nonlinear force vs displacement characteristics. Force increases exponentially as the contacts close, resulting in low and stable contact resistance. Since there is no lag between current and magnetic flux in a coil, magnetic actuation provides relatively fast switching speeds. Switch closure in the range of a few ms is typical in an EMR, with sub-millisecond closure available in small reed relays. Magnetic devices also produce hysteresis in operation which yields the desirable side effect of keeping the contacts closed until the coil current drops to a small fraction of its operating level. This is beneficial in stabilizing the device against minor variations in drive current.

The force produced by a magnetic actuator depends on the magnetic flux, hence the number of coil turns, amount of current, and flux concentration via ferromagnetic core materials. The three-dimensional nature of a magnetic coil is not well suited to MEMS fabrication, which is an inherently planar technique. Most problematic is the definition of coil windings. The lithographic methods used in MEMS to define conductor patterns work best when confined to a single plane. Combining successive planes to form even a primitive coil requires complex processing. Several groups have succeeded in producing electromagnetic MEMS relays [6–8]. Some of these devices have demonstrated very impressive performance with respect to speed and current carrying capacity, but the outlook for commercial success is uncertain due to their high manufacturing complexity and relatively large size compared with other MEMS approaches. For this reason, most commercially promising microrelay technologies are focused on non-magnetic actuation principles, mainly electrostatic or electrothermal effects.

Electrostatic actuation is perhaps the simplest means to envision a MEMS microrelay. In essence, two insulated conductive plates separated by a small air gap can be brought into contact by placing a sufficient voltage across the two plates. Arranging suitable conductors and contacts on the moving actuator parts allows electrostatic control of contact closure, hence relay action. The force generated by the electrostatic field must overcome the mechanical resistance of the plates in order to cause contact closure. The electrostatic force varies as the square of the electric field generated in the actuator, and the operating voltage increases linearly with the separation distance. Consequently, achieving large switch gaps requires application of large voltages to provide sufficient pull-in force for initiating contact closure. The main difficulties in designing an electrostatically actuated relay is achieving reasonable contact gaps (at least 10 μm, as noted above) while keeping the actuation voltage in a realistic range, i.e., less than 50 volts or so; and electrically isolating the drive circuit from the load circuit. The voltage/gap tradeoff has provided the impetus for a number of creative designs that make use of zipping or curling electrodes to initiate actuation with small drive voltages. Various groups [9, 10] have reported microrelays that make use of a curved silicon beam, the tip of which is initially deflected away from the contact due to residual stress in the beam. Electrostatic force overcomes this stress to close the contacts. In this manner, a switch gap of 10 μm can be closed with as little as 15 V.

Electrostatic actuator designs relying on controlled residual stress in beam members could prove difficult to manufacture due to the variable nature of thin film deposition parameters and their effect on internal stress. Commercially viable relays based on electrostatic actuation await resolution of these difficulties. Another drawback of electrostatic design lies in the fact that the load conductors must be quite thin, less than a micron or so, which may impose limits on current capacity and introduces series resistance in the device. Nevertheless, the high speed of operation, low power consumption, and small size of electrostatic switches makes them very attractive as a MEMS microrelay solution, particularly for low-current ATE applications.

A third approach to MEMS relay actuation relies on thermomechanical actuation to close a switch contact, usually by raising the temperature on a local scale. Such thermal actuation is well suited to the MEMS world because the small size of the moving structures requires relatively little power to heat on a local scale, and will heat and cool much more rapidly than macroscale structures. A variety of materials and geometries can be combined to produce useful bimorphic and monomorphic thermal actuators with bending modes that are either parallel or perpendicular to the substrate plane. Thermal actuation is reported to produce a theoretical work density of 4.6×10^5 J/m^3 [11], the highest of the three principal MEMS actuation methods, i.e., electromagnetic, electrostatic and electrothermal. This implies that, barring any unusual scaling effects, thermal actuation should be at least as capable as electromagnetic actuation in providing sufficient contact force in a relay application.

4. The MCNC microrelay

The MCNC microrelay is based on such a thermal actuator and is a product of a design originally developed at MCNC [12] for producing a MEMS in-package single-mode fiberoptic aligner [13]. Typical designs are fabricated in nickel using a process termed ‘nickel surface micromachining’, in which high aspect ratio structures are fabricated by electroplating nickel into lithographically-defined plating stencils. The lithographic approach permits nickel heights of tens of microns with widths as small as 5 μm. Structures formed with this approach also have nearly vertical sidewalls, hence high aspect ratio. This feature is crucial in constraining the allowed bending modes of the moving members. The two-dimensional nature of the plate-up process limits the mechanical design to one in which element motion occurs through bending about fixed points, or anchors, rather than by rotation around an axle or hinge. Thus, designs built with nickel surface micromachining are generally confined to a horizontal plane of motion and utilize members designed to bend elastically in-plane, but which are very stiff out-of-plane.

A major benefit of using in-plane mechanical actuation draws from the ability to co-fabricate a variety of metal structures at the same time, using a single lithographic step. For example, in patterning the relay, the actuator, contacts, conductor paths, and support structure are all defined in a single step. This parallel technique greatly simplifies relay integration, avoiding microscale assembly and all its complications. The penalty for this is the requirement to design all of the major relay components in a manner that they can co-exist in a single lithographic layout that can then be fabricated in a single plating process. Also, the use of elastic members means that a significant portion of the power budget must be diverted into material deflections rather than strictly into contact closure.

This is the approach taken for the MCNC microrelay. Figure 1 shows a finite element simulation for a series of actuators fabricated by this method. The geometry of the actuator can be scaled to produce a variety of force vs deflection characteristics. The actuators shown in Fig. 1 are 1.5 mm long by 0.5 mm wide. This size may be varied to obtain even greater range of deflection or force. A typical actuator design occupies 1 mm^2 and provides more than 10 mN force output with 300 mW of power output.

A process was developed to integrate this thermal actuator with microheaters and switching structures to form a complete microrelay on a chip. This prototype MEMS relay was targeted to meet a performance specification typical of a commercial PC-mount mini relay with a contact rating of one amp. Designs having switch gaps up to 25 μm were fabricated. Switch contacts are overplated with either rhodium or gold to achieve low contact resistance and acceptable lifetime. Prototype devices have demonstrated hotswitch capacity of more than one amp, voltage standoff up to 400 V, off isolation more than 10^{12} Ω, electrical lifetimes of $>10^6$ cycles and operation with as little as 6V with no contact bounce. A pair of form-A (SPST) relays with associated actuators and bond pads fits on a single 3 mm × 3 mm die. Figure 2 depicts a pair of packaged microrelay devices in a 10-pin SOIC package. Performance characteristics of this first-generation device are summarized in Table 1. Some of these performance attributes are discussed in detail below.

4.1. *Switching action*

The simplest action to achieve in a MEMS relay is the 'normally open' mode which closes the load circuit when the device is energized and opens when it is released.

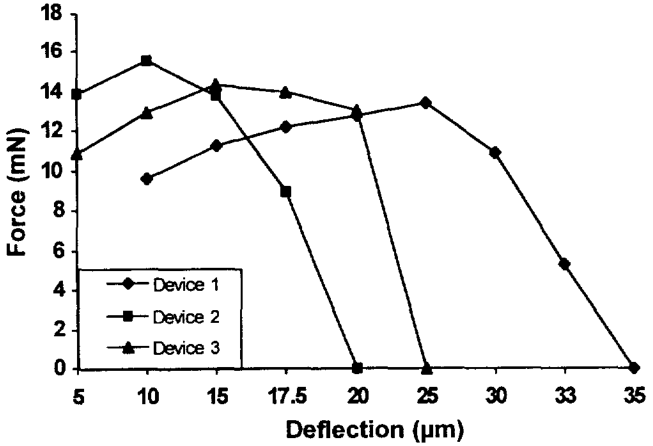

Fig. 1. Actuator force vs deflection for three thermal actuator designs.

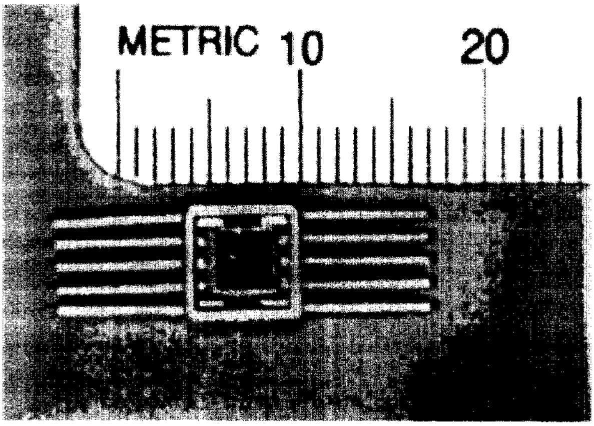

Fig. 2. Packaged pair of microrelays.

Table 1.
Prototype microrelay performance

Switching action	Monostable and latching
Dielectric breakdown	400 VDC
Actuator power	$\leqslant 300$ mW
Actuator voltage	6–9 V
Maximum current (hot switch)	1.0 A
Contact resistance	< 200 mΩ
Switching time	< 10 ms
Device footprint (1 switch)	1.0 mm^2
Lifetime (mechanical)	$> 10^7$ cycles
Lifetime (electrical)	$> 10^6$ cycles

Most of the prototype designs were of this variety. However, another useful variant is the 'latching' type that remains closed until reset by an auxiliary signal. This style is particularly useful in low duty-cycle switching, and especially where power consumption is an issue. In a MEMS relay this can be accomplished by inclusion of a mechanical latch that keeps the switch closed with no power applied. In this design, the switch locks in the closed position. A second actuator can then be used to reset the latch and open the switch. Several latching designs were evaluated and have shown promising results. Figure 3 shows a switch latched in the closed state for one of the early designs. The most challenging aspect of these devices is obtaining reliable mechanical latch operation, which must be addressed through improved designs.

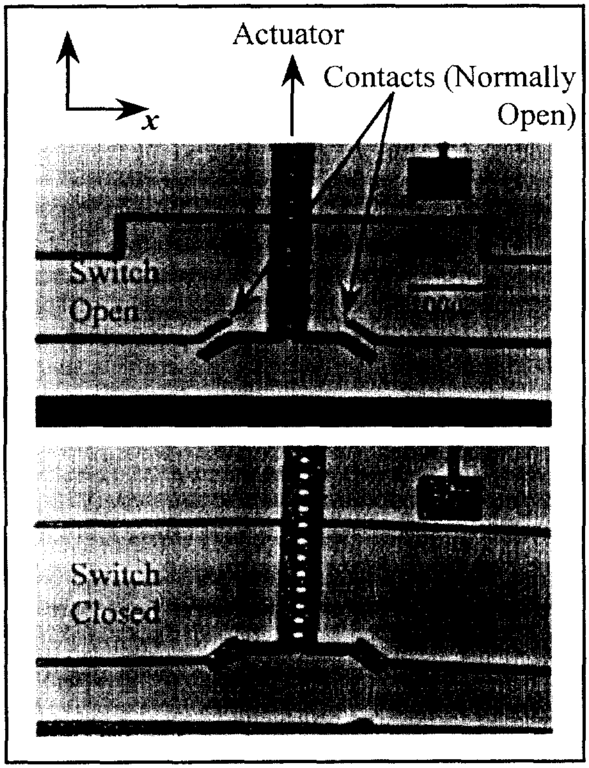

Fig. 3. Latched microrelay in open and closed positions.

4.2. Dielectric breakdown

This was determined for open contacts by placing a steadily increasing D.C. voltage across the load inputs until arcing was noted. The voltage at which failure occurred varied from as low as 400 V to as high as 650 V. As expected, this type of failure results in complete devastation of the switch contacts and surrounding materials. Figure 4 shows a typical failure observed for a switch subjected to 600 V. Failure sometimes occurred between adjacent conductor paths rather than at the switch itself. In general, failure behaves along the lines of data reported by Schimkat [ibid], i.e., observed behavior is consistent with the size of the air gaps evaluated. Breakdown of the dielectric layer isolating the load and drive signal was not measured, but is expected to be much higher due to the thickness and dielectric properties of the material used.

4.3. Current capacity

Progressively higher resistive loads were placed through the closed contacts to determine their current capacity and failure mode. Figure 5 shows a typical failure.

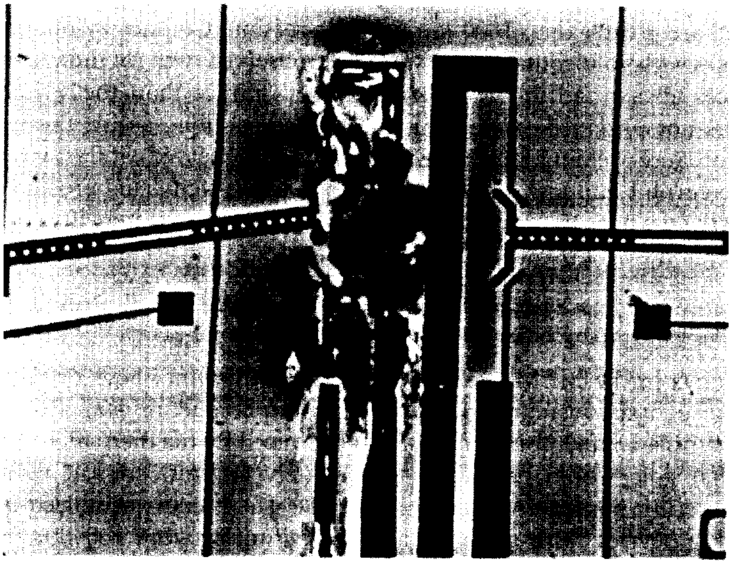

Fig. 4. A microrelay subjected to 600 V d.c.

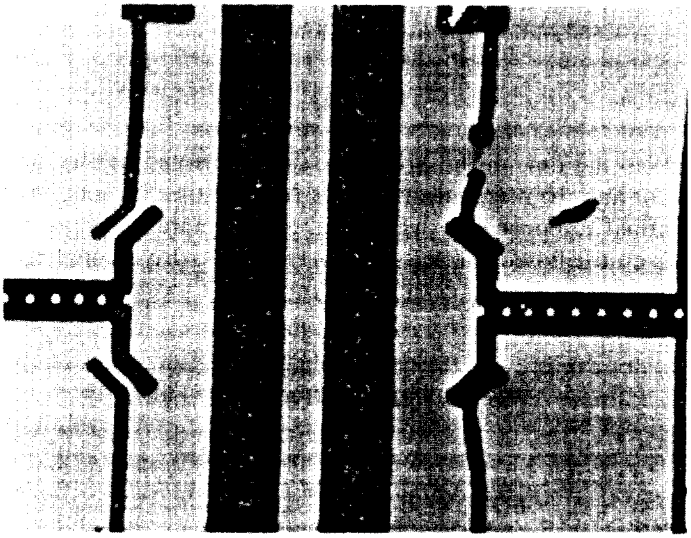

Fig. 5. Right microrelay driven to failure by application of 0.7A.

Two modes are generally observed: conductor fusing, and contact welding. Melting of the conductors leading into the switch, and the switch itself, occurs when the current density exceeds the material limits, which was observed to be approximately $1 \mathrm{mA}/\mu\mathrm{m}^2$ for electroplated nickel. A one amp microrelay therefore requires conductor paths which are greater than 1000 μm^2 in cross-section. Contact welding occurred in some samples with gold contacts, but was never observed with rhodium contacts. The latter devices always fail in the bulk conductors rather than the switch. Contact sticking was not observed, even for gold contacts, as long as the current was not sufficient to cause welding. Arcing was sometimes observed while switching loads near device current limits, but did not appear to cause significant erosion of contact material. Arcing would be expected to be a greater concern for inductive or capacitive loads, which were not evaluated.

4.4. Contact resistance

The contacts in the MEMS relay were coated with either gold or rhodium. Uncoated nickel contacts were found to give very poor contact resistance due to surface oxidation. With a contact force of 1–10 mN produced by the thermal actuator, it was expected that gold would produce approximately 100 mΩ contact resistance and rhodium would be somewhat higher at 400 mΩ. This trend was indeed observed in the prototype devices, with gold contacts measuring between 100–200 mΩ contact resistance, and rhodium giving 500–700 mΩ. In packaged devices, the bond pads, wirebonds and package leads contributed another 100 mΩ of series resistance; thus, the best gold contact devices yielded a minimum resistance in the range of 300–400 mΩ at 10 mA. This is demonstrated in Fig. 6, which shows cyclic operation of two similar devices at 1 Hz and 10 mA load current.

4.5. Switching time

The contact closing time in the MEMS relay is governed by the time required to heat the actuator and the mechanical response time of the contacts. In the prototype device, the thermal response time was found to dominate the total switching time. Figure 6 shows an oscilloscope trace superimposing the drive signal and load signal, and indicates the lag in contact closing and opening. Typical devices required more

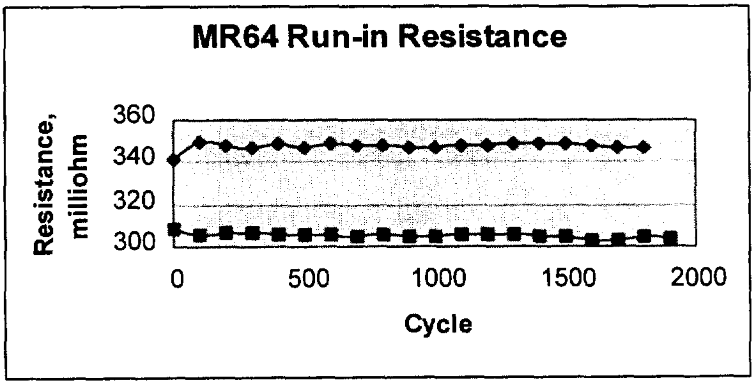

Fig. 6. Cyclic operation of two relays on a single device at 10 mA load current.

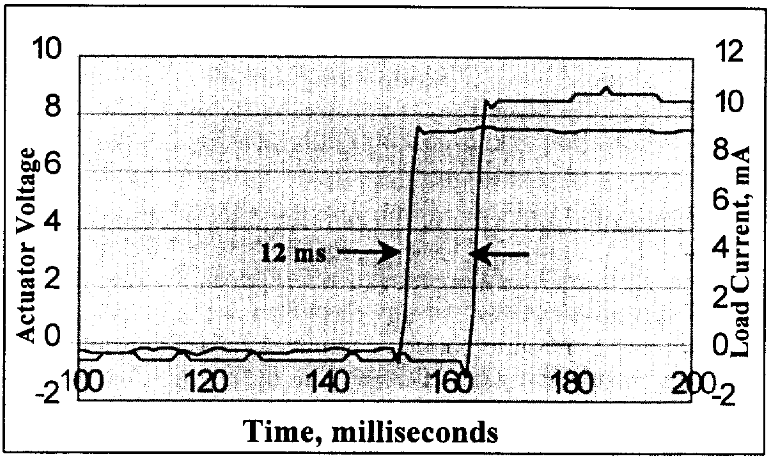

Fig. 7. Oscilloscope trace of superimposed drive voltage and load current for a 1 mm^2 microrelay.

time for closing than for opening. This is due to the need for less motion, hence less cooling, of the actuator upon opening the contact. The best of the prototype designs yielded closing and opening times of 11 ms and 12 ms, respectively. This is comparable to switching speeds of conventional EMRs and photoMOS SSR devices. No contact bounce could be observed on the time scale used. It is expected that reducing actuator size and thus thermal mass can produce significant gains in switching speed in future devices. This will require that smaller switchgaps be used, with some trade-off in open circuit isolation.

4.6. Device reliability

Relay actuators were cycled at 10 Hz for more than 10 million cycles with no apparent damage or fatigue. Since design limits were far below the yield stress for nickel, and there is no friction involved in actuator action, this result is not unexpected. Within the elastic limits of the material there appears to be no fundamental issue with device longevity. Of greater concern is the electrical lifetime of the device, which relies on both mechanical durability of the actuator and the electromechanical durability of the contacts. Initial samples had a very thin gold coating on the contacts (<0.2 μm) and showed electrical failure after hot-switching a 10 mA load for 10^5 cycles. In this sample, there was no evidence of mechanical failure of the switch, which would still close properly, but had very high contact resistance. It was therefore concluded that erosion of the gold layer caused device failure. Subsequent samples which had either much thicker gold coating (>2 μm) or rhodium on the contacts exhibited no failure after 2×10^6 cycles. This level of durability is comparable to quoted specifications for conventional EMR devices. Further investigation is required to understand how electrical durability depends on the type and magnitude of load carried by the device. For example, an inductive type of load can produce arcing which may drastically impact contact lifetime.

5. Conclusions

MEMS technology has proven a fertile area for driving extreme miniaturization of electronic relays. A number of basic approaches which employ electromagnetic, electrostatic, and electrothermal actuation are being pursued with a goal of producing smaller more capable electromechanical relays that are cost competitive to conventional EMRs and solid state devices. The batch fabrication techniques used in MEMS will allow economical production of thousands of matched relays on a single silicon wafer, and the integration of many relays on a single chip. Significant challenges still remain for refining production processes and finding cost-effective packaging techniques.

A prototype MEMS microrelay constructed by combining a thermal actuator with gold and rhodium coated contacts has been demonstrated. This device shows performance characteristics that approach objectives for a commercially viable product. Current capacity, power consumption, contact resistance, isolation, speed, and size are all on target for a first generation device. Contact withstanding voltage of 400 V is lower than conventional devices but will be useful nevertheless in certain applications such as for ATE. Obtaining higher withstanding voltage will require designs that have switch gaps larger than about 100 μm.

Monostable and latching devices with normally open contacts were demonstrated. Latching designs require more robust latching mechanisms for reliable operation, and we intend to pursue this in upcoming prototype runs. Latching capability is a key distinction between the in-plane actuation design and other out-of-plane designs driven by electrostatic or electromagnetic actuators, which are inherently difficult to latch in a particular state. This also represents a significant advantage over solid state relays, which cannot provide true bi-stable operation. Latching designs are expected to be useful in power-sensitive switching applications such as in wireless or portable devices.

Switching speed in the thermal device is comparable with conventional EMRs and small SSRs, but not competitive with very fast reed relays, which have sub-ms closing times. Scaling of the thermal device will make it possible to achieve 0.5–1 ms switching time, necessary for high duty cycle test equipment applications.

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