RedRock™

MEMS-Based Magnetic Reed Switch Technology

A White Paper by Coto Technology
on Emerging Reed Switch Technologies

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Abstract

Coto Technology, a leader in the design and development of small signal switching solutions, has introduced a new MicroElectroMechanical Systems (MEMS) magnetically operated switch named "RedRock™." This new switch merges the best features of conventional reed switches – including zero power operation and high power hot switching capability – with the inherent benefits associated with MEMS processing. These benefits include the economy of scale and item-to-item reproducibility that are achievable using lithographic semiconductor fabrication methods.

The RedRock MEMS switch represents the first use of High Aspect Ratio Microfabrication (HARM) to produce a commercially available switch. HARM produces switch structures that generate contact closure forces many times greater than those exhibited by previous MEMS-based magnetic switches, enabling hot switching up to several hundred milliwatts. Furthermore, the high retract forces developed in the switch when it opens alleviates any tendency for the switch to stick shut during hot switching or after long closure periods, a problem that plagued earlier MEMS switch designs. Wafer scale packaging results in a surface mount compatible switch with a footprint of only 2.4mm^2 and a height of 0.95mm, permitting cost effective use in size-limited applications.

This new MEMS-based magnetic switch is an ideal solution for demanding applications in medical devices such as ingestible capsule endoscopes, insulin pumps, and hearing aids. In these applications, the need for small size, zero power operation, a low parts count, and minimal circuit complexity favor passive switches such as magnetic reeds over active magnetic switches such as GMR or Hall devices. However, conventional reed switches are often simply too big for such applications. Other uses for the RedRock switch include high precision level and position sensing, and incorporation into extremely small reed relays with integrated coils developed using the same HARM technology.

The operating theory, operating characteristics, and specifications of the RedRock switch are compared and contrasted with other popular magnetic switching technologies including planar MEMS switches, Hall Effect, Giant Magnetoresistive (GMR), Anisotropic Magnetoresistive (AMR) and conventional reed switches. Experimental measurements of magnetic sensitivity and directionality are included, as well as references to prior patents and peer reviewed work regarding MEMS switch development.

> “*There is very strong demand for a reed switch that is much smaller than existing types but can still handle similar electrical switching power.*”

Introduction

The reed switch has been a widely used switching technology since its invention 70 years ago by scientists at Bell Labs, who were looking for an improvement to the clunky electromechanical relays then used in telephone exchanges.[1] However, in those 70 years its design has scarcely changed, at least until now. Traditional reed switches still consist of two springy ferrous metal blades sealed in a glass tube, with a small gap between their tips. (Figure 1) Bring a permanent magnet or a current-carrying coil of wire close by, and the blades become magnetized and attracted to each other, completing an electric circuit between the two blades. Despite their simplicity, reed switches have many advantages; they are robust and can switch high power for their size; they are hermetically sealed so that the contacts are protected from contamination, unlike an electromechanical armature relay; and they are not prone to damage from electrostatic discharge, unlike some solid state switches. Billions of reed switches and reed relays have been used in systems as diverse as automated test equipment (ATE), motor vehicles, washing machines, interplanetary probes, hearing aids, and laptop computers.

Fig.1 | Reed Switches from 1940 to 2013

However, reed switches have a couple of disadvantages. They are relatively expensive to make, and they can't shrink any further. In 1940 they were 50mm long – now they are down to about 5mm long, much smaller, but too big for many emerging applications. But now, microfabrication is about to revolutionize the way reed switches are made. Since the advent of smart phones, tablet computers and an abundance of other personal, portable electronic devices, electronic components have had to shrink to enable and test such technologies. Reed switches are no exception. As a result, there is very strong demand for a magnetically operated reed switch that is much smaller than existing types, that can handle similar electrical switching power, and that can be attached to a circuit board by surface mounting. Surface mount technology (SMT) components have displaced through-hole parts because of their higher packing density and ability to be mounted using automated pick-and-place machinery, and conventional reed switches have just not kept up with changing times. This White Paper describes a new kind of reed switch developed by Coto Technology that fills this void. In this white paper we distinguish the term "reed switch" from "reed relay." A reed switch is a standalone device that can be operated by a magnet, a current-carrying coil, or a combination of both. A reed relay combines a reed switch and a coil into one component. [2]

> *For the first time since the invention of the reed switch 70 years ago, this new switch is made a completely different way.*

RedRock™, a New Kind of Reed Switch

The new Coto RedRock switch is based on microlithography. All the elements and advantages of a reed switch are there, including metal blades that snap together in the presence of a magnetic field and complete an electric circuit, and hermetic sealing of the ruthenium-coated contacts. However, for the first time since the invention of the reed switch, the new switch is made a completely different way. Gone are the stamped nickel-iron blades and the sealed glass tube. In their place is a metal cantilever that bridges two massive electrically isolated metal blocks that act as magnetic field amplifiers, much like the external leads in a conventional reed switch. (Figure 2) There is a small gap between the cantilever and one of the blocks – magnetic flux from an external magnet builds up in the gap and pulls the cantilever into electrical contact with the block. The contacts are coated with Ruthenium for maximum contact longevity.

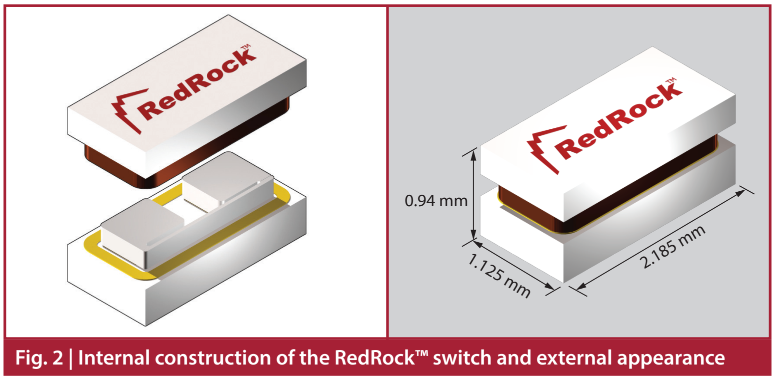


Fig. 2 | Internal construction of the RedRock™ switch and external appearance

The key to the construction of the new switch is the way that the reed switch blade is grown upwards from the ceramic base of the switch using a lithographically produced sacrificial mold. The precise dimensions of this mold and its extremely parallel walls ensure that the thickness of the reed switch blade and the contact gap are controlled to a fraction of a micrometer. Figure 3 illustrates a typical HARM microfabricated structure. This is much greater precision than can be achieved during the blade stamping and glass sealing processes of a conventional reed switch. In turn, this precise dimensional control results in far higher reproducibility of the switch closure sensitivity between different switches. This type of fabrication is termed "high aspect ratio microfabrication," or HARM, and it is the way the switch structure is grown vertically with respect to the switch substrate that distinguishes this new technology from planar MEMS switches. To explain this differentiation requires a brief discussion of MEMS, or MicroElectroMechanical Systems devices.

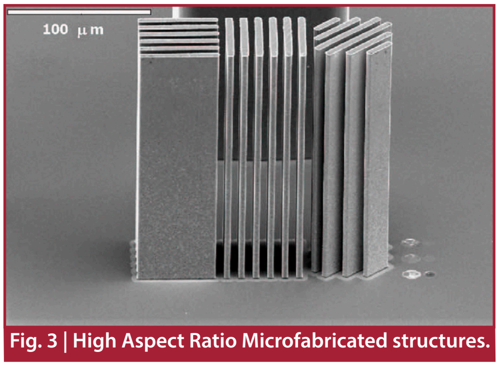


Fig. 3 | High Aspect Ratio Microfabricated structures.

Reed Switch Design Basics

Let's look at some background on reed switch design to illustrate why HARM is an excellent approach for building a magnetically operated reed switch. All reed switches have either one or two flexible metal blades that when magnetized are attracted together, completing an electrical circuit. Apply a stronger magnetic field and the blades become attracted more strongly together if, (and this is a BIG if) the blades don't become saturated with so much magnetic flux that they can't carry any more. When that happens, no more force is applied to the contacts, no matter how strong a magnetic field is applied. And as we will show, the contact force in a reed switch depends strongly on the flux that reaches the gap between the contacts. Here's an analogy; reed switch blades are to magnetic flux as water pipes are to water – throttle down the flow by using too narrow a pipe, and no matter how much pressure (magnetic force) you apply, water (flux) will just trickle out slowly. So you want to have reed switch blades with as large a cross-sectional area as possible to let lots of that flux through and get the highest possible contact force. But don't make them TOO thick, or like a badly designed diving board, they will get too stiff for the available magnetic force to bend them.. The trick is to get the cross-sectional area as big as possible by widening the blades, not making them thicker. A wide blade is just as flexible as a narrow blade, provided its thickness is the same. Its spring constant simply increases in direct proportion to its width. (Refer to any elementary Physics textbook that covers beam mechanics if you want reassurance.)

> *Reed switch blades are to magnetic flux as water pipes are to water – throttle down the flow by using too narrow a pipe, and no matter how much pressure (magnetic force) you apply, water (flux) will just trickle out slowly. So reed switch blades with as large a cross-sectional area are needed to let lots of that flux through and get the highest possible contact force.*

High Aspect Ratio Microfabrication (HARM) Compared to Planar MEMS

Making a reed switch the planar MEMS way

First, consider how a reed switch blade is made in the planar MEMS process. Figure 4 illustrates the typical construction of a planar MEMS magnetic switch. [3]

The blade is electroplated on top of a base substrate, and then a sacrificial layer under most of the blade is etched away, freeing up the blade so it can bend. But making thin, wide blades the planar MEMS way by conventional electroplating is difficult, for several reasons. As Rebeiz [4] points out, an unavoidable product of thin-film deposition is the presence of a stress gradient in the normal direction of cantilever beams. In layperson terms, it means it's difficult to get adequate blade thickness before plating stresses start to build up and cause the growing blade to start curling up or down. That results in switches that are too insensitive (curled up), or shorted out (curled down). Second, it's very difficult to get good control of the contact gap width, resulting in a very wide spread of magnetic closure sensitivity. So the plating has to stop before the blades are thick enough to carry a lot of magnetic flux. And of course, if you try to maximize the cross sectional area of the blades by plating them wider, it increases the footprint of the switch, defeating the point of trying to build as small a switch as possible. This is important, for in our experience most switch users are much more concerned about footprint of the switch (PCB "real estate") than they are about its height.

A better alternative – making a MEMS reed switch the HARM way

In HARM, the blades are grown by electroplating, but they are grown edge-on, and vertically relative to the switch substrate. Christenson [5] discusses the HARM microfabrication process in detail. (Figure 5) That way, we can make them as high (wide) as we want without increasing the footprint of the switch. And thanks to the characteristic of the HARM process, the sides of the blade are almost perfectly parallel, deviating by only about 100 ppm in width compared to height. To put that in perspective, it's equivalent to one inch between the ground floor of the Empire State Building and the roof. That is desirable because we want the contacts closing flat together, not just touching at an edge. Contacts that close flat together lead to

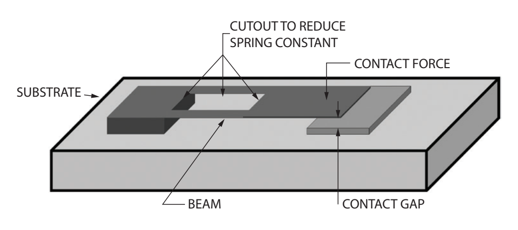


Fig. 4 | Typical planar MEMS construction. Reed cantilever beam is plated parallel to the substrate, and moves in the vertical plane

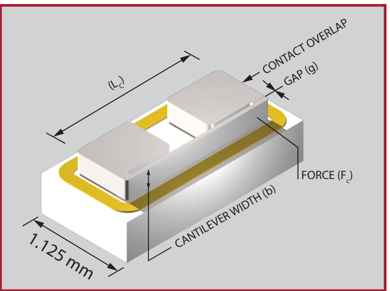


Fig. 5 | Single cantilever microfabricated HARM reed switch. Cantilever beam is grown upwards from substrate, and moves in the horizontal plane

low contact resistance and long life. HARM also gives us extremely good control of the blade thickness and the size of the contact gap, both of which affect the mean closure sensitivity of the manufactured switches. Recall that the spring constant of a cantilever beam varies as the cube of its thickness but only as the first power of its width. This means tight control of the beam thickness is needed to produce a narrow spread of switch closure sensitivities. The benefit is less sorting and binning at the end of the production line and therefore lower manufacturing costs.

So with HARM, we make the blades wider without increasing the "footprint" of the switch, by growing the blades upwards rather than parallel to the base substrate. There is very little plating stress because stresses on the edges (top and bottom sides) of the blades cancel out. (If this terminology of "up", "down", "top" and "bottom" is confusing, refer back to Figures 4 and 5, which illustrate the difference between the HARM and planar MEMS manufacturing process.)

The electromagnetic rules that define the performance of all types of reed switches are covered in detail in Appendix I. The relationship between reed switch blade spring forces, magnetic closure forces and the effect of the forces on magnetic sensitivity and contact resistance parameters are universal. They apply whether the switches are built with HARM, planar microfabrication, or conventional reed switch manufacturing processes.

Summary of Comparative Performance

	RedRock (HARM)	**Planar MEMS switch**	**Comments**
Contact Metal	Ruthenium (MP 2583K)	Rhodium (MP 2233K)	
Switch Dimensions (mm)	2.2 * 1.1 * 0.9	4.8 * 2.1 *1.4	Footprint, as packaged
Blade Dimensions (µm)			
Length	1500	550	
Width	200	100	
Thickness	25	6	
Contact gap	4	4	
Blade spring constant (N/m)	23	5.3	
Contact Forces (µN)			
Closure	400	21	Calculated assuming blades saturate at 1 Tesla
Opening	45	6	
Switching Performance			
Contact Resistance (Ω)	3 – 5	50 - 1000	
Min. melt current (mA)	250	0.7 - 14	Equals maximum carry current
Breakdown voltage (V)	200	75	

Table 1 | Comparative Performance of RedRock vs. Planar MEMS Switch

Refer to APPENDIX 1 for the derivation of the table entries.

Experimental Confirmation of the Predicted Maximum Carry Current

To validate the predicted maximum carry current for the RedRock switch, we soldered a test switch to solder pads at the center of a 2.5cm^2 piece of FR4 circuit board material, glued a small thermocouple to the sidewall of the switch, and measured the equilibrium temperature rise for different carry currents. The static contact resistance of the switch was approximately 5 ohms. The circuit board was suspended in still air at an ambient temperature of 22^{o}C. The results are shown graphically in Figure 6. The equilibrium temperature rise for a carry current of 100mA is seen to be approximately 12^{o}C. The temperature rise followed a power law with an exponent of 1.75 and above 100mA the temperature rose rapidly, as might be expected from simple I^{2}R Joule heating. At 250mA the switch temperature rose about 60^{o}C, and since we were measuring at an outside surface relatively remote from the contact area, the current seems consistent with the theoretical melting current of 160mA. Interestingly, the switch opened after the current was switched off, and no contact welding occurred, despite the fact that we were almost certainly causing spot melting of the ruthenium contacts.

We have therefore rated the maximum carry current for the RedRock switch at 100mA. It is clear from the results shown in Table 1 that the HARM approach to building a magnetically driven MEMS switch offers considerable advantages. Despite having a slightly smaller footprint than the competitive planar MEMS switch, the RedRock switch has over 30 times the closure force and 4 times the retract force of the planar MEMS design. This results in a much lower static contact resistance and the ability to switch and carry much higher currents before failure due to contact melting occurs. And, although our life testing is not yet complete, the higher contact forces promise a much higher contact switching life at intermediate loads. Furthermore, larger retract forces when the magnetic field is relieved suggest that sticking events (where the switch fails to open after a long period of closure) are much less likely with the HARM design.

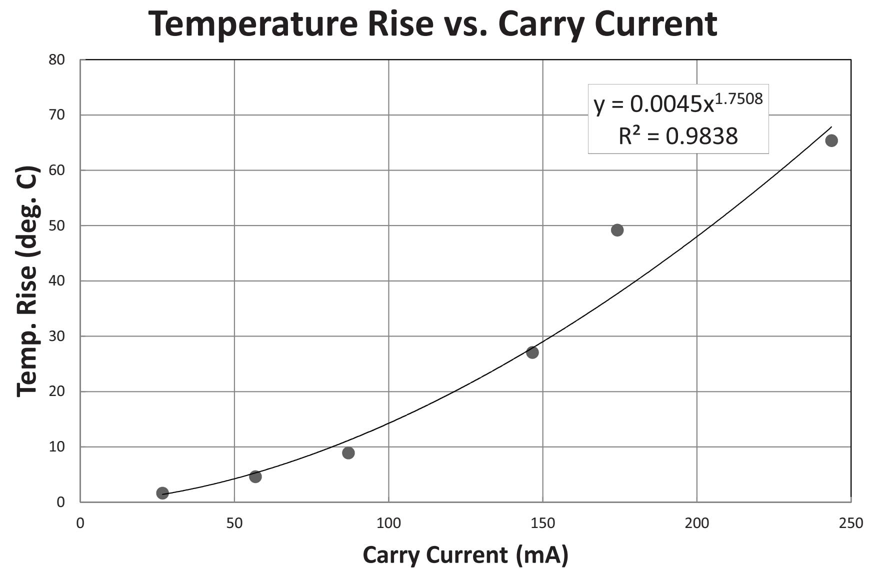


Fig. 6 | Effect of carry current on temperature of RedRock switch

Mechanical Contact Life

Mechanical life can be determined by testing for correct contact opening and closure using a low switched power, so that mechanical wear dominates as the failure mechanism. We took a sample of 30 RedRock switches and switched them on and off 300 million times using a 1V 1mA electrical load, looking for evidence of contact sticking or failure to close on each switching cycle. External solenoid coils were used to drive the switches. The resulting Weibull reliability plot is shown in Figure 7. Percentage failure is plotted on the y-axis, and millions of switching cycles on the x-axis. The Weibull slope (called the shape parameter or Beta in some reliability references) was 1.45, indicating that the switches tended to wear out after a lengthy period of reliable switching rather than exhibiting “infant mortality” failures. The estimated mean number of cycles to failure (MCBF) was 125 million cycles, with upper and lower 90% confidence limits of 158 and 100 million cycles respectively. In all cases the failure mechanism was contact wear leading to contact resistance greater than 100 ohms (miss events) rather than sticking events where the contacts stick shut and do not retract when the coil drive stimulus is turned off. This was encouraging, since missing is generally more acceptable than sticking as a switch failure mechanism.

> “*Large retract forces when the magnetic field is relieved means sticking is much less likely with the Redrock design.*”

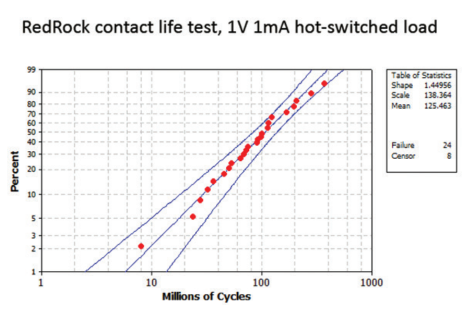


Fig. 7 | Weibull plot of RedRock switch contact life, 1V 1mA hot-switched load

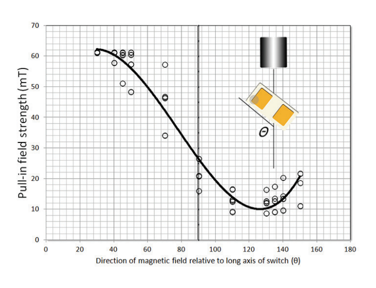


Fig. 8 | Magnetic field strength needed to close switch as a function of magnet angle. (Inset diagram shows magnet-switch orientation)

Magnetic Field Sensitivity Pattern

The magnetic field strength needed to close the RedRock switch depends on the angle of the magnet relative to the long axis of the switch. In this regard, RedRock switches behave in a similar fashion to conventional reed switches, though the sensitivity pattern is somewhat different. Figure 8 shows the sensitivity pattern for a sample of 40 RedRock switches having a nominal closure field of 10mT. The peak sensitivity occurs when the angle of the magnet’s principle N-S axis is located at 120 degrees relative to the long axis of the switch. When the switches are rotated, the sensitivity drops to about 60 mT at 45 degrees, according to the sinusoidal response pattern shown in the curve fit of Figure 8. For certain applications, the non-isotropic nature of the closure response pattern is advantageous, since the magnet and switch can be oriented to minimize the chance of stray external magnetic fields spuriously triggering switch closure.

RedRock vs. Alternative Magnetic Switching Technologies

Apart from small conventional reed switches and MEMS switches, a few other alternative technologies need discussion:

- GMR (Giant MagnetoResistive) switches
- Hall Effect switches
- AMR (Anisotropic MagnetoResistive)

Unlike RedRock, these solid-state magnetic switches are “active”, requiring a power supply for operation. Though solid state switches promise excellent switching life, active operation increases circuit complexity and PCB real estate requirements, since three electrical connections are now needed instead of two; one for the power supply, one for the sensor signal, and one for ground. Additional components such as pull-up resistors or bypass capacitors may also be needed, increasing the parts count. Battery drain also becomes a significant consideration in size-limited applications, and active device manufacturers often use sleep/wake hibernation modes to reduce the average power consumption. In contrast, reed switches such as RedRock require no internal power to operate. ESD sensitivity and current switching capability must also be considered before selecting an active magnetic switch.

The strengths and weaknesses of various magnetically operated switches are shown in the matrix below (Table 2). We have used a color code to grade our assessment of various relevant properties, from dark green (excellent) to dark red (unacceptable.)

PROPERTY	Coto RedRock	Hall	GMR	AMR	Planar MEMS	Conventional Reed
Small Size	5	4	4	2	4	2
Low Power Consumption	5	3	3	2	5	5
High Power Switching Capability	4	3	3	4	1	5
High Magnetic Sensitivity	4	4	5	5	3	4
Long Switching Life	4	5	5	4	2	4
Low ESD Sensitivity	5	2	2	2	2	5
Low Cost	3	4	3	3	2	4

5 Excellent 4 Good 3 Acceptable 2 Poor 1 Unacceptable

Table 2 | Comparison of Properties Amongst Magnet Switching Technologies

Four Basic Technologies for Magnetic Switches

We suggest that of the four basic technologies for magnetic switches: conventional reed switches, planar MEMS switches, active devices such as GMR and Hall effect, and RedRock technology, only the latter technology combines zero power operation, high current hot switching capability, and very small size in one package.

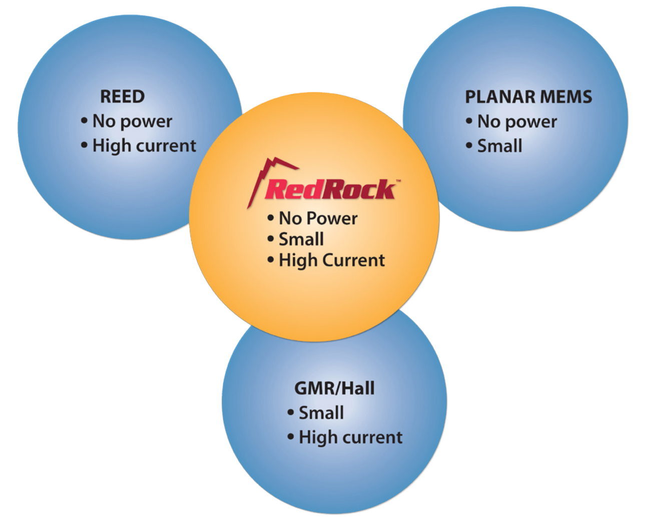


Fig. 9 | Four Basic Technologies for Magnetic Switches

> *Only the RedRock technology combines zero power operation, high current hot-switching capability and very small size in one package.*

Specifications for the new RedRock Switch

A detailed product specification is shown in Appendix II. Table 3 shows some highlights.

PARAMETER	VALUE	UNIT
Size and Form Factor	2.3, SMT	mm^3
Contact Type	Ruthenium	
Operate Range	10 - 25	mT
Release Range	5 - 15	mT
Switched Power	0.3	W
Switched Voltage DC, AC RMS	100, 70	V
Switched Current DC, AC RMS	50, 35	mA
Carry Current DC, AC RMS	100, 70	mA
Breakdown Voltage	200	VDC
Contact Resistance	3 (typ), 7 (max)	Ω
RoHS Compliant	Yes	

Table 3 | Specifications for the RedRock Switch

Applications and Case Studies

Hearing Aids


Fig. 10 | Various types of behind-the-ear and in-canal hearing aids

One ideal application is control functions in small portable medical devices such as hearing assistance devices (hearing aids). Increasingly, this is a baby-boomer market. Many boomers ran their Sony Walkmans too loud or went head-banging at too many Black Sabbath concerts, and now their hearing is suffering. The market is driven by ever-shrinking devices, since many hearing aid users prefer the aesthetics of a small, almost unnoticeable device. Hearing aids used to be controlled by mechanical switches, but as devices shrank, this became impractical, and a small magnetically operated switch became preferred for functions such as program switching and Telecoil operation because no power was needed to operate the switch. This was a good solution for bulky behind-the ear hearing aids, but as they shrank further into the ear canal itself, reed switches were too big. Zero power operation of the switch is still mandatory, since batteries have also shrunk, so a microfabricated reed switch is a perfect choice. The picture in the right hand panel of Figure 11 shows a typical hearing aid circuit board, with a microfabricated switch on the left and two conventional reed switches shown in comparison. Clearly, the RedRock microfabricated switch is far more compatible with the other small surface-mount components.

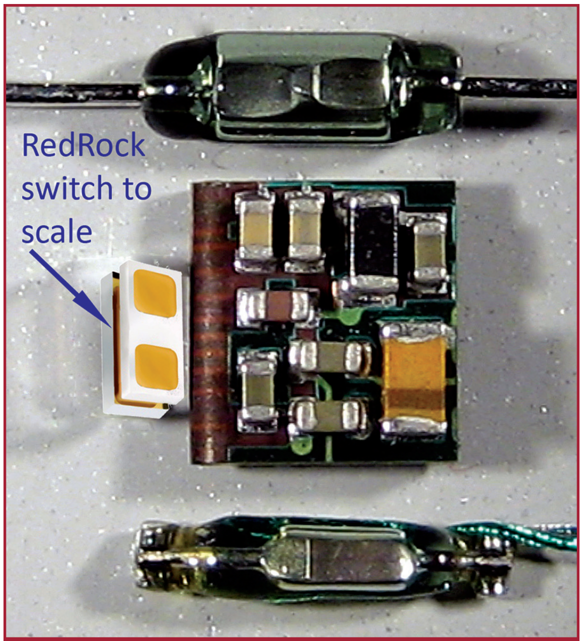


Fig. 11 | Hearing aid PCB (center) with conventional reed switches (top & bottom) and RedRock microfabricated switch (left).

Capsule Endoscopes

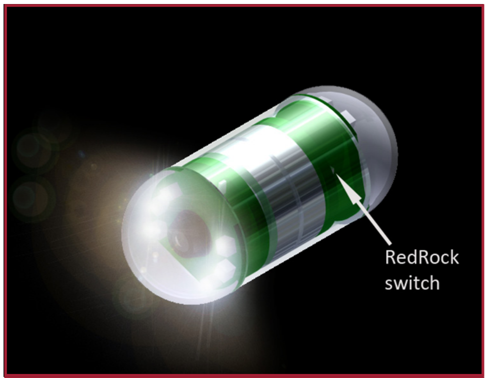


Fig. 12 | Typical capsule endoscope turned on and ready for ingestion

Capsule endoscopes are pill-sized devices that contain one or more video cameras and white LED "headlamps." (Figure 12) After a patient swallows the capsule, it takes pictures of the gastrointestinal tract and transmits them to an external monitoring system. Early warning of gastro-intestinal tract diseases is a true lifesaver, and the capsule endoscope can take pictures where a conventional colonoscope just can't go. To keep the device down to a size that can be swallowed comfortably, the electronic circuitry must be highly miniaturized, and it must include a mechanism to start the sealed capsule up just before it is swallowed. Additionally, the power consumption of the capsule must be extremely low to minimize the size of its batteries. Active switches such as GMR or Hall-effect devices are small enough but draw current while the capsule is in storage, reducing its shelf life. In addition, they require external components and more complex circuitry than a simple two-wire reed switch. It follows that a reed switch is an ideal solution since it requires no internal power and can be magnetically triggered through the sealed shell of the capsule. Unfortunately, conventional reed switches are too big for this application, even the smallest ones currently available. Finally, the tendency of planar MEMS switches to stick shut after long periods of shelf storage also rules them out. The RedRock™ microfabricated switch has the right combination of small size, zero power consumption and resistance to sticking that is needed for this application.

Insulin Delivery Control

Insulin pumps are used to administer insulin in the treatment of diabetes, as an alternative to multiple daily syringe injections. Generally, they contain a disposable insulin reservoir, whose presence in the pump unit has to be reliably detected. Like most portable medical devices, insulin pumps are shrinking, from the backpack-sized 1963 model shown in Figure 13 to modern credit card sized pumps, as shown in Figure 14.

Fig. 13 | Early Insulin Pump

Fig. 14 | Modern Insulin Pump

Typically, a reed switch in the pump body is triggered by a magnet attached to the reservoir. The reed switch may also detect when the insulin reservoir is running low. It is vitally important that this switching link works reliably, to ensure correct dosing or sound an alarm when the reservoir needs to be replaced. It's also extremely important that the reed switch can't be triggered by extraneous magnetic fields, for example from a cell phone speaker, to avoid false dosing or spurious low insulin level warnings. This is an ideal application for the RedRock switch, not just because of its small size and zero power requirement, but also its customizable magnetic sensitivity pattern.

Automotive Switching Applications

At first, applications for small magnetically operated switches in motor vehicles might seem less compelling than medical device applications. After all, a motor vehicle is a much larger system with plenty of battery power, and conventional low-cost reed switches are widely used for a variety of functions such as door lock control, gear lever position sensing, and ABS systems. What use would a smaller reed switch be? It turns out there are compelling applications for smaller switches. Consider the level sensor that tells the vehicle's computer if there is sufficient fluid in the brake fluid reservoir. In most low-end and mid-range vehicles, fluid sensing is binary – a single reed switch is triggered by a float magnet in the fluid reservoir, indicating that there is either enough fluid, or there isn't. Unfortunately, this system has significant limitations. The worst is that it does not provide a "limp home" early warning capability. If that red warning light comes on, the fluid could simply be low, in which case it might be safe to drive home carefully. Or it could be totally depleted, ready to cause complete brake failure. One answer is to use two or more reed switches in a ladder to provide a "low but not completely depleted" fluid warning. Something like the arrangement in Figure 15, perhaps. But that design has its own limitations – for one thing, it's obviously too tall, and constrained in height by the size of the reed switches. But what if the switches were much smaller, so they could be spaced much more closely together, as shown in the right hand picture in Figure 15? In that case several switches could be installed in the same space of the conventional level sensor. That solution saves brake fluid, saves reservoir plastic, and the reduced mass decreases the carbon footprint of the vehicle while still keeping brake fluid system costs low.

> *The RedRock switch maintains the desirable properties of conventional reed switches in a package about one-tenth the size.*

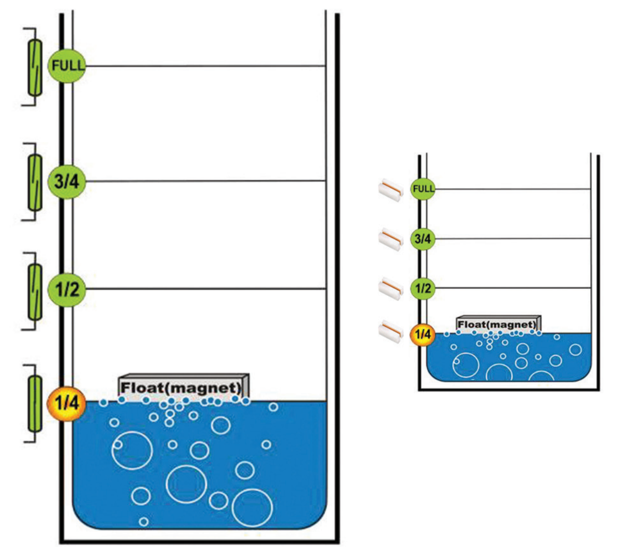


Fig. 15 | Multi-level detection using reed switches –conventional on left, RedRock microfabricated on right.

Conclusions

We have developed a new type of reed switch based on high aspect microfabrication. The switch maintains the desirable properties of conventional reed switches – high current carrying capability, hermetically sealed contacts, high resistance to ESD and zero power operation, in a package about one-tenth the size of the smallest available reed switches. Potential applications include portable medical devices where small size and zero power operation are mandatory, automotive applications such as high resolution level sensing, and process control applications requiring precision position sensing. Extension of the technology to integrated reed relays incorporating lithographically produced coils is feasible and is being investigated. For samples of the new switch or evaluation kits, contact us at the address shown below.

References

[1] Ellwood, W.B., U.S. Patent 2,289,830

[2] Day, S., *Dry Reed Relays and Mercury Wetted Relays, in The Engineers' Relay Handbook*, (6th Ed., 17.1 – 17.20), Electronic Components & Materials Assoc., Arlington VA, 2006

[3] See, for example, Guiessaz et. al., U.S. Patent 6,040,748 or Bornand, E., U.S. patent 5,605,614

[4] Rebiez, G.M., *RF MEMS Theory, Design and Technology*, Wiley Interscience, NewJersey, 2003, p.34

[5] Christenson, T.C., High Aspect Ratio Microfabricated Structures, in *"X-Ray Based Fabrication,"* Ch.5, Vol. 2 in *The MEMS Handbook*, (2nd ed.), CRC Press, 2005

For further information contact us at redrock@cotorelay.com or call USA (401) 943-2686.

The RedRock™ technology is protected by US Patent 8,327,527 B2, with other patents pending, and is a joint development between Coto Technology Inc. and HT MicroAnalytical Inc.

DISCLAIMER

Coto Technology, Inc. furnishes the information contained in this publication without assuming any liability or creating any warranty, express or implied, relating to such information or switches. Inclusion of pictures of devices or references to those devices does not imply endorsement by their manufacturers.

APPENDIX I

The Science of HARM vs. Planar MEMS Reed Switches

Knowing the length (L_c), width (b) and thickness of a single cantilever reed switch blade (t), its modulus of elasticity (E) and the size of the contact gap (g), the mechanical force needed to close the switch (F_c) can be calculated from [4]:

$$F_c = Ebt^3g/(4L_c^3) \qquad (1)$$

Referring to Figure AI-1, with dimensions in meters and the modulus in Pa, the force is expressed in Newtons (N). This force also represents the retract force of the reed switch blades when the magnetic driving field is relieved.

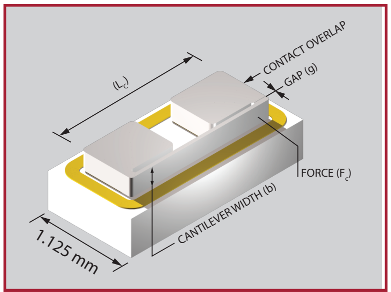


Fig. AI-1 | Critical dimensions of a HARM reed switch. (Wafer cap removed for clarity)

Clearly, for the switch to close, the magnetic force supplied by a permanent magnet or a coil must exceed F_c. The magnetic force is obtained [AI-1] from

$$F_m = \tfrac{1}{2}\,(\varphi)^2(1/u_0 db) \qquad (2)$$

where φ is the magnetic flux in the blade, u_0 is the permeability of free space (4πE-07 H/m), d is the length of the contact overlap, and b the contact width. If a wire coil supplies the magnetomotive force to close the switch, the flux in the circuit φ is obtained from|

$$\varphi = NI/\,\Re_t \qquad (3)$$

where N is the number of turns in the driving coil and I is the current. $\Re_t$ is the reluctance of the magnetic circuit driving the switch, and is equivalent to resistance in an electric circuit. It is the sum of all the magnetic resistance elements in the circuit, including the blade or blades, the contact gap and the air return paths surrounding the switch. Methods beyond the scope of this White Paper are used to estimate the reluctance of the air return paths. The interested reader is referred to Roters [AI-2], Cullen [AI-3], Peek [AI-4], and Hinohara [AI-5].

Practical experience with reed switch applications shows that the switching reliability is highly dependent on the contact closure force developed by the driving coil or magnet and the spring retract forces that take over when the magnetic field is relieved. Holm [AI-6] suggests that the resistance between a set of contacts (CR) operating in the elastic regime is related to the contact force F_c by the expression

$$CR = K\,F_c^{-1/n} \tag{4}$$

where n = 3. In our experience measuring the contact force of early prototype RedRock switches, the value of n in Eq. 4 is closer to 1 than 3, since these switches had relatively spongy contacts rather the elastic behavior assumed in Holm's formula In other words, the contact resistance was linearly proportional to the simple reciprocal of the contact force. Rebeiz [AI-7] assumes this behavior is due to surface contamination, quite possible for these early prototypes. As a compromise between Holm's estimate and ours for more recently developed switches with better contact quality, we have used n = 2 (in other words, an exponent of -1/2) in estimating the contact resistance vs. force of this newly developed switch in comparison to that of a typical planar MEMS device. This exponent corresponds to a so-called plastic regime. Figure AI-2 illustrates the relationship between the relative contact resistance and the contact force for the three different models.

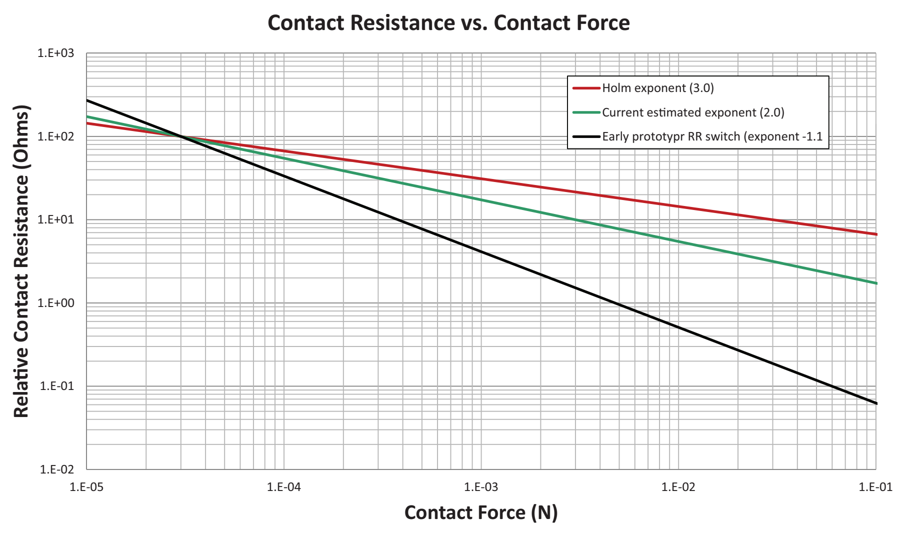


Fig. AI-2 | Relationship between contact force and relative contact resistance

Knowing the predicted contact resistance from the magnetic closure force allows prediction of the maximum carry current. The relationship is obtained using the Wiedemann-Franz-Lorenz law described by Holm [AI-6] that relates the electrical and thermal conductivities of the contact material to the maximum current that can flow through the contacts before contact material melting occurs. An estimate of the minimum voltage drop across the contacts that will cause spot melting is obtained from

$$V_c = \sqrt{(4L_0(T_c^{2} - T_0^{2}))} \qquad (5)$$

where V_c is the voltage drop, T_c is the melting point of the contact material (K) and T_0 is the bulk temperature. L_o is the Lorenz number, 2.4E-08, with units of V^2/K^{-2} For the Ruthenium contacts used in the RedRock switch (melting point 2583K), and assuming T = 293K, $V_c = 0.795$. Therefore, for a contact resistance of (say) 5Ω, the maximum carry current before spot melting occurs is $V_c/3$ = 160mA. Clearly, this is only an approximate estimate of the maximum carry current since other forces such as the contact retract force come into play, and it is not valid to assume that contact welding will occur as soon as the melting temperature is reached. But the Wiedemann-Franz-Lorenz relationship does allow a useful comparison of different contact designs to be made. Figure AI-3 shows the relationship between melting current and contact resistance for three common contact materials: ruthenium, rhodium and gold. The graph reveals that rhodium contacts with a contact resistance of 1000 ohms have a predicted melting current of only about 800 µA. In contrast, the 5 ohm ruthenium contacts of the RedRock MEMS switch are predicted to reach a 200 times higher spot melting current of approximately 160 mA, as described above.

Armed with Equations (1) through (5), it is possible to estimate from first principles the contact forces of MEMS switches with different mechanical designs, and estimate their relative contact resistances and current carrying capability. In Table 1, we show the estimated contact forces for the new HARM switch compared to a typical planar MEMS switch, and their expected influence on several different switching parameters.

Fig. AI-3 | Relationship between contact resistance and melting current for different contact coating materials

References

AI-1 Del Toro, V, *Principles of Electrical Engineering*, pp 452-455, Englewood Cliffs, NJ: Prentice Hall, 1972

AI-2 Roters, H.C., *Electromagnetic Devices*, Article 53. New York: Wiley, 1948

AI-3 Cullen, G.W, *A Practical Theory for Reed Switches*, in Proc. 19th Annual National Relay Conference, Oklahoma State University, Stillwater, OK. April 1971.

AI-4 Peek, R.L, *Magnetization and Pull Characteristics of Mating Magnetic Reeds*, Bell Systems Technical Journal 40:2 (March 1961) pp 523-546

AI-5 Hinohara, K, *Reed Switches, in Electrical Contacts: Principles and Applications*, pp 535-572, Ed. Slade, Paul G. New York: Marcel Dekker, 1999

AI-6 Holm, R, *Electric Contacts*, 4th. Ed., Berlin: Springer Verlag, 1967

AI-7 Rebiez, G.M., *RF MEMS Theory, Design and Technology*, p. 196 New Jersey: Wiley Interscience, 2003

Appendix II

See following pages.

REDROCK™ MEMS-BASED REED SWITCH

RedRock™ MEMS-Based Reed Switch

Ideally suited to the needs of Medical, Industrial, Automotive, and other applications where small size, zero power operation, and hot switching capabilities are required, the RedRock™ MEMS-Based Reed Switch is a single-pole, single throw (SPST) device with normally open ruthenium contacts. The sensor may be actuated by an electromagnet, a permanent magnet, or a combination of both.

RedRock™ MEMS-Based Reed Switch

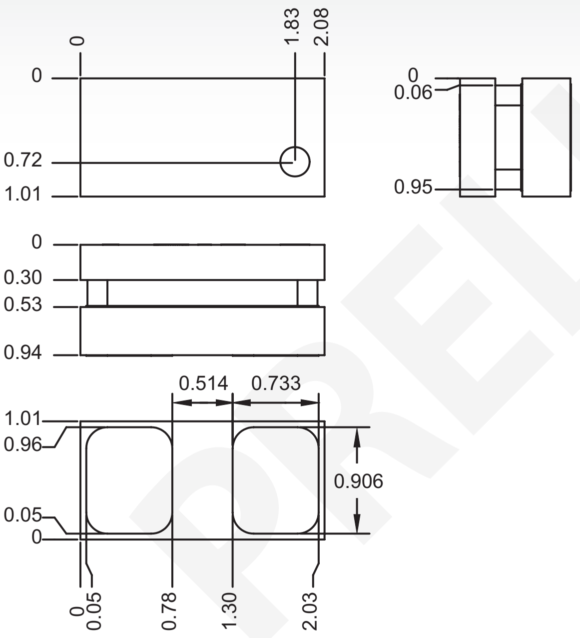
- $2mm^2$ Footprint – World's Smallest Reed Switch
- 0.3 W Switching Power
- Highly Directional Magnetic Sensitivity
- Hot Switchable
- 1000 G Shock Resistance
- Broad Operating Temperature Range
- Hermetically Sealed
- Ideal for SMD Pick and Place
- Tape and Reel Packaging
- RoHS Compliant

APPLICATIONS

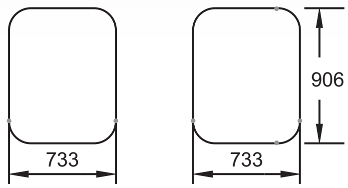
- High Resolution Position & Level Sensing
- Pulse Counters
- Medical
- Relays

DIMENSIONS

in Millimeters



Pad Dimensions in micrometers as viewed from bottom of die (pad side)



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REDROCK™ MEMS-BASED REED SWITCH

REDROCK™		**RS-A-2515**
Parameters	**Units**	**Nominal Value**
OPERATING CHARACTERISTICS		
Operate Range[1]	mT	<25 (see note #2)
Release Range[1]	mT	>15 (see note #2)
Operate Time (including bounce)	µs	<500
Bounce Time	µs	<100
Release Time	µs	<200
Pull Strength[3]	gm	>500
ELECTRICAL CHARACTERISTICS		
Switched Power	W	0.3
Switched Voltage DC	V	100
Switched Voltage AC, RMS	V	70
Switched Current DC	mA	50
Switched Current AC, RMS	mA	35
Carry Current DC	mA	100
Carry Current AC, RMS	mA	70
Rise in temperature (mounted on FR4)	°C	<10
Breakdown Voltage	VDC	200
Contact Resistance (typ. @ 40 mT)	Ω	3
Contact Resistance (max @ 40 mT)	Ω	7
Contact Capacitance	pF	<2
Insulation Resistance (min.)	Ω	10^{12}
LIFE EXPECTANCY		
No Load	Operations	10^{8}
PHYSICAL CHARACTERISTICS		
Dimensions (LxWxH)	mm	2.185 x 1.125 x 0.94
Volume	mm^3	2.3
Mass	mg	12
ENVIRONMENTAL RATINGS		
Storage Temperature	°C	-55 to +150
Operating Temperature	°C	-40 to +125
Vibration Resistance	g	50
Shock Resistance	g	1,000

Notes:

[1] For a magnet positioned at 45 degrees away from an axis perpendicular to the long axis of the switch, in the plane of the switch base.

[2] For other switch sensitivities, please contact Coto Technology.

[3] For a force applied to the top edge of the long axis, normal to that axis, in the plane of the switch base.

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