



# **MEMS-Based Magnetic Reed Sensor Technology**

**A White Paper by Coto Technology on  
Emerging Reed Sensing 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 sensor named "RedRock™." This new sensor incorporates the best features of conventional reed switches, on which its technology is based. These combine zero power operation with the inherent benefits associated with MEMS processing, such as the economy of scale and item-to-item reproducibility that are achievable using lithographic semiconductor fabrication methods.

The RedRock MEMS sensor represents the first use of High Aspect Ratio Microfabrication (HARM) to produce a commercially available sensor. HARM produces switching structures that generate contact closure forces many times greater than those exhibited by previous MEMS-based magnetic sensors, greatly improving contact reliability. Furthermore, the high retract forces developed in the sensor when it opens alleviates any tendency for it to stick shut during hot switching or after long closure periods, a problem that plagued earlier MEMS sensor designs.

“  
*There is very strong demand  
for a reed sensor that is much  
smaller than existing types  
and yet requires no power to  
operate it.*”

Wafer scale packaging results in a surface mount compatible sensor with a footprint of only 1.1mm<sup>2</sup> and a height of 1.05mm, permitting cost effective use in size-limited applications.

This new MEMS-based magnetic sensor 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 sensors such as magnetic reeds over active magnetic sensors such as GMR or Hall devices. However, conventional reed switches are often simply too big for such applications. Other uses for the RedRock sensor include high precision level and position sensing, and incorporation

into extremely small relays with integrated coils developed using the same HARM technology.

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

## Introduction

The reed switch has been a widely used sensing technology since its invention 75 years ago by scientists at Bell Labs, who were looking for an improvement to the clunky electromechanical relays then used in tele-

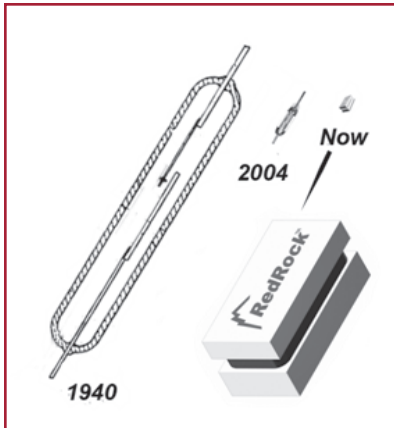


Fig.1 | Reed Switches from 1940 to 2015

phone exchanges.[1] However, in those 75 years its design has scarcely changed, at least until now. Traditional reed sensors 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 sensors 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 sensors 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.

However, reed sensors 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 sensors 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 sensors are no exception. As a result, there is very strong demand for a magnetically operated reed sensor 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 sensors have just not kept up with changing times. This White Paper describes a new kind of reed sensor developed by Coto Technology that fills this void. In this white paper we distinguish the term “reed sensor” from “reed relay.” A sensor based on reed switch technology 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 75 years ago, this new sensor is made a completely different way.*  
”

## RedRock™, a New Kind of Reed Sensor

The new Coto RedRock sensor is a reed switch that 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 sensor 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 sensor. (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.

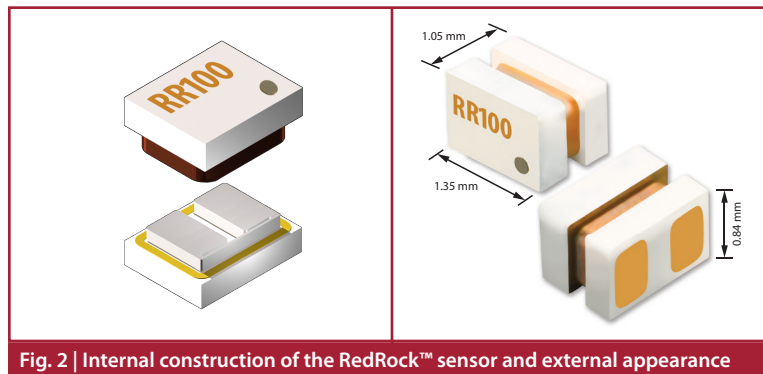


Fig. 2 | Internal construction of the RedRock™ sensor and external appearance

The key to the construction of the new sensor is the way that the reed sensor blade is grown upwards from the ceramic base of the sensor using a lithographically produced sacrificial mold. The precise dimensions of this mold and its parallel walls ensure that the thickness of the reed sensor 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 sensor. In turn, this precise dimensional control results in far higher reproducibility of the sensor closure sensitivity between different sensors. This type of fabrication is termed “high aspect ratio microfabrication,” or HARM, and it is the way the sensor structure is grown vertically with respect to the sensor substrate that distinguishes this new technology from planar MEMS sensors. To explain this differentiation requires a brief discussion of MEMS, or MicroElectroMechanical Systems devices.

# HARM - Background

## Reed Sensor Design Basics

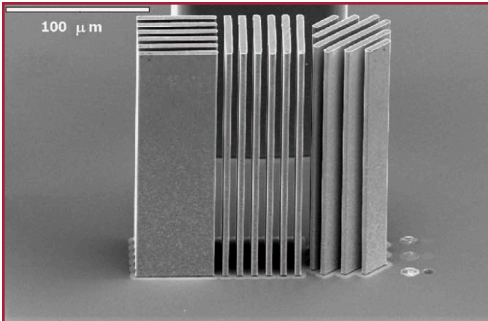


Fig. 3 | High Aspect Ratio Microfabricated structures.

Let's look at some background on reed sensor design to illustrate why HARM is an excellent approach for building a magnetically operated sensor. All reed sensors 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 sensor depends strongly on the flux that reaches the gap between the contacts. Here's an analogy; reed sensor 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 sensor 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 sensor 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 sensor blades with as large a cross-sectional area are needed to let lots of that flux through and get the highest possible contact force.*  
”

## Making a reed sensor the planar MEMS way

First, consider how a reed sensor blade is made in the planar MEMS process. Figure 4 illustrates the typical construction of a planar MEMS magnetic sensor. [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 the cantilever beam. 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 sensors 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 sensor, defeating the point of trying to build as small a sensor as possible. This is important, for in our experience most sensor users are much more concerned about the footprint of the sensor (PCB "real estate") than they are about its height.

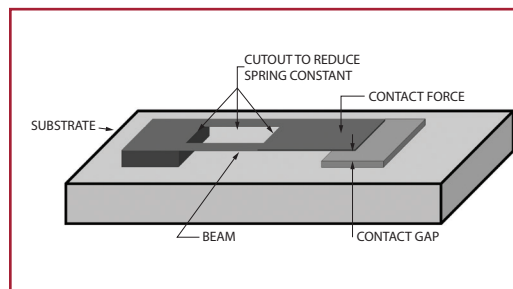


Fig. 4 | Typical planar MEMS construction. Reed cantilever beam is plated parallel to the substrate, and moves in the vertical plane

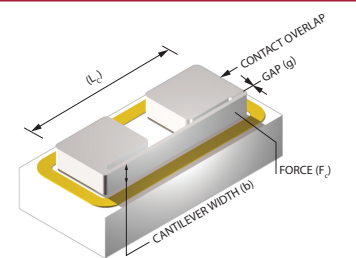


Fig. 5 | Single cantilever microfabricated HARM reed sensor. Cantilever beam is grown upwards from substrate, and moves in the horizontal plane

## A better alternative – making a MEMS reed sensor the HARM way

In HARM, the blades are grown by electroplating, but they are grown edge-on, and vertically relative to the sensor 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 sensor. And thanks to the characteristic of the HARM process, the sides of the blade are almost perfectly parallel, deviating only slightly compared to their height. That is desirable because it enables the contacts to close flat together, and contacts that close like this tend to have 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 sensors. 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 sensor 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 sensor, 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 sensors are covered in detail in Appendix I. The relationship between reed sensor 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 sensors are built with HARM, planar microfabrication, or conventional reed switch manufacturing processes.

## Summary of Comparative Performance

	RedRock (HARM)	Planar MEMS sensor	Comments
<b>Contact Metal</b>	Ruthenium (MP 2583K)	Rhodium (MP 2233K)	
<b>Sensor Dimensions (mm)</b>	1.32 x 0.84 x 1.05mm	4.8 x 2.1 x 1.4	Footprint, as packaged
<b>Blade Dimensions (µm)</b>			
Length	900	550	
Width	200	100	
Thickness	25	6	
Contact gap	4	4	
<b>Contact Forces (µN)</b>			
Closure	700	21	Calculated assuming blades saturate at 1 Tesla
Opening	650	6	
<b>Switching Performance</b>			
Contact Resistance (Ω)	10	50 - 1000	
Min. melt current (mA)	80	0.7 - 14	
Breakdown voltage (V)	50	75	

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

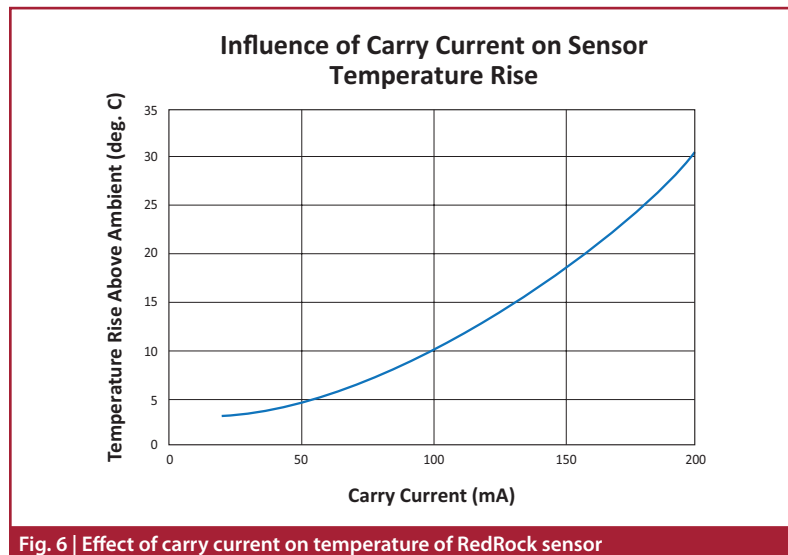
Table 1 | Comparative Performance of RedRock vs. Planar MEMS Switch

## Experimental Confirmation of the Predicted Maximum Carry Current

To validate the predicted maximum carry current for the RedRock sensor, we soldered a test sensor to solder pads at the center of a 2.5cm<sup>2</sup> piece of FR4 circuit board material, glued a small thermocouple to the sidewall of the sensor, and measured the equilibrium temperature rise for different carry currents. The static contact resistance of the sensor was approximately 10 ohms. The circuit board was suspended in still air at an ambient temperature of 22°C. The results are shown graphically in Figure 6. The equilibrium temperature rise for a carry current of 100 mA is seen to be approximately 10°C. Above 100 mA the temperature rose rapidly, as might be expected from simple I<sup>2</sup>R Joule heating. At 200 mA the sensor temperature rose about 30°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 80 mA. Interestingly, the sensor 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.

Since the RR100 is designed as a magnetic sensor, we recommend that, despite these encouraging experimental carry current results, the carry current be restricted to a maximum of 10 mA, and the hot-switched current be limited to the specified limit of 1 mA.

It is clear from the results shown in Table 1 that the HARM approach to building a magnetically driven MEMS sensor offers considerable advantages. Despite having a slightly smaller footprint than the competitive planar MEMS sensor, the RedRock sensor has over 30 times the closure force and 100 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 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 sensor fails to open after a long period of closure) will be much less likely with the HARM design.



# 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 20 RedRock sensors and switched them on and off 10 million times using a 1.2V 1 mA electrical load, looking for evidence of contact sticking or failure to close on each switching cycle. External solenoid coils were used to drive the sensors. The resulting Weibull reliability plot is shown in Figure 7. Percentage failure is plotted on the y-axis, and the number of switching cycles on the x-axis. The estimated mean number of cycles to failure (MCBF) was 10 million cycles, with upper and lower 95% confidence limits of 5 and 17 million cycles respectively. In all cases the failure mechanism was contact wear leading to contact resistance greater than 1000 ohms (miss events) rather than sticking events where the contacts stuck shut and did not retract when the coil drive stimulus was turned off. This was encouraging, since missing is generally more acceptable than sticking as a switch failure mechanism.

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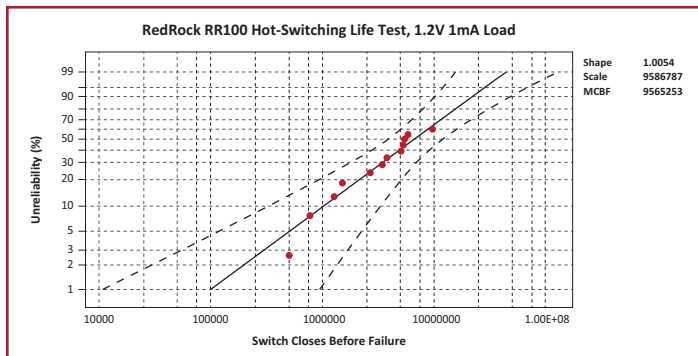


Fig. 7 | Weibull plot of RedRock sensor contact life, 1.2V 1 mA hot-switched load. Upper and lower 95% confidence limits shown by dotted lines.

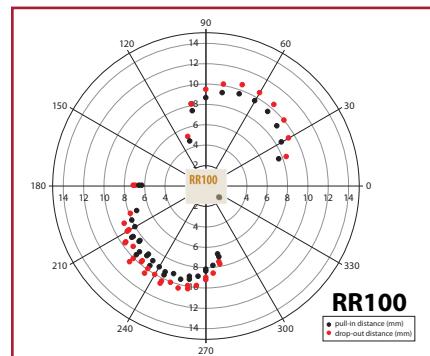


Fig. 8 | Relative closure sensitivity, as a function of magnet angle. Peak sensitivity occurs at 60°.

# Magnetic Field Sensitivity Pattern

The magnetic field strength needed to close the RedRock sensor depends on the angle of the magnet relative to the long axis of the sensor. In this regard, RedRock sensors behave in a similar fashion to conventional reed sensors, though the sensitivity pattern is somewhat different. Figure 8 shows the sensitivity map for a 15mT RedRock sensor. The peak sensitivity occurs when the angle of the magnet’s principle N-S axis is located at 60 degrees relative to the long axis of the sensor. The sensitivity drops to a minimum at 150 degrees, according to the sensitivity lobes shown in Figure 8. For many applications, the non-isotropic nature of the closure response pattern is advantageous, since the magnet and sensor can be oriented to minimize the chance of stray external magnetic fields spuriously triggering switch closure.



# RedRock vs. Alternative Magnetic Sensing Technologies

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

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

Unlike RedRock, these solid-state magnetic sensors are “active”, requiring a power supply for operation. Though solid state sensors promise excellent switching life, active operation increases the 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 sensors such as RedRock require no internal power to operate. ESD sensitivity must also be considered before selecting an active magnetic sensor, since many are highly susceptible to static discharge.

The strengths and weaknesses of various magnetically operated sensors 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
Power Switching Capability	3	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

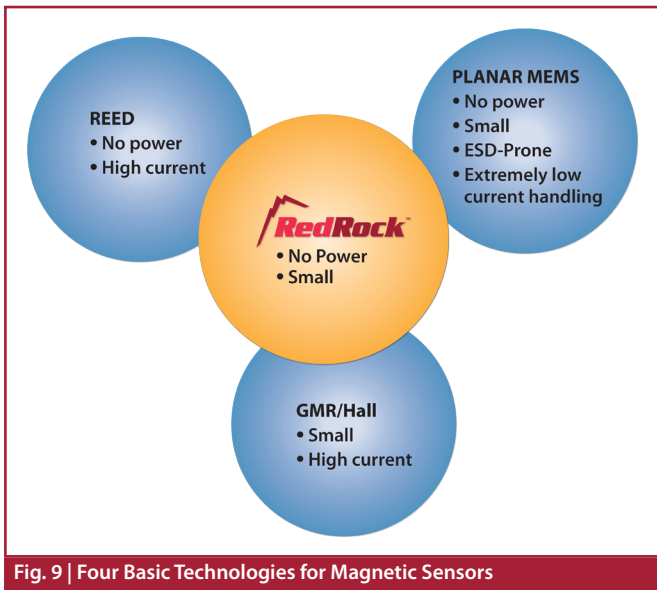
5 Excellent  
 4 Good  
 3 Acceptable  
 2 Poor  
 1 Unacceptable

Table 2 | Comparison of Properties Amongst Magnet Sensing Technologies

# Four Basic Technologies for Magnetic Sensors

Of the four basic technologies for magnetic sensors: conventional reed sensors, planar MEMS sensors, active devices such as GMR and Hall effect, and RedRock technology, only the latter technology combines zero power operation, lack of ESD sensitivity, good magnetic sensitivity, and very small size in one package.

“  
*Only the RedRock technology combines zero power operation, lack of ESD sensitivity, good magnetic sensitivity, and very small size in one package.*  
 ”



# Specifications for the new RedRock Sensor

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

PARAMETER	VALUE	UNIT
Size and Form Factor	1.2, SMT	mm <sup>3</sup>
Contact Type	Ruthenium	
Available Operate Range	8 - 27	mT
Release Range	7 - 25	mT
Max. Switched Power	0.006	W
Max. Switched Voltage DC, AC RMS	6	V
Max. Switched Current DC, AC RMS	1	mA
Max. Carry Current DC, AC RMS	10	mA
Breakdown Voltage	50	VDC
Contact Resistance	10 (initial)	Ω
RoHS Compliant	Yes	

**Table 3 | Specifications for the RedRock Sensor**

# Applications and Case Studies

## 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,



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

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 sensor became preferred for functions such as program switching and Telecoil operation because no power was needed to operate the sensor. This was a good solution for bulky behind-the ear hearing aids, but as they shrank further into the ear canal itself, reed sensors were too big. Zero power operation of the sensor is still mandatory, since batteries have also shrunk, so a microfabricated reed sensor is a perfect choice. The picture in Figure 11 shows a typical hearing aid circuit board, with a microfabricated sensor on the left and two conventional reed sensors shown in comparison. Clearly, the RedRock microfabricated sensor is far more compatible with the other small surface-mount components.

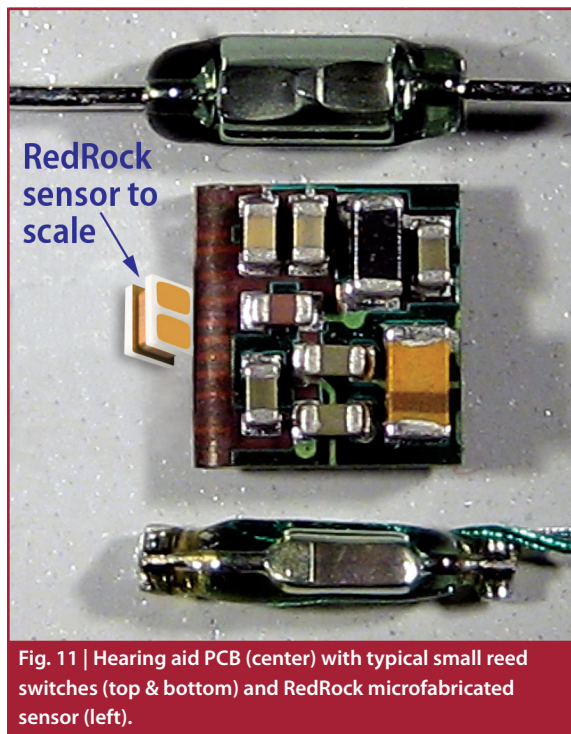


Fig. 11 | Hearing aid PCB (center) with typical small reed switches (top & bottom) and RedRock microfabricated sensor (left).

## Capsule Endoscopes

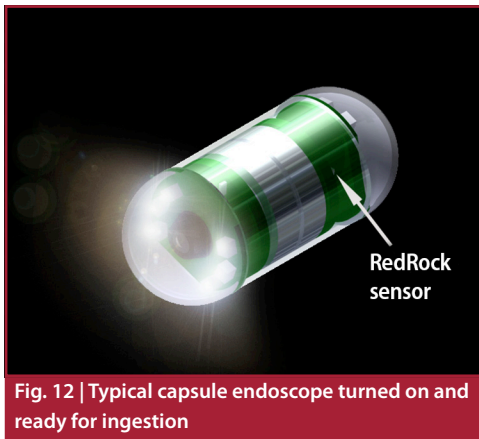


Fig. 12 | Typical capsule endoscope turned on and ready for ingestion

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 sensors 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 sensor. It follows that a reed sensor 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 sensors are too big for this application, even the smallest ones currently available. Finally, the tendency of planar MEMS sensors to stick shut after long periods of shelf storage also rules them out. The RedRock™ microfabricated sensor 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 sensor in the pump body is triggered by a magnet attached to the reservoir. It is vitally important that this sensing 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 sensor 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 sensor, not just because of its small size and zero power requirement, but also because of its customizable magnetic sensitivity pattern.

## Automotive Sensing Applications

At first, applications for small magnetically operated sensors 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 sensors are widely used for a variety of functions such as door

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

lock control, gear lever position sensing, and ABS systems. What use would a smaller reed sensor be? It turns out there are compelling

applications for smaller sensors. 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 sensor is triggered by a float magnet in the fluid reservoir, indicating that there is either enough fluid, or there isn't. Figure 15 shows a typical arrangement. Unfortunately, this system has significant limitations. The worst is that it does not provide a "limp home" early warning capability. If that red warn-

ing 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 sensors in a ladder to provide a "low but not completely depleted" fluid warning. Something like the arrangement in Figure 16, perhaps. But that design has its own limitations – for one thing, it's obviously

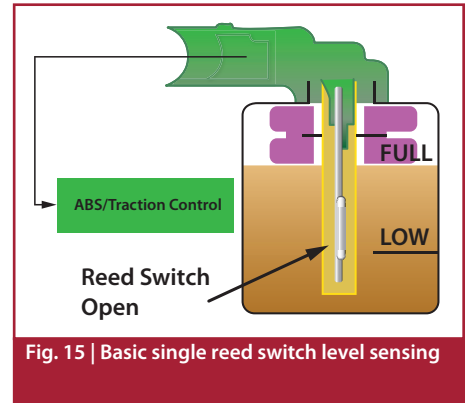


Fig. 15 | Basic single reed switch level sensing

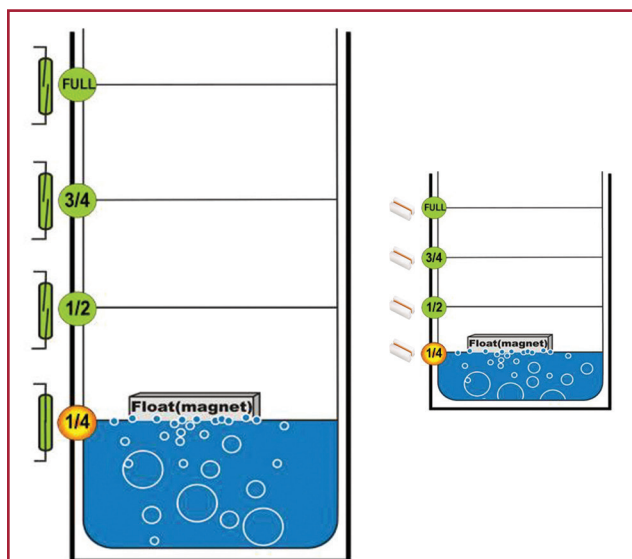


Fig. 16 | Multi-level detection using reed sensors –conventional on left, RedRock microfabricated on right.

too tall, and constrained in height by the size of the reed sensors. But what if the sensors were much smaller, so they could be spaced much more closely together, as shown in the right hand picture in Figure 16? In that case several sensors 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.

## Conclusions

We have developed a new type of magnetic reed switch sensor based on high aspect microfabrication. The sensor maintains the desirable properties of conventional reed sensors – hermetically sealed contacts, high resistance to ESD and zero power operation, in a package about one-tenth the size of the smallest available reed switch. 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 sensor or evaluation kits, contact us [redrock@cotorelay.com](mailto:redrock@cotorelay.com).

## References

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- [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, Guissaz 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, New Jersey, 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

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

The RedRock™ technology is protected by US Patent 8,327,527 B2, and US Patent 8,665,041 B2 with other patents pending, and is a joint development between Coto Technology Inc. and HT MicroAnalytical Inc.

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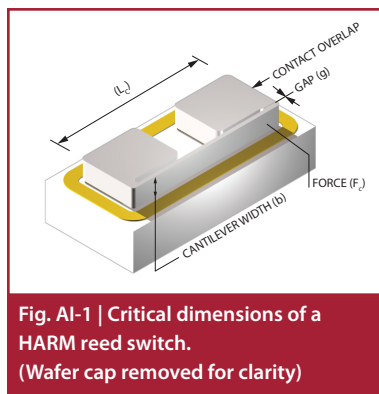
# APPENDIX I

## The Science of HARM vs. Planar MEMS Reed Sensors

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 sensor ( $F_c$ ) can be calculated from [4]:

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

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.



Clearly, for the sensor 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

$$F_m = \frac{1}{2} (\varphi)^2 / (u_0 db) \quad (2)$$

where  $\varphi$  is the magnetic flux in the blade,  $u_0$  is the permeability of free space ( $4\pi E-07$  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 sensor, the flux in the circuit  $\varphi$  is obtained from

$$\varphi = NI / \mathfrak{R}_t \quad (3)$$

where  $N$  is the number of turns in the driving coil and  $I$  is the current.  $\mathfrak{R}_t$  is the reluctance of the magnetic circuit driving the sensor, 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 sensor. 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 sensor 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

$$CR = K F_c^{-1/n} \quad (4)$$

where  $n = 3$ . In our experience measuring the contact force of early prototype RedRock sensors, the value of  $n$  in Eq. 4 is closer to 1 than 3, since these sensors had relatively spongy contacts rather than 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 sensors 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 sensor 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.

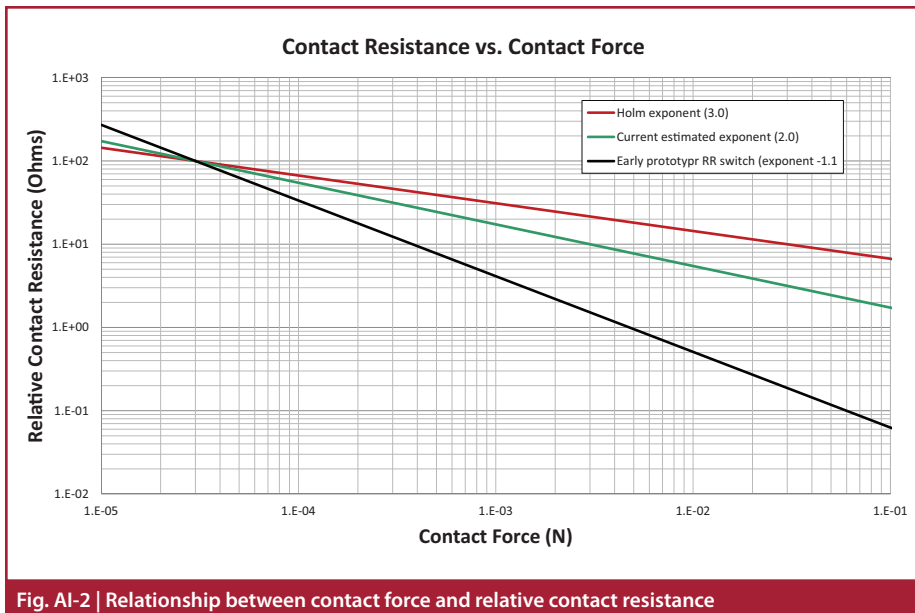


Fig. AI-2 | Relationship between contact force and relative contact resistance

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

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

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.  $L_0$  is the Lorenz number,  $2.4E-08$ , with units of  $V^2/K^2$ . For the Ruthenium contacts used in the RedRock sensor (melting point 2583K), and assuming  $T = 293K$ ,  $V_c = 0.795$ . Therefore, for a contact resistance of (say)  $5\Omega$ , the maximum carry current before spot melting occurs is  $V_c/3 = 160$  mA. 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  $\mu$ A. In contrast, the 5 ohm ruthenium contacts of the RedRock MEMS sensor 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 sensors 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 sensor compared to a typical planar MEMS sensor, and their expected influence on several different switching parameters.

For a more theoretical and in-depth discussion of HARM science, see Day and Christenson [AI-8].

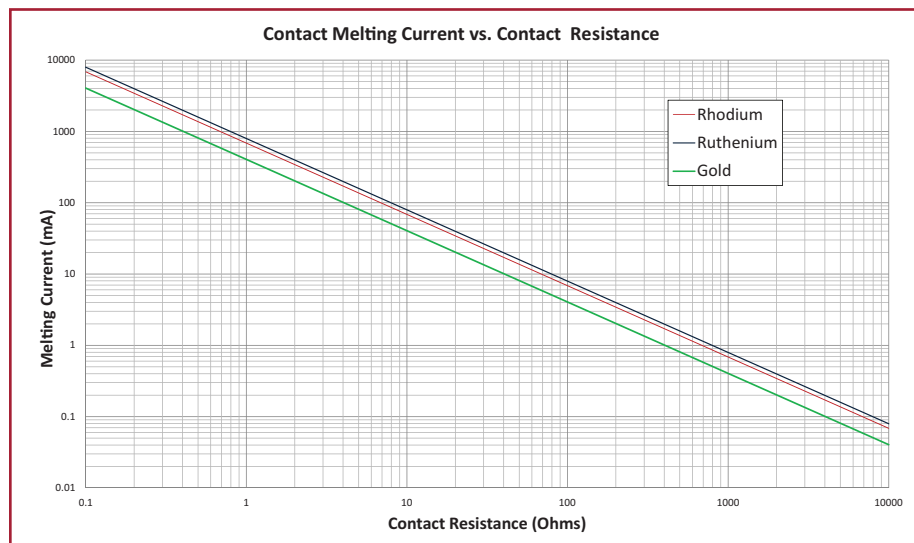


Fig. AI-3 | Relationship between contact resistance and melting current for different contact coating materials

## 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 1971v
- 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
- AI-8 Day, S. and T. Christenson, "A High Aspect Ratio Microfabricated Reed Switch Capable of Hot Switching", Proc. IEEE Holm Conference on Electrical Contacts, Newport, RI, 2013. Paper #26

## Appendix II

See following pages.

# REDROCK™ MEMS-BASED REED SWITCH



## RedRock™ MEMS-Based Reed Sensor

Ideally suited to the needs of Medical, Industrial, Instrumentation, Automotive, and other applications where small size, zero power operation, and directional magnetic sensitivity are required, the RedRock™ MEMS-Based Reed Sensor 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 Sensor

- ▶ 1.11mm<sup>2</sup> Footprint – World's Smallest Reed Sensor
- ▶ Highly Directional Magnetic Sensitivity
- ▶ Hot Switchable
- ▶ 750 G Shock Resistance
- ▶ Wide Operating Temperature Range
- ▶ Hermetically Sealed
- ▶ Ideal for SMD Pick and Place
- ▶ Tape and Reel Packaging
- ▶ RoHS Compliant

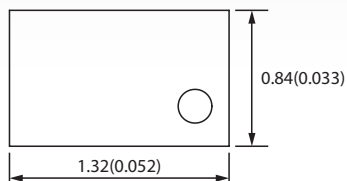
## APPLICATIONS

- ▶ Medical Devices
- ▶ Battery Powered Devices
- ▶ Prosthetics
- ▶ Robotics
- ▶ Animal Tracking
- ▶ High Resolution Position & Level Sensing

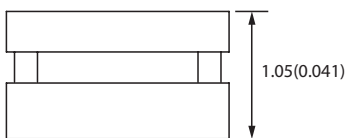
## DIMENSIONS

*in Millimeters (Inches)*

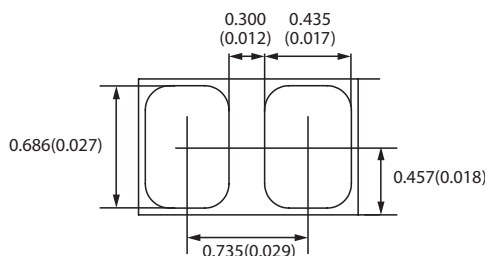
### Top View



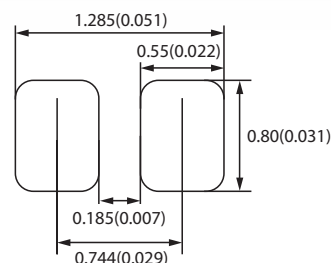
### Side View



### Bottom View



### Recommended PCB Land pattern as viewed from bottom of die (pad side)



## Ordering Information

Part Number **RR100-XWTR**

Model Number

RR100

Product Packaging

TR=Tape/Reel

Typical Magnetic Sensitivity

J=20mT

K=12mT

Package Style

W=Wafer Level

Operating Temperature Range is -40°C to +85°C

## Ordering Information (Evaluation Kit)

Part Number: **RR100-EK1**

All specifications are typical unless otherwise specified and subject to change without notice. For more information please refer to Coto Technology's Product Warranty, Trademarks & Disclaimers.

rev. 04022015

# REDROCK™ MEMS-BASED REED SWITCH

REDROCK™		RR100		
Parameters	Units	Min	Typ	Max
<b>OPERATING CHARACTERISTICS</b>				
Operate Sensitivity <sup>1</sup> - K J	mT		12 20	
Operate Time (including bounce)	μs			500
Release Time	μs			500
<b>ELECTRICAL CHARACTERISTICS</b>				
Switched Voltage	VDC			6
Switched Current	mA DC			1
Breakdown Voltage	VDC		50	
Contact Resistance (Initial)	Ω		10	
Contact Capacitance	pF		0.2	
Insulation Resistance (Min.)	Ω		10 <sup>12</sup>	
<b>LIFE EXPECTANCY</b>				
1.2VDC, 1mA switching load <sup>2</sup>	Operations		10 <sup>7</sup>	
<b>ENVIRONMENTAL RATINGS</b>				
Storage Temperature	°C		-55 to +150	
Operating Temperature	°C		-40 to +85	
Vibration Resistance - Functional <sup>3</sup>	G	100		
Shock Resistance - Functional <sup>4</sup>	G	750		
Shear Force <sup>5</sup>	gm	400		

## Notes:

<sup>1</sup> Individual switches may vary in magnetic closure sensitivity by  $\pm 4$  mT (Model K) or  $\pm 7$  mT (Model J) from the typical value.

If your application requires a different sensitivity range, please contact Coto at [redrock@cotorelay.com](mailto:redrock@cotorelay.com).

<sup>2</sup>Life expectancy defined as mean cycles before failure with end of life defined as contact resistance  $>1000 \Omega$ .

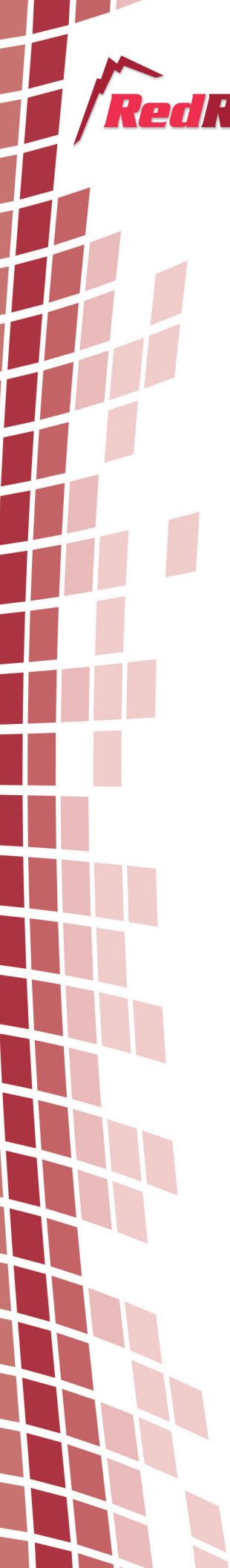
<sup>3</sup>Functional Vibration Resistance is defined as the mechanical-only force (in G, 110 Hz - 3 kHz), that a switch can withstand without causing a contact closure.

<sup>4</sup>Functional Shock Resistance is defined as the mechanical-only force (in G), that a switch can withstand without causing a contact closure.

<sup>5</sup>Shear Force is the mechanical force (applied to the top half, in a plane parallel to the PCB) that a switch can withstand without causing damage to the switch.

**For all inquiries,  
please contact [redrock@cotorelay.com](mailto:redrock@cotorelay.com)**

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