The Fundamentals of Analog Devices' Revolutionary MEMS Switch Technology

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Abstract

This article describes Analog Devices' (ADI) breakthrough in microelectromechanical systems (MEMS) switch technology. When compared to traditional electromechanical relays, ADI's MEMS switch technology enables a huge leap forward in RF and dc switch performance, reliability, and in miniaturization.

Introduction

Over the last 30 years, MEMS switches have been consistently touted as a superior replacement to limited performance electromechanical relays, and therefore revolutionizing how electronic systems are realized by providing an easy to use, small form factor switch that can route 0 Hz/dc to 100s of GHz signals reliably with minimal losses. This performance advantage impacts across a huge spectrum of equipment types and applications. Electrical test and measurement systems, defense systems applications, and healthcare equipment are just some areas that will reach previously unattainable levels of performance and form factor, all enabled by MEMS switch technology.

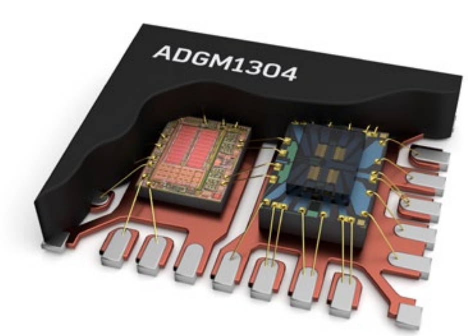

Figure 1. ADI MEMS switch technology.

Contemporary switching technologies all have drawbacks with no one technology being an ideal solution. Relay drawbacks include narrow bandwidths, limited actuation lifetimes, limited number of channels, and large package sizes. MEMS technology has always had the potential to deliver world class RF switch performance and orders of magnitude improvements in reliability in a small form factor, compared to relays.

The challenge that has thwarted many companies who have tried to develop MEMS switch technology has been delivering reliable products in high volume mass production. One of the first companies involved in MEMS switch research was The Foxboro Company, who filed one of the world's first electromechanical switch patents in 1984. ADI has been involved in MEMS switch technology research since 1990 with early academic projects. By 1998, ADI had managed to develop a MEMS switch design that led to early prototypes. In 2011, ADI increased their MEMS switch project investment significantly. This drove the building of their own state-of-the-art MEMS switch fabrication facility. Now ADI is in a position to deliver what was always needed; a mass produced, reliable, high performance, small form factor MEMS switch to replace aging relay technology.

ADI has a rich history with MEMS. The first MEMS accelerometer product successfully developed, manufactured, and commercialized in the world was ADI's ADXL50 accelerometer, which was released in 1991. ADI released the first integrated MEMS gyroscope, the ADXRS150, in 2002. From these beginnings ADI has built a huge MEMS product business and an unrivalled reputation for manufacturing reliable, high performance MEMS products. ADI has shipped over one billion inertial sensors for automotive, industrial, and consumer applications. It is this pedigree that brought the experience and belief to drive the MEMS switch technology through to realization.

MEMS Switch Fundamentals

Central to the ADI MEMS switch technology is the concept of an electrostatically actuated, micromachined cantilever beam switching element. In essence, it can be thought of as a micrometer scale mechanical relay, with metal-to-metal contacts that are actuated via electrostatics.

The switch is connected in a three terminal configuration. Functionally, the terminals can be thought of as a source, gate, and drain. Figure 2 shows a simplified graphic representation of the switch with Case A showing the switch in the off position. When a dc voltage is applied to the gate, an electrostatic pull down force is generated on the switch beam. This is the same electrostatic force as would be seen in a parallel plate capacitor, having positive and negative charged plates that attract each other. When the gate voltage ramps to a high enough value, it creates enough attraction force (red arrow) to overcome the resistive spring force of the switch beam, and the beam starts to move down until the contacts touch the drain. This is shown in Case B in Figure 2. This completes the circuit between the source and the drain, and the switch is now on. The actual force it takes to pull the switch beam down is related to the spring constant of the cantilever beam and its resistance to movement. Notice that even in the on position, the switch beam still has a spring force pulling the switch up (blue arrow), but as long as the electrostatic force (red arrow) pulling down is larger, the switch will remain on. Finally, when the gate voltage is removed (Case C in Figure 2), that is, 0 V on the gate electrode, then the electrostatic attraction force disappears, and the switch beam acts as a spring with sufficient restoring force (blue arrow) to open the connection between the source and the drain, and then, returns to the original off position.

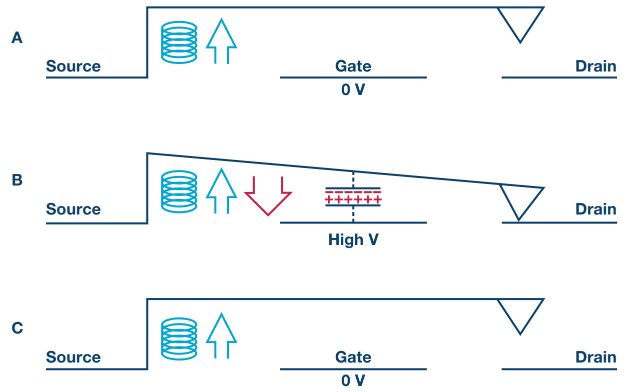

Figure 2. MEMS switch actuation process, A and C show the switch turned off, B shows it turned on.

Figure 3 shows the four main steps in fabricating a switch using the MEMS technology. The switch is constructed on a high resistivity silicon wafer (1), which has a thick dielectric layer deposited on top to provide superior electrical isolation from the substrate below. A standard back-end CMOS interconnect process is used to realize interconnections to the MEMS switch. Low resistivity metal and polysilicon are used to make an electrical connection to the MEMS switch, and are embedded into the dielectric layer (2). Metal vias marked in red (2) are used to provide a connection to the switch input, output, and the gate electrode to wire bond pads elsewhere on the die. The cantilever MEMS switch itself is surface micromachined using a sacrificial layer to create the air gaps under the cantilever beam. The cantilever switch beam structure and bond pads (3) are formed using gold. Switch contact and gate electrodes are formed using a low resistance thin metal, deposited on the surface of the dielectric.

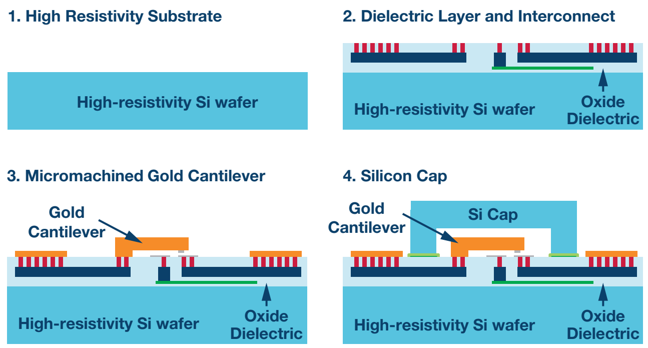

Figure 3. MEMS switch fabrication overview.

Wire bond pads are also built using the above steps. Gold wire bonding is used to connect the MEMS die to a metal leadframe, ensapsulated into a plastic quad-flat, no-lead (QFN) package for easy surface mounting on PCBs. The die is not limited to any one type of packaging technology. This is due to the fact that a high resistivity silicon cap (4) is bonded to the MEMS die to form a hermetic protective housing around the MEMS switch device. Hermetically enclosing the switch in this way increases the environmental robustness and cycle lifetime of the switch, regardless of what external package technology is used.

Figure 4 shows a zoomed in graphic of four MEMS switches in a single-pole four-throw (ST4T) multiplexer configuration. Each switch beam has five ohmic contacts in parallel to reduce resistance and increase power handling when the switch is closed.

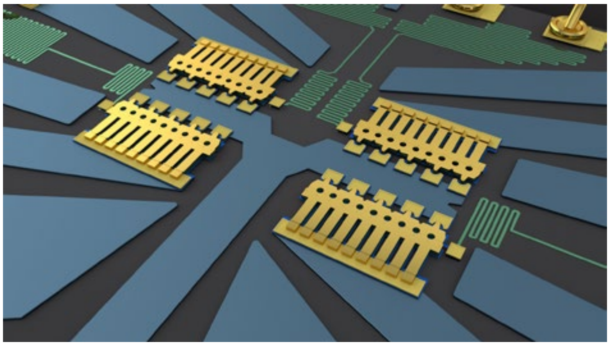

Figure 4. Close-up graphic showing four MEMS cantilever switch beams (SP4T configuration).

As outlined at the beginning, the MEMS switch requires a high dc drive voltage to electrostatically actuate the switch. To make the part as easy to use as possible and further guarantee performance, a companion driver integrated circuit (IC) has been designed by ADI to generate high dc voltages and copackaged with the MEMS switch in a QFN form factor. In addition, the high actuation voltage generated is applied to the gate electrode of the switch in a controlled manner. It is ramped up to a high voltage in microsecond time scales. The ramping helps to control how the switch beam is attracted and pulled down, and improves actuation, reliability, and cycle lifetime of the switch. Figure 5 shows the driver IC and MEMS die in situ in a QFN package. The driver IC only requires a low voltage, low current supply, and is compatible with standard CMOS logic drive voltages. This copackaged driver makes the switch very easy to use and it has very low power requirements, in the region of 10 mW to 20 mW.

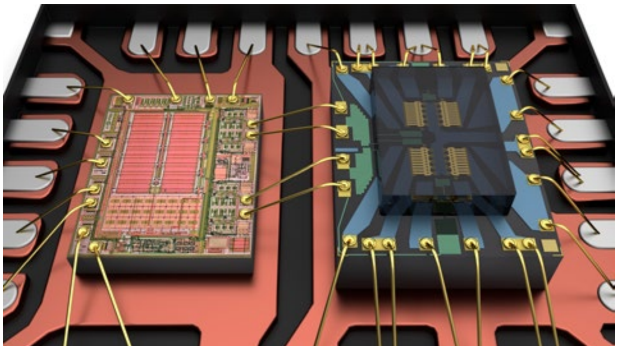

Figure 5. Drive IC (Left), MEMS switch die (Right) mounted on and wire bonded to a metal lead frame.

Reliability

A key tenet to any new technology is how reliable it is, and this is something ADI is keenly aware of. The new MEMS technology manufacturing process was the base that enabled the development of mechanically robust, high performance switch designs. This coupled with a hermetically sealed, silicon capping process were crucial to delivering truly reliable long life MEMS switches. To successfully bring the MEMS switch to commercialization required extensive reliability testing specific to MEMS, such as switch cycling, lifetime testing, and mechanical shock testing. In addition to this qualification, and to guarantee the highest level of quality possible, the part has been qualified using a whole range of standard IC reliability tests.

Table 1 shows a summary of the environmental and mechanical testing that was performed.

Table 1. MEMS Switch Technology Qualification Tests

Test Name	Specification
HTOL 1 kHz, 1 Billion Cycles, 1000 Hours	JESD22-A108
HTOL II Switch Continuously on at +85°C, 1000 Hours	JESD22-A108
ELF 5 kHz Burst Mode Cycling, 85°C, 48 Hours	MIL-STD-883, M1015
HAST +130°C, 85% RH, Biased, 96 Hours	JESD22-A110
SHR MSL 3 Precondition	J-STD-20
Random Drop	AEC-Q100 Test G 5, 0.6 m
Vibration Testing Cond B, 20 Hz to 2000 Hz at 50 *g*	MIL-STD-883, M2007.3
Mechanical Shock 1500 *g* 0.5 ms Vibration 50 *g* Sine Sweep 20 Hz to 2000 Hz Acceleration 30,000 *g*	Group D Sub 4 MIL-STD-883, M5005
Temperature Cycle 1 Cycle per Hour –40°C to +125°C, 1000 Cycles	JESD22-A104
High Temp Storage +150°C, 1000 Hours	JESD22-A103
Autoclave 121°C, 100% RH, 96 Hours	JESD22-A102

Long switch actuation lifetimes are of utmost importance in RF instrumentation applications. The MEMS technology has been developed to bring an order of magnitude improvement in cycle lifetimes compared to electromechanical relays. The high temperature operation lifetime (HTOL I) test at 85°C and the early life failure (ELF) qualification test, rigorously guarantee the cycle lifetime of the part.

Continuously on lifetime (COL) performance is another key parameter for MEMS switch technology. For example, RF instrumentation switch usage can be varied and a switch can be left in the on condition for extended periods of time. ADI has recognized this fact and has focused on achieving excellent COL lifetime performance for the MEMS switch technology to mitigate lifetime risks. From an initial COL performance level of seven years (mean time before failure) at 50°C, ADI has further developed the technology to deliver a class leading 10 years of COL at 85°C.

The MEMS switch technology has undergone a comprehensive suite of mechanical robustness qualification tests. Table 1 lists a total of five tests that ensure the mechanical endurance of the MEMS switch. Due to the small size and low inertia of the MEMS switch element, it is significantly more robust than electromechanical relays.

Compelling Performance Advantage

The key strength of the MEMS switch is that it brings together 0 Hz/dc precision and wideband RF performance, and superior reliability vs. relays in a tiny surface mountable form factor.

One of the most important figures of merit for any switch technology is the on resistance multiplied by the off capacitance of a single switch. This is commonly referred to as RonCoff product and expressed in units of femtoseconds. As RonCoff reduces, the insertion loss of the switch also reduces, and the off isolation improves.

The ADI MEMS switch technology RonCoff product for a single switch unit cell is <8, guaranteeing its position as the technology of choice to enable world class switch performance.

This fundamental advantage is what has been utilized, along with careful design, to reach superior RF performance levels. Figure 6 shows measured insertion loss and off isolation for a prototype QFN, single-pole double-throw (SPDT) MEMS switch. Insertion loss is only 1 dB at 26.5 GHz, and bandwidths to over 32 GHz have been achieved in a QFN package.

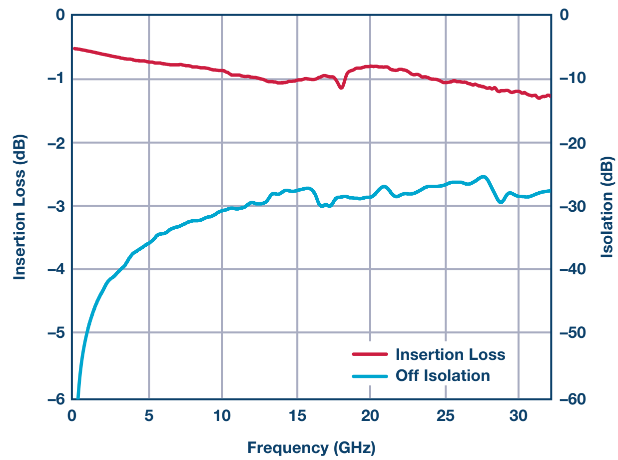

Figure 6. SPDT MEMS switch performance, QFN packaged.

Figure 7 shows a wider frequency sweep of insertion loss and off isolation from a prototype, on die single-pole double-throw (SPST) MEMS switch probed measurement. At 40 GHz, an insertion loss of 1 dB and off isolation in the region of –30 dB were achieved.

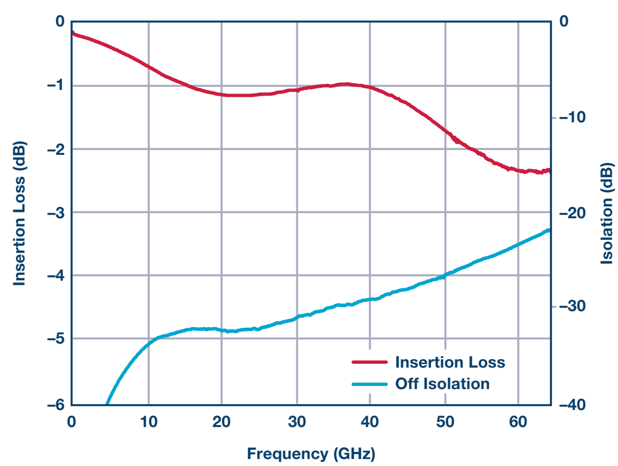

Figure 7. SPST MEMS switch performance, on die probed measurement.

In addition, the MEMS switch design inherently delivers a very high performance in the following areas:

- Precision dc performance: precision performance levels of <2 Ω R_{ON}, 0.5 nA off leakage, and –110 dBc total harmonic distortion (THD + N) have been realized, with potential to improve all levels based on beam and substrate optimizations.
- Linearity performance: third-order intermodulation intercept (IP3) levels of over 69 dBm have been realized with input tones of 27 dBm. There is potential to increase beyond 75 dBm over the full frequency band of operation.
- Actuation lifetime: guaranteed to a minimum 1 billion actuation cycles. This far exceeds any mechanical relay on the market today, which would typically be rated below 10 million cycles.
- Power handling (RF/dc): powers beyond 40 dBm have been tested over the full frequency band of operation, and does not degrade at lower or higher frequencies. In terms of dc signals, the switch technology can pass over 200 mA of current.

Finally, having a small size solution is typically a critical requirement across all markets. MEMS again delivers a compelling advantage here. Figure 8 shows a to-scale comparison of a packaged ADI SP4T (four switches) MEMS switch design compared to a typical DPDT (four switches) electromechanical relay. In terms of volume, space saving is huge. Here the MEMS switch would only take up 5% of the volume of the relay. This very small size significantly drives board area savings, particularly enabling double sided board development. This advantage is especially valuable for automatic test equipment manufacturers, where increasing channel density is paramount.

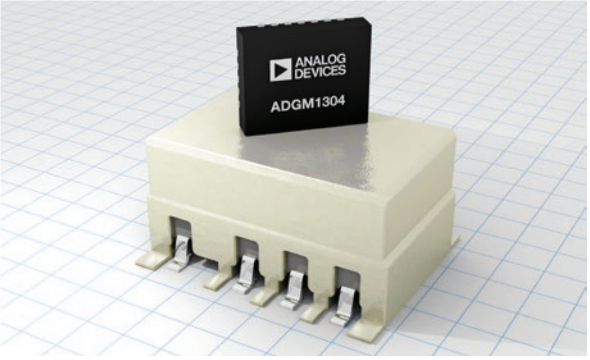

Figure 8. ADI MEMS switch (four switches) in a lead frame chip scale package compared to a typical electromechanical RF relay (four switches).

Conclusion

The MEMS switch technology that ADI has developed enables a leap forward in switch performance and size reduction. Best-in-class performance from 0 Hz/dc to Ka-band and beyond, orders of magnitude cycle lifetime improvements vs. relays, excellent linearity, very low power requirements, and availability in chip scale packages, makes ADI's MEMS switch technology a revolutionary new addition to Analog Devices overall switch offerings.

New MEMS Switch Products

ADGM1304

0 Hz/dc to 14 GHz, SP4T MEMS switch with integrated driver

ADGM1004

0 Hz/dc to 13 GHz, 2.5 kV HBM ESD SP4T MEMS switch with integrated driver

References

Carty, E., Fitzgerald, P., Stenson, B., McDaid, P., Goggin, R.: "Development of a DC to K-Band Ultra Long On-Life RF MEMS Switch with Integrated Driver Circuitry.", European Microwave Conference (EuMC), European Microwave Association (EuMA), 4-6 October 2016.

Gabriel Rebeiz. "RF MEMS, Theory, Design and Technology.", Wiley, 2003

Goggin, R., Fitzgerald, P., Stenson, B., Carty, E., McDaid, P.: "Commercialization of a Reliable RF MEMS Switch with Integrated Driver Circuitry in a Miniature QFN Package for RF Instrumentation Applications.", Microwave Symposium (IMS), IEEE MTT-S International, 17-22 May. 2015.

Goggin, R., Wong, J.E., Hecht, B., Fitzgerald, P., Schirmer, M.: "Fully integrated, high yielding, high reliability DC contact MEMS switch technology & control IC in standard plastic packages.", Sensors, 2011 IEEE, pp. 958, 961, 28-31 Oct. 2011.

Maciel, J., Majumder, S., Lampen, J., Guthy, C.: "Rugged and reliable ohmic MEMS switches", *Microwave Symposium Digest* (MTT), IEEE MTT-S International, 17-22 June 2012.

Rebeiz G., Patel C., Han S., Ko Chih-Hsiang., Ho K.: "The Search for a Reliable MEMS Switch?.", *IEEE Microwave Magazine*, Jan/Feb 2013.

Stephen D. Senturia, "Microsystem Design.", Springer, 2000.

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Eric Carty received his masters of science degree in experimental physics from the National University Maynooth, Ireland, in 1998. Before joining Analog Devices he spent a total of 10 years working as an RF passive component design engineer. Since 2009 he has been a senior applications engineer in Analog Devices, focusing on RF switches and MEMS technology research and development. He currently manages the Switch and Multiplexer Applications Department in Analog Devices.

Padraig Fitzgerald graduated from University of Limerick in 2002 with a bachelor's degree in electronic engineering. He started at Analog Devices, Limerick, Ireland, as an evaluation engineer working on solid-state switches in 2002 and moved to switch design in 2007. Padraig completed a research master's at Cork Institute of Technology on the reliability of MEMS switches. He is currently a senior staff designer in the Precision Switch Group, and is a device designer for the MEMS switch.

Padraig McDaid received his bachelor of engineering degree in electronic engineering from University of Limerick, Ireland, in 1998. Padraig manages the Switch and Multiplexer Marketing Department in Analog Devices, with a primary focus on MEMS technology research and development. Prior to joining Analog Devices in 2009, Padraig worked in various RF design, applications and marketing roles, within multinational companies and small-to-medium size businesses.

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