Reducing Actuation Voltage in RF MEMS Switches and the Impact of Scaling on Performance and Reliability

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Abstract

For over two decades, researchers have written about microelectromechanical switches and their remarkable performance in terms of low insertion loss, high linearity, high isolation, and extremely low power consumption. Although these characteristics are highly desired in RF applications, the high actuation voltage currently required to operate these switches—typically in the 20 to 80 volts range [1], presents a challenge for incorporating MEMS switches into portable wireless, low-power, and battery-operated systems. Continuing to push for yet smaller dimensions can help in reducing actuation voltage requirements and provides additional benefits such as higher integration and speed. Despite these advantages, scaling down can also emphasize reliability concerns that reduce the lifetime of the switch. The work presented here touches on the fundamentals of electrostatically actuated RF MEMS switches and the impact of scaling to both reliability and performance.

1. Introduction

Switches and relays are simple yet crucial components widely used in RF applications for signal routing and control. Today, the RF switch industry is dominated by two main switch categories: macro-scale electromechanical (armature, reed, and electromagnetic relays) and solid-state (PIN diode and GaAs FET). Macro-scale electromechanical relays have been used in industry for a long time and are known to have excellent characteristics such as low insertion loss, high isolation, and high linearity; but they also have some serious disadvantages including their large size—which makes it impossible to integrate in small portable devices, as well as other significant drawbacks including high cost, short lifetime, and slow switching speed [2]. Solid-state switches on the other hand offer small size, low cost, and very fast switching speed; but their performance suffers from insertion loss, limited linearity, limited isolation, and power consumption due to leakage current. The holy grail of exceptional RF switching performance in a small package that can be produced at a low cost, may be achievable using RF MEMS switches. Research efforts have already been able to produce MEMS switches with excellent performance characteristics including low loss (<0.25 dB at 35 GHz), good isolation (35 dB at 35 GHz), and very low (virtually zero) power dissipation [3]. So far, high actuation voltage, high cost (when compared to their solid-state counterparts), and reliability concerns prevent RF MEMS from penetrating the market. Nevertheless, the recent boom in wireless communications and increased demands driven by 5G and IoT (increased switching, additional bandwidth, low loss requirements, high cutoff frequencies, small space availability in mobile phones and battery-operated devices) offer an ideal opportunity space for MEMS switches.

2. RF MEMS Switch Fundamentals

The two main switches used in RF applications are the shunt switch and the series switch. An ideal shunt switch provides a short circuit to ground when a voltage bias is applied and leaves the transmission line uninterrupted when the bias is not present. In contrast, an ideal series switch provides a path for signals to travel in the transmission line when a bias is applied and results in an open circuit when the bias is not present. In essence, the ideal shunt switch provides infinite isolation when bias is applied and zero insertion loss otherwise, while the ideal series switch provides zero insertion loss in the presence of a voltage bias and infinite isolation when the bias is removed.

Electrostatically actuated microelectromechanical systems based (MEMS) switches use surface micromachining to build suspended beam structures that collapse in the presence of an electrostatic force. This force is induced by a DC voltage bias applied to a pull-down electrode placed underneath the beam structure. While the beam or bridge is down, it can be used to establish direct contact between two open ends of a transmission line (direct-contact ohmic series switch) or to generate a large capacitance between the transmission line and ground, effectively creating a short circuit at microwave frequencies (capacitive shunt switch). A thin dielectric layer is used to prevent direct contact in the capacitive shunt case. Figure 1 illustrates a capacitive switch built with a fixed-fixed beam, and a direct-contact ohmic switch built using a cantilever style beam.

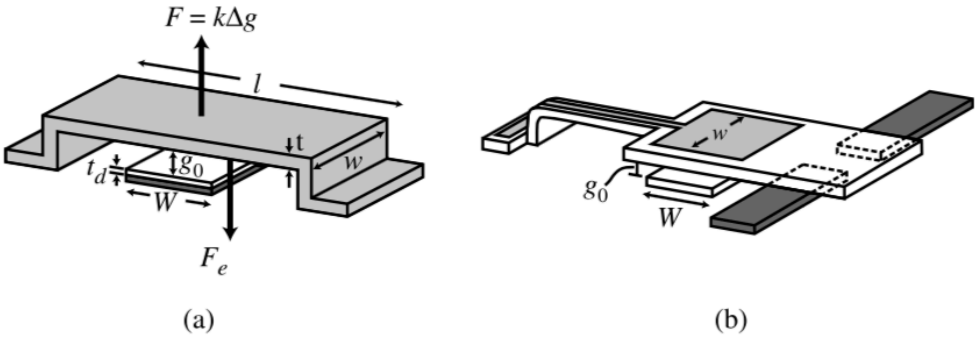

Figure 1. (a) Capacitive fixed-fixed beam and (b) ohmic cantilever style beam RF MEMS switches with pull-down electrode

Mechanically speaking, the structure can be approximated as a damped spring-mass system. Further, since the amount of displacement needed for switch operation is limited to a small deflection, the mechanical behavior of the switch can be modeled using Hooke's law where the mechanical restoring force is given by

$$F_m = kx \tag{1}$$

Where x is the amount of deflection and k represents the stiffness or spring constant—an important parameter for describing the elastic deformation of the beam, and a function of material properties including the Young's modulus (E) and the beam's dimensions (width W, thickness H, and length L). In the case of a cantilever beam, the stiffness k_c is given by [4]:

$$k_c = \frac{1}{4} EW \left(\frac{H}{L}\right)^3 \tag{2}$$

To induce the electrostatic force necessary to actuate the switch, a voltage is applied to the pull-down electrode placed below the beam. This voltage induces a force equivalent to the electrostatic force seen by parallel-plate capacitors which is given by [4]:

$$F_e = \frac{\varepsilon A V^2}{2g^2} \tag{3}$$

Where A is the overlapping area between the beam and the pull-down electrode, V is the applied voltage and g corresponds to the height of the beam above the electrode. To properly actuate the switch, the electrostatic force (F_e) must overpower the restoring force (F_m) in order to collapse the bridge. As the voltage applied increases, the electrostatic attraction also increases, and the gap between the beam and the electrode is reduced. When the gap reaches $(2/3)g_0$ the beam position becomes unstable and collapses to the down position. The voltage necessary to reach this instability determines the minimum voltage required to actuate the switch, which is known as the pull-in voltage (V_P) and is given by [5]:

$$V_P = \sqrt{\frac{8kg_0^3}{27\varepsilon A}} \tag{4}$$

Current implementations of RF MEMS switches have pull-in voltages ranging from 20 to 80 V which are too high for applications such as portable wireless, low-power, and battery-operated systems. However, based on Equation 4, it is clear that manipulating device dimensions has a direct impact on the pull-in voltage. Lower pull-in voltages are therefore achievable as switch dimensions are scaled down. Naturally, scaling switch dimensions not only affects pull-in voltage, but it also influences other important parameters which ultimately determine performance and reliability. Hence, the impact of scaling is analyzed next.

3. Impact of Scaling on Performance

To obtain a general idea of how scaling influences the performance of RF MEMS switches, an analysis of the impact of scaling on key switch parameters is performed. For the purposes of this paper, it is assumed that all dimensions are scaled by the same factor S. Evidently, different dimensions could be scaled differently to emphasize specific parameters or to achieve a particular design goal.

A. Resistance:

Contact resistance is particularly important for ohmic switches where a small resistance is desired to reduce insertion loss. Contact resistance depends on many factors, including material hardness, contact force, and contact area. Resistance also varies over time due to material deformations that appear as a result of repeated actuation [6]. Since a precise model of contact resistance in ohmic switches can be complicated, a simplified model where resistance is proportional to l/A (l being the length of the beam and A corresponding to the contact area) is assumed for the purposes of this paper. Under this assumption, resistance will change by

$$scaling\ factor = \frac{S}{S^2} = S^{-1}$$

Implying that, in general, contact resistance will increase as dimensions are reduced. Depending on the intended application, additional contact beams in parallel may be used to reduce the overall contact resistance of the switch. Additionally, contacts made using harder metal are preferred to reduce issues related to adhesion.

B. Capacitance:

The capacitance of the switch is another parameter that influences switch performance and is particularly key for capacitive shunt switches where high on capacitance (C_{ON}) is needed for high isolation and small (C_{OFF}) is needed for low insertion loss. Capacitance is given by

$$C = \frac{\varepsilon A}{g} \tag{5}$$

Where ε corresponds to permittivity, A is the parallel plate area, and g is the gap between plates. Consequently, capacitance scales by

$$scaling\ factor = \frac{S^2}{S} = S$$

Therefore, capacitance will be reduced as dimensions are scaled down. This is good for C_{OFF} and any parasitic capacitance but not great for achieving large C_{ON}. Depending on the desired performance, additional switches (in a $SPNT$ configuration) may be used to increase capacitance.

C. Pull-in voltage and stiffness:

As seen in Section 2, the pull-in voltage is a function of the mechanical stiffness of the beam k, the overlapping area A, and the gap g between the suspended beam and the pull-down electrode (see Equation 4). Where k (given by Equation 2) is key in modeling the mechanical behavior of the switch and has a direct impact not just on pull-in voltage, but also on resonance frequency and switching speed (see part D). Based on its equation, stiffness will scale by

$$scaling\ factor = S\left(\frac{S}{S}\right)^3 = S$$

This is an advantage in terms of reducing pull-in voltage and increasing switching speed but it can also reduce reliability (see Section 4). Taking into consideration the scaling factor for stiffness and applying it to the pull-in voltage equation, then pull-in voltage scales by

$$scaling\ fator = \sqrt{\frac{S \cdot S^3}{S^2}} = S$$

Proving that actuation voltage requirements are reduced as dimensions are reduced. This is significant since it makes RF MEMS more attractive for applications where low-power operation and size are critical, such as portable wireless and battery-operated systems. Furthermore, research has shown that reducing applied bias improves reliability [7]. This is explained in more detail in Section 4.

D. Switching speed and resonance frequency:

Another important parameter in switch performance is switching speed and is given by[1]:

$$t = \sqrt{\frac{27}{2}}\frac{V_P}{V_A\omega_0} \tag{6}$$

Where V_P is the pull-in voltage, V_A is the bias voltage (i.e., the actual voltage applied during operation, typically 1.2 – 1.4V_P), and ω_0 is the beam resonance frequency determined by [4]:

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{7}$$

Where k represents the stiffness (which scales by S) and m represents the mass. Mass is proportional to volume and scales by S^3, thus ω_0 scales by S^{-1}. Consequently, switching speed increases with scaling as given by:

$$scaling\ factor = \frac{S}{S \cdot S^{-1}} = S$$

4. Impact of Scaling on Reliability

A major concern regarding RF MEMS switches is reliability. Many research efforts both by universities and private companies [5] have proven the disctinct advantages of RF MEMS switches, yet very few of these devices are commercially available. Several companies including Motorola, IBM, Texas Instruments, Teledyne Scientific, as well as many others, have attempted to develop RF MEMS switches but released no products [2]. Omron Scientific released an RF MEMS Switch in 2009 but discontinued the product in 2014. Analog Devices, a pioneer in MEMS devices and manufacturer of well-known, widely used accelerometers and gyroscopes, has been working with MEMS since the early 1990s and only released an RF MEMS switch until 2016 [9]. The short number of commercially available products compared to the long list of attempts made by the industry reveals that despite all the great promises, manufacturing these devices in a commercially viable way is not an easy task. To understand the challenges that arise with miniaturization of RF MEMS switches, this paper analyses some of the common issues that result from scaling. Just as in Section 4, to establish a general idea of the impact of scaling, it is assumed that all dimensions are scaled equally by a factor S.

A. Stiction:

For proper switch operation, the beam structure needs to remain suspended above the substrate and collapse only in the presence of a bias voltage. However, surface tension forces, chemical bonding, and van der Waals all become significant in micro-scale [4] and can easily overcome the mechanical restoring force of the beam (which is proportional to stiffness as shown in Equation 1), leaving the switch permanently stuck. For instance, if water or humidity finds its way into the gap between the beam and the electrode, its force can be estimated by:

$$F_s = \frac{2A\gamma cos\theta}{g} \tag{8}$$

Where A refers to area, γ is the surface tension per unit length, and θ is the contact angle between the liquid and the surface. When the switch is actuated the gap g becomes very small and therefore F_s increases significantly. Hermetic packaging is therefore critical to prevent humidity and contamination from finding its way and causing stiction. This, however, increases the cost significantly and makes it hard to compete for example with solid state switches which sell starting at US$0.12 [2].

B. Dielectric Charging and Switch Lifetime:

Charge build-up in the dielectric layer of capacitive RF MEMS switches increases over time causing erratic behavior [10]. If enough charge gets trapped in the dielectric (σ_{crit}), Coulomb attraction between the charges trapped and the beam can become strong enough to leave the switch permanently stuck in the down position, even after bias voltage is completely removed. Research by Spengen, et al., has shown that the time required for the enough charge to accumulate, is exponentially dependent on actuation voltage V and is given by [7].

$$t_{fail} = -\tau(\exp \alpha V) \ln\left(\frac{\sigma_{crit}}{N_0 q} - 1\right) \tag{9}$$

Therefore, reducing actuation voltage exponentially extends switch lifetime.

C. *Spring Phenomenon or Creep:*

This phenomenon is produced by long and sustained switch actuation times, where the switch remains actuated for days or even months. Long actuation induces stress and fatigue in metal beams and can lower stiffness, resulting in changes in beam displacement for a given driving voltage [2, 10]. This shifts the pull-in voltage over time and compromises dependability. Low stresses in the actuated beam minimizes this problem [2].

5. Results Summary

The following table (Table 1) summarizes the advantages and disadvantages of downscaling RF MEMS switches:

Parameter	**Scaling Factor**	**Advantages**	**Disadvantages**
Stiffness	S	Improved switching speed and contact force.	Reduced recovery force, higher changes of sticking
Actuation Voltage	S	Pull-in voltage is reduced. Improved lifetime (slower dielectric charging)	
Resistance[1,2]	1/S		Increased contact resistance, additional switches can be used to reduce resistance.
Capacitance[3]	S	Reduced parasitic capacitance and insertion loss	Reduced isolation
Mass	S^3	Improved switching speed, less sensitive to inertial forces (dropping, acceleration, environmental vibrations)	More sensitive to surface physics (air damping, surface tension forces, stiction)
Resonance	1/S	Faster switching	
Switching Time	S	Faster switching	

1- relevant for ohmic switches, 2- simplified resistance model is assumed, 3- relevant for capacitive switches

Table 1. Summary of scaling factor and tradeoffs

6. Conclusion

The advantages of RF MEMS switches have been clearly outlined by multiple research efforts in the past 20 years. Their small size, high linearity, low insertion loss, high isolation, and extremely low power consumption make MEMS based switches ideal for portable wireless and low-power, battery-operated systems. Despite these advantages, high actuation voltage requirements combined with reliability concerns makes it difficult for these switches to make the leap from research projects to commercially available products. As shown in this work, continuing to downscale switch dimensions promises actuation voltage reduction, switching speed improvement, and increased switch lifetime. Certainly, there are some tradeoffs in terms of reliability but some reliability concerns can be appeased by using hermetic packaging. If the cost of packaging is significantly reduced, RF MEMS switches can provide the performance advantages of mechanical switches along with the small size and high integration benefits of solid-state switches.

References:

[1] Rebeiz, G.m., and J.b. Muldavin. "RF MEMS Switches and Switch Circuits." IEEE Microwave Magazine, vol. 2, no. 4, Dec. 2001, pp. 59–71., doi:10.1109/6668.969936.

[2] Rebeiz, G.m., et al. "The Search for a Reliable MEMS Switch." *IEEE Microwave Magazine*, vol. 14, no. 1, 2013, pp. 57–67., doi:10.1109/mmm.2012.2226540.

[3] Goldsmith, C.l., et al. "Performance of Low-Loss RF MEMS Capacitive Switches." *IEEE Microwave and Guided Wave Letters*, vol. 8, no. 8, Aug. 1998, pp. 269–271., doi:10.1109/75.704410.

[4] Senturia, Stephen D. *Microsystem Design*. Kluwer Academic Publ., 2001.

[5] Rebeiz, Gabriel M. *RF MEMS: Theory, Design, and Technology*. John Wiley & Sons, 2003.

[6] Hyman, D., and M. Mehregany. "Contact Physics of Gold Microcontacts for MEMS Switches." *IEEE Transactions on Components and Packaging Technologies*, vol. 22, no. 3, Sept. 1999, pp. 357–364., doi:10.1109/6144.796533.

[7] Spengen, W Merlijn Van, et al. "A Comprehensive Model to Predict the Charging and Reliability of Capacitive RF MEMS Switches." *Journal of Micromechanics and Microengineering*, vol. 14, no. 4, 2004, pp. 514–521., doi:10.1088/0960-1317/14/4/011.

[8] Kaajakari, Ville. *Practical MEMS*. Small Gear Pub., 2009.

[9] E. Carty, P. Fitzgerald, and P. McDaid, "The Fundamentals of Analog Devices' Revolutionary MEMS Switch Technology", *Technical Article*, Analog Devices, 2016.

[10] J. Park, H. Kim, Y. Kwon, Y. Kim, "Tunable millimeter-wave filters using a coplanar waveguide and micromachined variable capacitors", in *Journal of Micromechanics and Microengineering*, vol. 11, no. 6, 2001.