Scaling Effect on RF MEMS Switch

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Abstract

The purpose of this project is to study the scaling effect on (radio frequency) RF micro electromechanical systems (MEMS) Switch. Many MEMS devices' performance could be enhanced tremendously by scaling. This capstone report talks about the benefits and drawbacks of scaling. A detailed analysis on reliability will be introduced. Scaling effects on other parameters such as switching speed and actuation voltage will be discussed. This paper will point out a suggestion of how RF MEMS switch could be optimized and designed in the future.

1. Introduction

RF MEMS Switch has many advantages, over mechanical switches such as relays, including reduced volume, integration compatibility, and the ability of scaling. Scaling is a very important and fruitful topic in MEMS design. The key idea is to achieve better performance of parameters such as operating speed and power consumption through the reduction in size. In following sections, a detailed study on scaling effect on reliability, switching speed, Con/Coff ratio, etc will be analyzed to show the advantages and disadvantages of scaling on RF MEMS Switch. Although there are many structures of MEMS switches including suspended beam, cantilever beam, direct contact ohmic switches, etc. this paper will mainly focus on capacitive suspended beam type structure to explore the scaling.

2. Literature Survey

This section will discuss different types of modern RF MEMS switch design. Their performance will be analyzed to show the room for improvement before scaling. The use of MEMS for RF switching applications was first demonstrated in 1971 using bulk-micromachined cantilever switches. These switches relied on ohmic connection between micro-contacts to establish the RF path. The development of RF MEMS switches using metal membranes with capacitive coupling has also gained its popularity in the following years. Metal membrane switches show good insertion loss, reasonable switching voltages, fast switching speeds, and excellent linearity.

The first type of switch introduced in this section is RF MEMS capacitive switch. According to the reference of Goldsmith et al [2], their switches are built on high-resistivity silicon substrates, with a 1-um-thick layer of silicon dioxide used as a buffer layer. The switch circuitry is fabricated on top of the silicon dioxide using 4-um-thick aluminum coplanar waveguide transmission lines. A top view of the switch is shown in Figure 1. The transmission line metal connects to the lower electrode and dielectric materials to form the through path of a shunt switch.

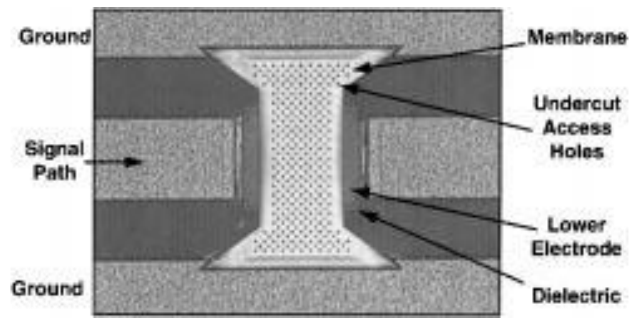

Figure 1. Top view of a MEMS capacitive switch

The insertion loss was kept < 0.3dB up to 35GHz. Most of the loss was due to the transmission line. The isolation is ~-30dB at 35GHz. This isolation is still not enough for applications such as transmitting/receiving switches in radar. The value of Con is 2-4pF and Coff is 20-50 fF. The actuation voltage is 30-50V, which is too high and can cause problems like high power consumption and low reliability. Figure 2 shows insertion loss, return loss for this device vs. frequency.

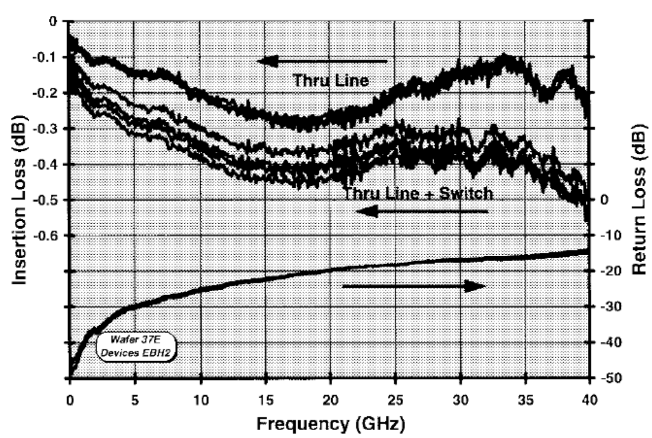

Figure 2. Insertion loss and return loss vs. frequency

The second switch type introduced in this section is a cantilever beam switch with metal-to-metal contacts that are actuated via electrostatics. The switch is connected in a three terminal configuration and can be fundamentally thought of as a source, gate, and drain. Figure 3 shows a simplified graphic representation of the switch structure according to the study of Carty et al [8]. When a dc voltage is applied to the gate, an electrostatic pull-down force is generated on the switch beam. When the gate voltage ramps to a high enough value, it creates enough attraction force to overcome the resistive spring force of the switch beam, and the beam starts to move down until the contacts touch the drain.

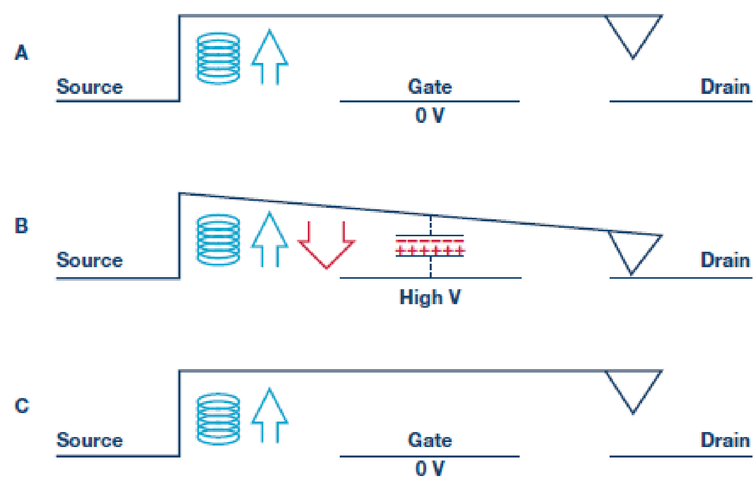

Figure 3. Cantilever based direct contact switch

One of the most important figure of merit is the product of on resistance multiplied by the off capacitance. This is commonly referred to as the RonCoff product and as RonCoff reduces, the insertion loss of the switch also reduces, and the off isolation loss improves. Figure 4 shows a frequency sweep of insertion loss and off isolation for this type of switch designed by Analog Device Inc. At 40GHz, an insertion loss of 1dB and off isolation of ~-30dB were achieved. Other key performances include a minimum of 1 billion actuation cycles lifetime and low power consumptions from 10mW to 20mW.

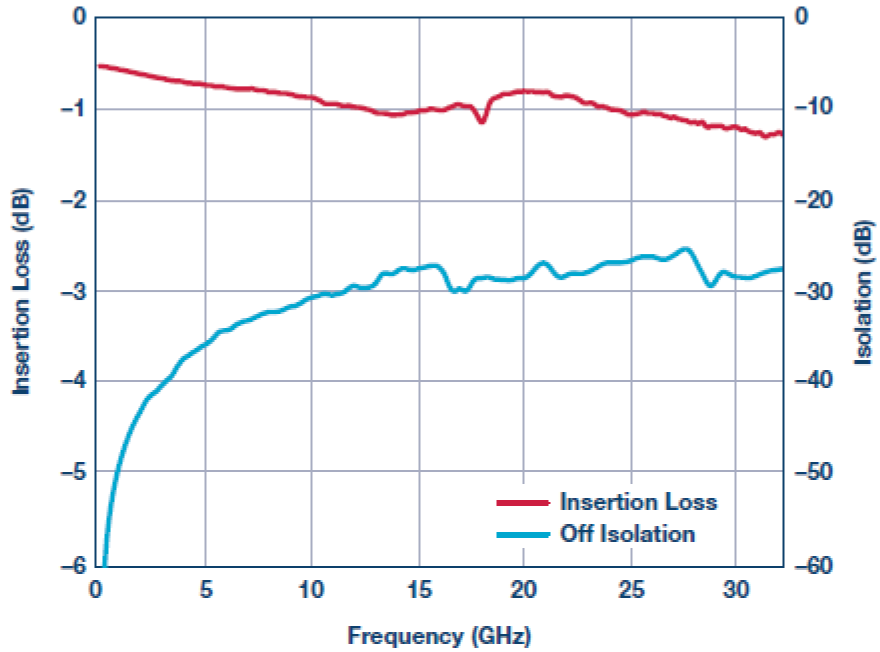

Figure 4. Insertion loss and off isolation vs. frequency

3. Reliability

The commercialization of RF MEMS switch is hampered by reliability. Even if we can enhance a lot of performance of switches such as speed and power consumption, it is useless without reliability. Therefore, reliability is a very crucial topic that this paper will tackle on.

For capacitive RF MEMS switch, the reliability problem is mainly caused by the dielectric charging. The defects that were generated during manufacturing create traps within dielectric films. Those traps will be filled up during the lifecycle of the switch due to the charging and discharging of devices. At later lifetime, the accumulated charges serve as a “built-in” voltage and will affect the actual pull-in and pull-out voltage. It might appear that the switch could “pull-in” easier, but at the same time, the switch would “pull-out” harder because of the built-in voltage. And that will cause the switch’s erratic behavior.

Figure 5 shows the diagram of a standard RF MEMS capacitive switch with suspended beams. Once the applied voltage exceeds the pull-in voltage, the suspended beam would bend down and contact the dielectric as a result of electro-static force.

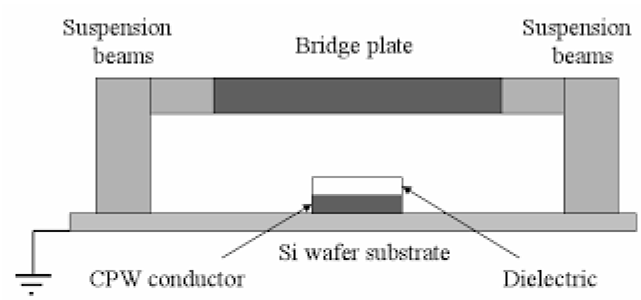

Figure 5. Cross section of an RF MEMS capacitive switch

In order to calculate the effective interface charge, we need to establish a mathematical model to analyze the charge on the bridge related to voltage across plates, parasitic interface, and bulk charges. We will follow the derivation from Spengen et al [9] to get the expression of t_{fail} and explore the scaling effect on reliability from there. Figure 6 shows the geometry of charge modeling. K is the stiffness of bridge, σ_1 is the charge in bridge plate, σ_2 is the charge in dielectric, σ_3 is the charge in substrate, z_1 to z_2 is the gap distance, d is displacement, ε_0 is permittivity of free space, ε_r is relative permittivity of dielectric.

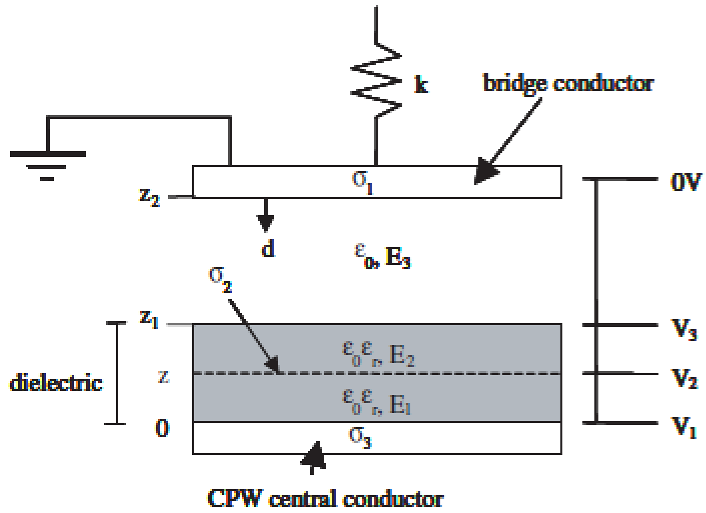

Figure 6. Geometry of the charging model

If we add up the charge related to voltage across plates and parasitic interface and consider interface charge σ_i as a function of $(z_2 - d)$, we can get charge σ_1 expression as:

$$\sigma_1 = -\frac{1}{\varepsilon_r(z_2-d-z_1)+z_1}(\varepsilon_0\varepsilon_r V_1 + z_1\sigma_i) \ (1)$$

Electro-static force F equals charge times electric field. In equilibrium, the force also equals k*d and Q*E could also be rearranged as following equation. The factor $\frac{1}{2}$ is because part of the field is shielded by the charges themselves.

$$F = \frac{1}{2}QE \longrightarrow -kd = \frac{A\sigma_1^2}{2\varepsilon_0} \ (2)$$

In order to better understand the charge model, we will introduce the capacitance vs. actuation voltage curve. For an RF switch in its early lifetime, the CV curve should be similar to Figure 7. For an ideal switch, when the pull-in voltage is reached, Con is higher compared to a practical switch. A practical switch will also pull-out at a voltage slightly higher than 0 because of the effective air gap between the bridge and the dielectric. Through the switching on and off, charge traps are filled through tunneling and accumulated charges serve as a “built-in” voltage. This “built-in” voltage could shift the CV curve and make the pull-out voltage less than 0. And if the pull-out voltage < 0, when we apply the same 0V, the bridge will not pull-out and remain stuck. And that is the moment switch fails. Figure 8 shows this CV curve shift phenomenon.

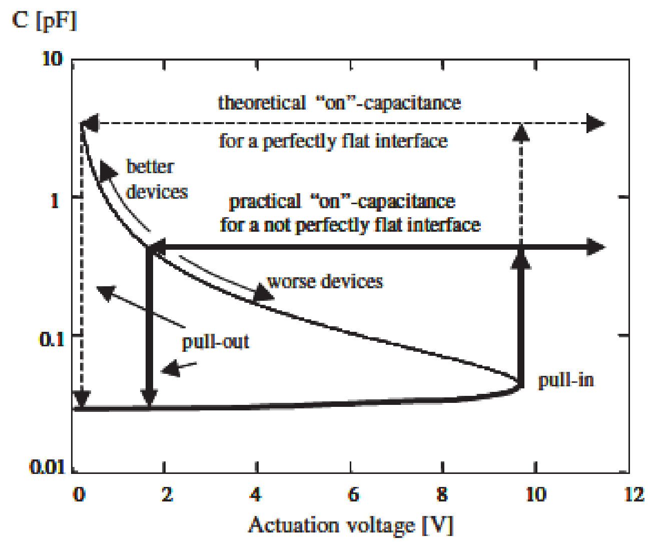

Figure 7. Capacitance vs. Voltage curve for ideal and practical devices

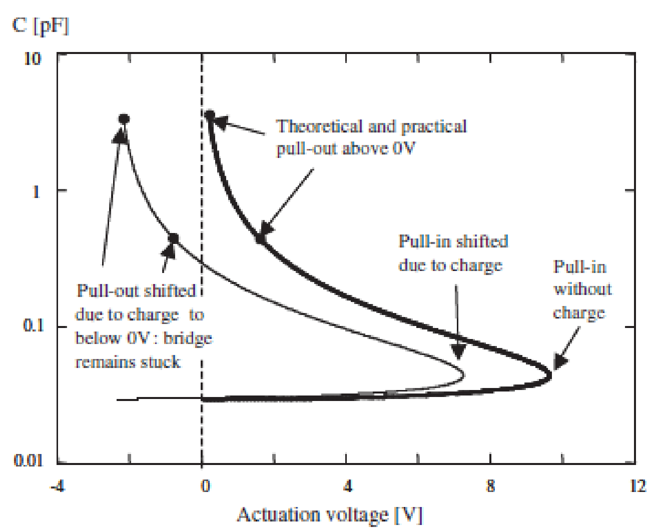

Figure 8. Capacitance vs. Voltage curve shifts over lifetime

And we call the charges that makes the CV curve cross 0V the critical charge or σ_{crit}. By definition, σ_{crit} occurs when $d = z_1 - z_2$ and $V_1 = 0V$. Plug into equations (1) and (2), we get:

$$\sigma_{crit} = -\sqrt{\frac{2\varepsilon_0 k(z_2 - z_1)}{A}}\left(\frac{\varepsilon_r(2z_2 - 2z_1) + z_1}{z_1}\right) \quad (3)$$

For a device with trap density of $N_0$with stressing time t, we can express the accumulated charge in the dielectric as:

$$\sigma = N_0 q(1 - e^{-\frac{t}{\tau}}) \quad (4)$$

According to the study of Goldsmith *et al* [10], the time constant τ of switch is exponentially dependent on the actuation voltage because applied field is responsible for tunneling and trapping, thus the failure of the device. Therefore, after rearranging equation (4), we can get the time to failure t_{fail}. In order to achieve higher t_{fail}, we could either reduce N_0, that is make the device less defective, or we could reduce actuation voltage.

$$t_{fail} = -\tau(\exp(\mathrm{aV})) * \ln\left(\frac{\sigma_{crit}}{N_0 q} - 1\right) \quad (5)$$

For a scaling factor of S, we know that $\sigma_{crit} \sim 1$ and $-\tau(\exp(\mathrm{aV})) \sim \exp(\frac{1}{S})$. Therefore, $t_{fail} \sim \exp(\frac{1}{S})$. And we can plot t_{fail} as:

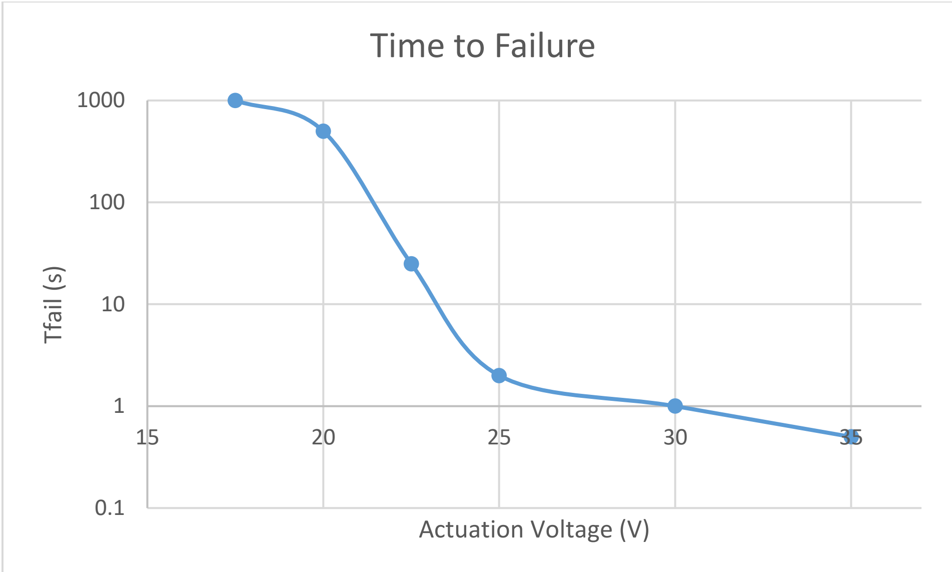

Figure 9. Time to failure vs. Actuation voltage

As Figure 9 suggested, we could improve RF MEMS switch reliability tremendously by reducing the actuation voltage. And that could be achieved by scaling. The scaling benefits and drawbacks will be discussed in the following sections.

4. Scaling Effects

After exploring scaling effect on reliability, this section will investigate scaling effects on other key parameters. The fundamental motivation of scaling is to operate the switch on a lower actuation voltage, a lower power, and a higher speed. Fortunately, scaling could realize all of that.

Pull-in voltage scales with scale factor of S. The fact that pull-in voltage could scale linearly with S makes it possible to actuate the switch with the same voltage applied on other parts' of the integrated circuits without amplifying stage. Power reduced remarkably with S^3. This is one of the most important benefits of scaling on MEMS switches because power consumption is becoming a very serious challenge especially for mobile devices. The switching speed also improved linearly with S because it is in reciprocal relationship with resonance frequency. The increase of resonance frequency could also help with reliability because many industry test shows that the switch is more susceptible to failure when the switch is operated faster than the resonance frequency. The reason behind that is because of difference between electrical actuation signal and mechanical response of the switch. Figure 10 shows a summary of scaling effects on key parameters.

Parameter	Equation	Scaling factor	Typical values* (before scaling)	Target values (after scaling)
Stiffness	$k \propto Ew(\frac{h}{l})^3$	S	5 - 40 N/m	1 - 8 N/m
Resistance	$R \propto \rho\frac{l}{A}$	S^{-1}	0.5 Ω	2.5 Ω
Capacitance	$C = \frac{\varepsilon A}{g}$	S	C_{on}: 1 - 3.6 pF C_{off}: 2 - 8 fF	C_{on}: 0.2 - 0.72 pF C_{off}: 0.4 - 1.6 fF
Pull-in voltage	$V_P = \sqrt{\frac{8kg_0^3}{27\varepsilon A}}$	S	20 - 35 V	4 - 6 V
Resonance	$\omega_0 = \sqrt{\frac{k}{m}}$	S^{-1}	30 - 100 kHz	150 - 500 kHz
Switching Time	$t = 3.67\frac{V_P}{V_S\omega_0}$	S	40 - 91 μs	8 - 18 μs
Power	$P = \frac{1}{2}f_s CV^2$	S^3	2 - 55 μW	0.016 - 0.4 μW

Figure 10. Scaling hypothesis

There are some drawbacks of scaling and the most obvious one is capacitance. Con/Coff ratio does not improve over scaling. And the insertion loss is impacted by reduced Con. For a decent RF switch, we want the insertion loss to be < -30dB. However, with a Con of 0.5 pF, which is normal after scaling, we could only get ~-15dB at 60GHz and that will impact isolation negatively. To accommodate this issue, a parallel set of switches is proposed since the parallel capacitance could add up to achieve better insertion loss. Figure 11 and 12 shows the simulation of Off and On state insertion loss.

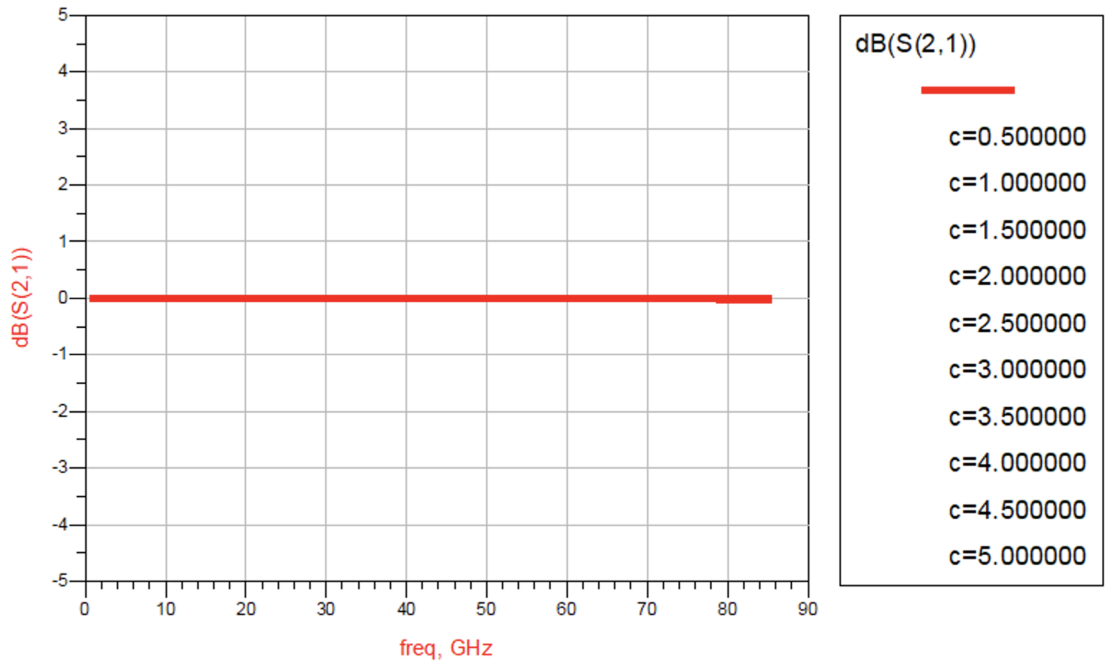

Figure 11. Off state insertion loss

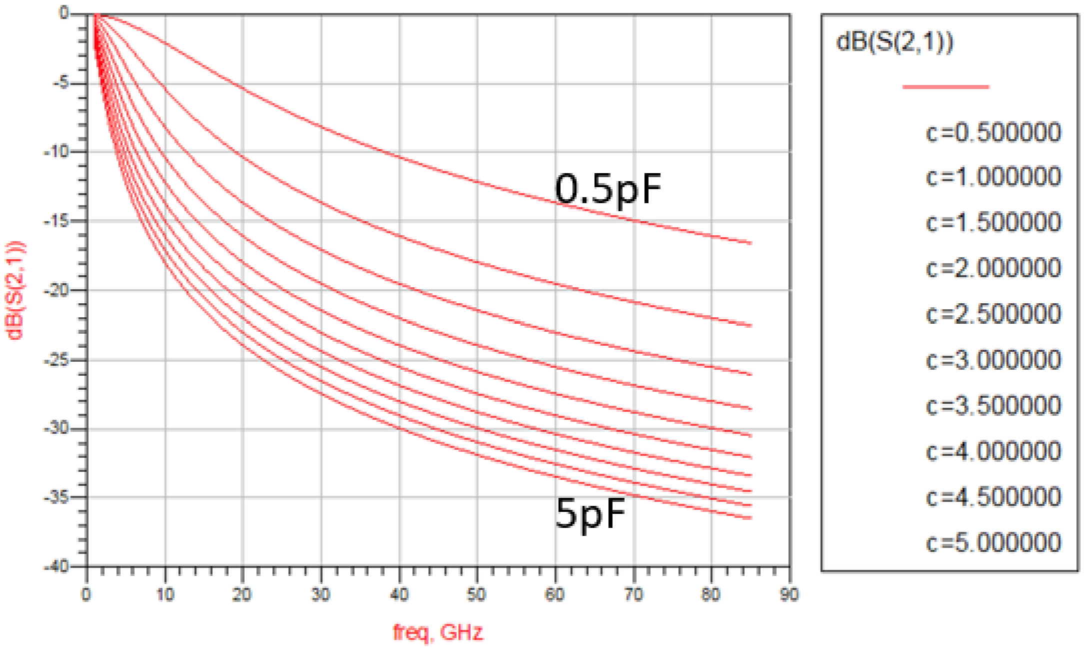

Figure 12. On state insertion loss

Almost all of the performance improved except Con/Coff. Another potential problem with scaling is manufacturability. In this paper, all the dimensions are scaling down. That means the gap is reduced too. In order to achieve the performances mentioned in Figure 6, we should keep the gap at ~200nm. That is a challenge to ensure integrity of the switch structure on the process side. Another challenge is design for test. Industries such as military and automobile applications hold higher standard on the reliability and lifetime of the switch. Even a lot of the theories behind dielectric charging were explained and analyzed in Section 3, cautions must still be taken while transforming the design into products. Different tests with different actuation frequencies, duty cycles, under various humidity and temperature environments should be designed to completely understand the impacts of how scaling is impacting on the device. Figure 13 shows some standard industry test. Use of stiction-free chemicals and oxidation-resistant materials (e.g. SiC) could be considered when designing the switch since metal-to-metal contacts are susceptible to mechanical and electrical stresses such as deformation, fatigue, arcing, melting etc.

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
Random Drop	AEC-Q100 Test G 5, 0.6m
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

Figure 13. Different Industry Standard Reliability Tests

5. Applications

There are majorly 2 types RF switches: electromechanical relays and semiconductor-based devices. The disadvantages of relays is its size and switching speed. Moreover, relays cannot be integrated onto chips, even though many IC companies still use relays on their automatic test equipment nowadays. RF MEMS capacitive switches could be utilized as essential applications in many fields, ranging from military/aerospace to RF communication. This section will discuss some interesting applications among many to reveal its essence in modern IC design.

Most industry experts agree that smartphone market will be the main driving force for the high-volume production of RF MEMS ICs. Since it does not require advanced node for MEMS switch like mobile CPU requires, many small-size vendors seek opportunities to cooperate with smartphone giants such as Samsung and Apple. The technology node required for advanced RF MEMS switch is only ~180nm. Those vendors aim is to provide reliable switching, fast switching time, and a MEMS device that can be integrated using over-molding and bumping techniques. For example, DelfMEMS uses a patented push-pull, anchorless membrane MEMS switch structure that it claims is a new approach to ohmic switching. It is supported by just two pillars and because it is anchorless, it has no package or temperature dependencies. This device has small gap and high restoring force and offers a controlled switch state.

Another important application is in the ATE arena. Because many ATE equipment are supposed to test mixed-signal up to 10s GHz and requires very low noise and reflection, the spec or qualities of such switches have higher standard. For instance, Omron Corp introduced a 10 GHz SPDT RF MEMS switch aimed at ATE applications in 2009. It has a life expectancy of 100 million operations, 30-dB isolation, and 1-dB insertion loss. The switch uses an electrostatic drive mechanism and can be manufactured on both 5-in. and 8-in. MEMS wafer production lines. Like the smartphone segment, ATE sectors foresee large benefits and many applications from the use of RF MEMS switch developments. However, additional research needs to be performed for mass-production of such switches at low cost and improved reliability and increased lifetime.

6. Conclusions and Future Work

In this paper, a detailed RF MEMS switch failure model was analyzed and the theoretical time to failure was calculated. Scaling down could improve switch lifetime exponentially. Also with scaling, pull-in and pull-out voltage could be reduced linearly. Power consumption could be reduced with S^3. Switching time could be reduced linearly. Due to the requirement of high isolation for some applications, multiple switches need to be instantiated in parallel. To maintain the reliability of the switch, discharging of the dielectric is a must and limit the switching speed lower than the resonance frequency of the switch to avoid failure.

Future work is to investigate on the manufacturability at the proposed scale (~200nm). After scaling down, the film stress and structure stability needs to be requalified to ensure that real device's performance is consistent with scaling hypothesis.

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