Chapter 2

Review and Objective

2.1 Introduction

MEMS switches are devices whose operation is based on the use of mechanical movement to achieve a short circuit or an open circuit in a RF transmission line. Mostly electrostatic and magnetostatic type switches have been demonstrated at 0.1-100 GHz with high reliability (100 million to 60 billion cycles) and wafer scale manufacturing techniques [1]. As outlined in the next section there are several advantages of MEMS switches over other traditional switches.

2.2 Advantages of MEMS switches over traditional switches

With the increased demand for faster, smaller, highly tunable and cheaper communication systems that consume less power and have wider bandwidths for increased data rates, micromachining techniques have gained much importance. Structures such as low loss and high isolation MEMS switches, reconfigurable antennas, filters and tuners, high-Q passives and resonators, low loss planar THz waveguide components and low loss phase shifters are a few examples of revolutionary RF/microwave components that the implementation of this technology has led to. The essential idea in RF MEMS is to use miniature mechanical devices and physical motion to achieve the function of a microwave switch or a variable capacitor. The high performance is due to the very low capacitance and contact resistance, which can be achieved using RF MEMS technology as compared to GaAs PIN diodes or FETs. It is possible to build RF
MEMS switches with a figure-of-merit cut-off frequency of 30-80THz, which is about 100 times better than GaAs transistors. MEMS switches enjoy several advantages over semiconductor switches in the RF applications namely [1]

a) Near-Zero Power Consumption: Electrostatic actuation requires 20-80 V but does not consume any current, leading to very low power dissipation; (10-100 nJ per switching cycle).

b) Very High Isolation: RF MEMS series switches are fabricated with air gaps, and therefore, have very low off-state capacitances (2-4 pF) resulting in excellent isolation at 0.1-40 GHz.

c) Very Low Insertion Loss: RF MEMS series and shunt switches have an insertion loss of -0.1dB up to 40 GHz.

d) Intermodulation Products: MEMS switches are highly linear devices and, therefore, result in very low intermodulation products. Their performance is around 30 dB better than PIN or FET switches.

e) Very Low Cost: RF MEMS switches are fabricated using surface micromachining techniques and can be built on quartz, Pyrex; low-temperature co fired ceramic (LTCC), mechanical-grade high-resistivity silicon, or GaAs substrates.

However, RF MEMS switches also have their share of problems, such as:

a) Relatively Low Speed: The switching speed of most MEMS switches is around 2-60 μs. Certain communication and radar systems require much faster switches.

b) Power Handling: Most MEMS switches cannot handle more than 20-50mW. MEMS switches that can handle 5-10 W with high reliability simply does not exist commercially.
c) High-Voltage Drive: Electrostatic MEMS switches require 20-80 V for reliable operation, and this necessitates a voltage up-converter chip when used in portable telecommunication systems.

d) Reliability: The reliability of MEMS switches is 0.1-10 billion cycles. However, many systems require switches with 20-200 billion cycles. Also, the long-term reliability (years) has not yet been addressed.

e) Packaging: MEMS switches need to be packaged in inert atmospheres (nitrogen, argon, etc.) and in very low humidity, resulting in hermetic or near-hermetic seals. Packaging costs are currently high, and the packaging technique itself may adversely affect the reliability of the MEMS switch.

f) Cost: While MEMS switches have the potential of very low cost manufacturing, one must add the cost of packaging and the high-voltage drive chip. It is, therefore, hard to beat a $0.30-0.60 single-pole double-throw 3V PIN or FET switch, tested, packaged and delivered.

It is important to point out that RF MEMS switches developed today, even if quite small; still follow the basic mechanical laws developed a few hundreds of years ago. However, the scale and relative importance of the forces are significantly different from the macro world. Surface forces and viscous air damping dominate over inertial and gravitational forces. The switches have very low mass and therefore are not sensitive to acceleration forces. Based on the type of circuit configuration RF MEMS switches can be of two types: (a) series switch and (b) shunt switch.

2.3 Series MEMS capacitive switch

There are two types of MEMS series switch [1]: the broadside series switch [Figure 2.1(a) and (b)] and the inline series switch [Figure 2.1(c)]. The
actuation of the broadside switch is in a plane that is perpendicular to the transmission line, while the actuation of the inline switch is in the same plane as the transmission line. The actuation mechanism is achieved using an electrostatic force between the top and bottom electrodes.

Figure 2.1: Broadside MEMS-series switches with (a) one electrode, (b) two electrodes, and (c) inline MEMS-series switches.

2.4 Shunt MEMS capacitive switch

There are different types of MEMS shunt capacitive switches, which provide different performances. One example of those switches is given in figure 2.2, in which the shunt switch is based on a fixed-fixed beam design. The anchors are connected to the CPW ground plane, and the membrane is grounded. The center electrode provides both the electrostatic actuation and the RF capacitance between the transmission line and the ground. When the switch is in the up state it provides low capacitance to the ground, and it does not affect signal on the transmission line. When the switch is actuated in the downstate, the capacitance to
the ground becomes higher and this results in an excellent short circuit and high isolation at microwave frequencies [1].

Figure 2.2: MEMS capacitive shunt switch: (a) Top-view, (b) Cross-sectional view and (c) electrical CLR model

2.5 Comparison between different switches

2.5.1 Comparison between series and shunt switches

There is a marked difference in isolation between the series and shunt MEMS shunt switch configurations which can be explained qualitatively, at least at low frequencies by the equivalent circuits as in figure 2.3. In these circuits $Z_s$ is the impedance of the switch in the off state and $Z_0$ is the characteristic impedance of the transmission line in which the switch is embedded. For both configurations $Z_s \sim 1/j\omega C_s$, in the off state; where $C_s$ is relatively small in the series switch and large in the parallel switch. By definition, isolation $I$ is the power from the source divided by the power delivered to the load or $I = 1/|S_{21}|$; where $S_{21}$ is the forward scattering parameter. For the series model of figure 2.3(a), circuit analysis yields $I = (\omega Z_0 C_s)^2 /[1 + (\omega Z_0 C_s)^2]$. For the parallel switch in figure 2.3(b) it is
seen that \( I = 1/[1 + (\omega Z_0 C_s)^2] \). Both expressions are consistent with the observed low frequency behavior. The isolation of the series switch approaches zero in the limit of zero frequency and degrades with frequency as \( \omega^2 \). The isolation of the parallel switch approaches unity in the limit zero frequency and remains relatively constant up to a roll off frequency of \( f \sim 1/(2\pi Z_0 C_s) \). Well above this frequency, the isolation improves with frequency as \( \omega^{-2} \). The MEMS capacitive shunt switch thus is a better choice for high frequency applications [1].

![Figure 2.3: Equivalent circuit diagrams for (a) series switch and (b) shunt switch](image)

### 2.5.2 Comparison between metal to metal and capacitive contact switches

There are two different contacts in RF MEMS switches, a capacitive contact and a metal to-metal (or DC) contact. The capacitive contact is characterized by the capacitance ratio between the up-state (open circuit) and down-state (short-circuit) positions, and this is typically 80-160 depending on the design. The down-state capacitance is typically 2-3 pF, and is suitable for 8-100GHz applications. In general, it is hard to obtain a large down-state capacitance using nitride or oxide layers, and this limits the low-frequency operation of the device. On the other hand, DC-contact switches with small up-state capacitances (open circuit) can operate from 0.01 to 40GHz, and in some cases, to 60GHz (for
example, the Rockwell Scientific switch has an up-state capacitance of only 1.75 fF and an isolation of 23 dB at 60GHz). In the down state position (short-circuit), the DC-contact switch becomes a series resistor with a resistance of 0.5-2Ω, depending on the contact metal used. Whereas ohmic contact switch reliability issues are centered on the metal-metal contact, reliability issues for electrostatically-operated capacitive switches revolve around dielectric charging of the switch dielectric when high voltage is applied to the switch terminals. The primary failure mechanism of ohmic switches is the degradation of the switch contacts due to contamination. Again, capacitive switches experience a non-permanent accumulation of dielectric charge, which increases when the switch is on and decreases when the switch is off. Excess charge accumulation ultimately causes the capacitive switch to operate in an intermittent fashion. Strategies for improving capacitive switch longevity involve 1) reducing operating bias voltages, 2) incorporating electrical designs which trade capacitance ratio for lifetime (typically achieved through a change in the dielectric to air ratio), and 3) innovative materials development.

### 2.5.3 Comparison between actuation mechanisms

The actuation forces required for the mechanical movement can be obtained using electrostatic, magneto-static, piezoelectric or thermal designs. Electrostatic actuation is the most prevalent technique in use today due to its virtually zero power consumption, small electrode size, thin layers used, relatively short switching time (2-60μs), 50-200μN of achievable contact force, and the possibility of biasing the switch using high-resistance bias lines. In many cases, thermal actuation is coupled with an electrostatic (voltage) hold, or a magnetostatic actuation (current in a coil) is coupled with a permanent magnetic field.
To date, only electrostatic-type switches have been demonstrated at 0.1-100GHz with high reliability at low RF powers for metal contact and medium power levels for capacitive contacts (100 Million to 50 Billion cycles depending on the manufacturer) and wafer-scale manufacturing techniques. Other switches which have demonstrated excellent performance are the Microlab Latching switch (up to 100 Million cycles) using magnetic actuation, and the thermal switches developed independently by Cronos Microsystems and the Univ. of California, Davis [2]. It is hard to test thermal switches for long cycle times due to their slow switching response (1-3ms).

2.6 RF MEMS Limitations and present research scenario

Like any other technology RF MEMS too comes with its own share of problems. Apart from the major drawbacks like high actuation voltage and slow switching speed there are also two problems associated with standard MEMS capacitive devices which are dielectric charging problems in the isolator layers (leading to stiction) and temperature sensitivity of the movable membrane, especially for fixed-fixed beam designs [5].

2.6.1 Improvements in the micromechanical aspect

(a) Improvement in actuation voltage

The use of low spring constant designs like meandering suspensions [6, 7] or thin springs [8, 9] to achieve lower actuation voltage has been a standard practice in the past. But such designs often compromise with the reliability of the device and the switching speed. The use of push-pull concepts [10, 11, 12] have also been investigated but it requires a relatively high actuation voltage. A novel low cost spring less RF MEMS switch has also been reported with a mechanically unconstrained armature. A prototype has been fabricated on a PCB bonded to a
glass slide but the device suffers from very high actuation voltage and low switching speed [13]. Also, the use of low-height bridges has been reported to lower the actuation voltage but the price paid is a reduction in the capacitance ratio [14]. The use of new materials like AlSi$_{0.04}$[15] or Pt [16] as membrane for the MEMS switch, use of electromagnetic actuation along with electrostatic forces [17] and exploiting buckling and bending effects induced by well controlled residual stress [18] has been demonstrated for lowering the actuation voltage. The residual stress in the MEMS bridge is a key parameter affecting the actuation voltage and studies have been carried out to analyze its effect on the electromechanical performance of the switch [19-22]. Niu et al. [23] have presented a miniature RF MEMS switch design optimized for high residual stress and stress gradient available in the thin metal layer process. A simple analytical method for residual stress measurement of suspended MEMS structures using surface profilometry has been presented in [24]. It is also seen that the introduction of corrugation in the bridge also helps to reduce the residual stress in the diaphragms for achieving low actuation voltages [25]. One may note here that the internal stress gradients in the bridge cause it to warp. A thick and stiff bridge may be developed to overcome this problem but will result in a complex fabrication procedure if low actuation voltage is to be achieved [26]. However, AlSi$_{0.04}$ has a much higher RF transmission loss, a switch with two actuation mechanisms has an elaborate and complicated fabrication procedure and the controlling of the residual stress is a major challenge. Recently a totally free flexible membrane supported over three pillars to lower the actuation voltage has been proposed but it requires a double sacrificial layer system and suffers in switching speed [27]. Very recently, low actuation voltage through three electrodes topology is presented [28], but such structures are difficult to realize. Special mechanical structures for stiffness enhancement have also been designed. A method of using dimple lines to reduce the stress sensitivity of the bridge is shown with complete modeling and
simulation [29]. Recently a RF MEMS switch with a differential gap between electrodes has been presented for high isolation and low voltage operation. However, the proposed RF MEMS switch was fabricated with seven (7) photomasks on a quartz wafer [30]. Summing up, the lowering of the actuation voltage will allow for RF MEMS-CMOS device integration which is an interesting area of current research [31]. A low actuation voltage design for RF CMOS-MEMS switches has also been reported [32] along with a low actuation voltage RF MEMS switch for WiMAX applications [33]. It is important to note here that any design to reduce the actuation voltage will involuntarily cause an increase in the switching time.

(b) Improvement in switching speed

Achieving a high switching speed remains a major limitation, and little work has been done to improve the speed of RF MEMS capacitors and switches. It is seen that by introduction of damping holes in the base substrate wafer for a wafer-level encapsulated RF MEMS DC shunt switch the squeeze-film damping may be reduced thereby increasing the switching speed of the device [34]. However the technique proposed by Mercier et al. by the miniaturization of the switches to obtain high speed and reliability by far remains the best method [35]. Further, Mercier et al. [36] have demonstrated sub-microsecond switching times using dielectric membrane switches with built in tensile stress, and Lacroix et al. [37] have demonstrated that adding simple bent sides on miniaturized beam edges enhances the spring constant of the beam causing a further increase in the mechanical resonance frequency leading to a sub-microsecond switching time. The fundamental processes including electron conduction and adhesion of metallic contacts pertaining to the scaling of the switches has also been presented in [38]. Generally, the improvement of switching speed of a RF MEMS switch affects
adversely the switching voltage. A faster switching can be obtained with increased stiffness, but it will inevitably increase the actuation voltage.

### 2.6.2 Improvement in the dielectric layer

The influence of surface roughness of the dielectric layer severely affects the capacitance ratio of such switches. An accurate description of the roughness by utilizing the statistical approach is reported [39]. It is seen that when the metal bridge is driven down, the normalized contact area between the metal bridge and the surface of the dielectric layer governs the up state and down state capacitance of the device [40]. Frameworks are also proposed to understand how contact resistance evolves due to changes in the contact area, the number of asperities in contact, temperature and resistivity profiles at the contact points [41]. The reliability of the RF MEMS capacitive shunt switch is mainly dependent on the dielectric charging phenomenon and comprehensive models to predict the same has been reported [42]. The impact of the dielectric material [43, 44, 45], distributed dielectric charging [46] and the modeling of dielectric charging [47, 48, 49, 50] has been demonstrated for better understanding. Many materials systems are currently under consideration as potential replacements for SiO$_2$/Si$_3$N$_4$ as the dielectric material for RF MEMS technology. They include Al$_2$O$_3$/ZnO alloys, amorphous diamond, PZT, PZT/HfO$_2$ multi layers, HfO$_x$N$_y$, polymer-ceramic composites, BST, TiO$_2$, HfTiAlO etc. Recently, RF MEMS capacitive shunt switch with leaky nano diamond dielectric film has been studied and compared with silicon nitride and it shows that the charge trapping is reduced as compared to silicon nitride [51]. The use of parylene as the dielectric for lateral RF MEMS capacitive switch also shows promising results [52]. Very recently a high isolation lateral RF MEMS capacitive switch based on HfO$_2$ dielectric for high frequency applications has been demonstrated where the film has been deposited by Atomic Layer Deposition (ALD) process. The results demonstrate that HfO$_2$ film is a good
candidate for RF MEMS applications [53]. The use of AlN as an alternative dielectric has also been investigated [54]. Consideration of the required properties of dielectric material as insulation layer indicates that the key guidelines for selecting an alternative dielectric are (a) dielectric constant, (b) dielectric strength, (c) resistivity, (d) leakage current, (e) surface roughness, (f) ferroelectric properties and (g) charge trapping density. Many dielectrics appear favorable in some of these areas, but very few materials are promising with respect to all of these guidelines. While work is ongoing, much research is still required, as it is clear that any material which is to replace SiO$_2$/Si$_3$N$_4$ as dielectric faces a formidable challenge. The requirement for process integration compatibility is a major concern and an alternative will only emerge through continued and intensive probing. Research is still ongoing on silicon nitride films and very recent work shows that Kelvin Probe Method has been directly applied to capacitive MEMS switches in order to investigate temperature activated mechanisms in PECVD silicon nitride films [55]. Long term RF burn-in effects on dielectric charging of MEMS capacitive shunt switches has been recently researched and it is seen that high RF power could be applied periodically to rejuvenate the switches [56]. The humidity in the environment is also seen to affect the dielectric charging effect in RF MEMS capacitive switches. It is seen that the injected charge quantity increases linearly with increasing humidity [57]. The hysteresis in the operation cycle of the switch also plays an important role in the static and dynamic behavior of the device. The hysteresis in voltage arises due to different stresses suffered by the bridge when changing states. At the pull-down voltage the beam makes contact with the bottom electrode but when the bias is decreased the move up occurs in a voltage much lower than the threshold voltage, characterizing an intrinsic hysteresis of MEMS switches.
2.6.3 **Improvement in the power handling capability**

Power handling capability of the RF MEMS switches are mainly limited by two factors (a) Joule heating for high power which causes melting and welding of the contact and (b) Self biasing and / or RF latching. Authors have reported electro thermal models to predict the power handling capability of RF MEMS switches and have also presented analytical equations to show how the negative feedback of the electrostatic force introduced by the capacitive mismatch changes the pull in characteristics of the structures and can even stabilize it, totally avoiding the pull in phenomenon [58]. The use of switch matrices [59, 60, 61] and two bridge level topology [62] has been investigated till 8W of RF power. Also, RF MEMS switched capacitors using a thick metal process has been shown to handle powers up to 10W [63, 64]. The use of Au- Ru contact also helps in achieving a high power handling capability [65]. A novel design which increases both the restoring force and the self – actuation voltage has been demonstrated for high power handling [66]. Further with a Pt-Au microspring contact, the power handling ability and reliability of metal to metal contact RF MEMS switch also improves [67]. Alternatively, LMEMS (Laminate MEMS) technology can be used to realize a switch functioning up to 10GHz and 50W power handling capability [68]. It is also seen that an enhancement of RF MEMS switch reliability may be obtained by a mechanism which exploits the heat generated to induce deformations in the MEMS structures resulting in shearing and vertical restoring forces [69]. The optimization of the actuation pulse by Taguchi’s optimization method is seen to give better control over the switching conditions for achieving high reliability and longevity [70]. A comparison between voltage waveforms to enhance the lifetime of MEMS switch has been reported in [71]. It is also seen that mitigation of MEMS switch contact bouncing may be overcome by an effective dual pulse actuation waveform [72]. For the design of high reliability RF MEMS switch, an
estimate of the RF performance from low frequency measurements can be obtained by the use of a very accurate lumped equivalent circuit model and wafer-level measurements of the up and down state capacitances. The technique is efficient in tracking or predicting deviations due to the manufacturing process which is difficult to account for experimentally [73]. Active thermal recovery capability (active restoring mechanism) to counteract stiction has also been proposed for high reliability switches [74]. It is also seen that RF MEMS switches with RuO$_2$-Au contacts can be cycled up to 10 billion times [75]. Very recently, a rugged and reliable ohmic MEMS switch has been demonstrated by Maciel et al. [76]. The robustness of RF MEMS capacitive shunt switches in harsh environments has been presented which overviews the advances in packaging, reliability and environmental robustness [77].

2.6.4 Improvement in the RF performance by reduction in parasitic

The resistivity–frequency plane of such devices can be divided in three main regions: the dissipative dielectric region, the slow-wave region and the skin effect region [78]. Analysis [79] indicates that the parasitics play an important role in determining the Q factor of the device. CMOS-grade low-resistivity silicon substrate is not suitable for high-frequency applications due to its attenuation for RF signals. For the high resistivity substrates, a frequency of 10 GHz or more is large enough to drive the silicon substrate into its dissipative dielectric mode. Thus the role of substrates and the use of a suitable passivation layer play an important role in the RF performance of the device. By using polymers tens of microns thick [80, 81, 82], such as polyimide resin, BCB resin and Kapton as the passivation layer on the low resistivity Si substrate, the insertion loss could be reduced to less than 3dB/cm at 40 GHz [80]. Etching away the silicon substrate, leaving only polymer under the CPW line would further reduce the insertion loss to 1 dB/cm or less at 40 GHz [80].
2.7 **Objective of the thesis**

By keeping in mind the limitations of the RF MEMS technology discussed above, a novel design having the manifold advantage of simultaneously reducing the actuation voltage, switching time and substrate parasitics has been presented. The objective of the thesis is as follows:

- To design, model and simulate the novel RF MEMS switch for evaluating its static, dynamic and electromagnetic performance.
- To fabricate and characterize the optimized design obtained from the above mentioned analysis.
- To design and realize a performance enhanced tunable filter and phase shifter as applications of RF MEMS switch.

**References**


