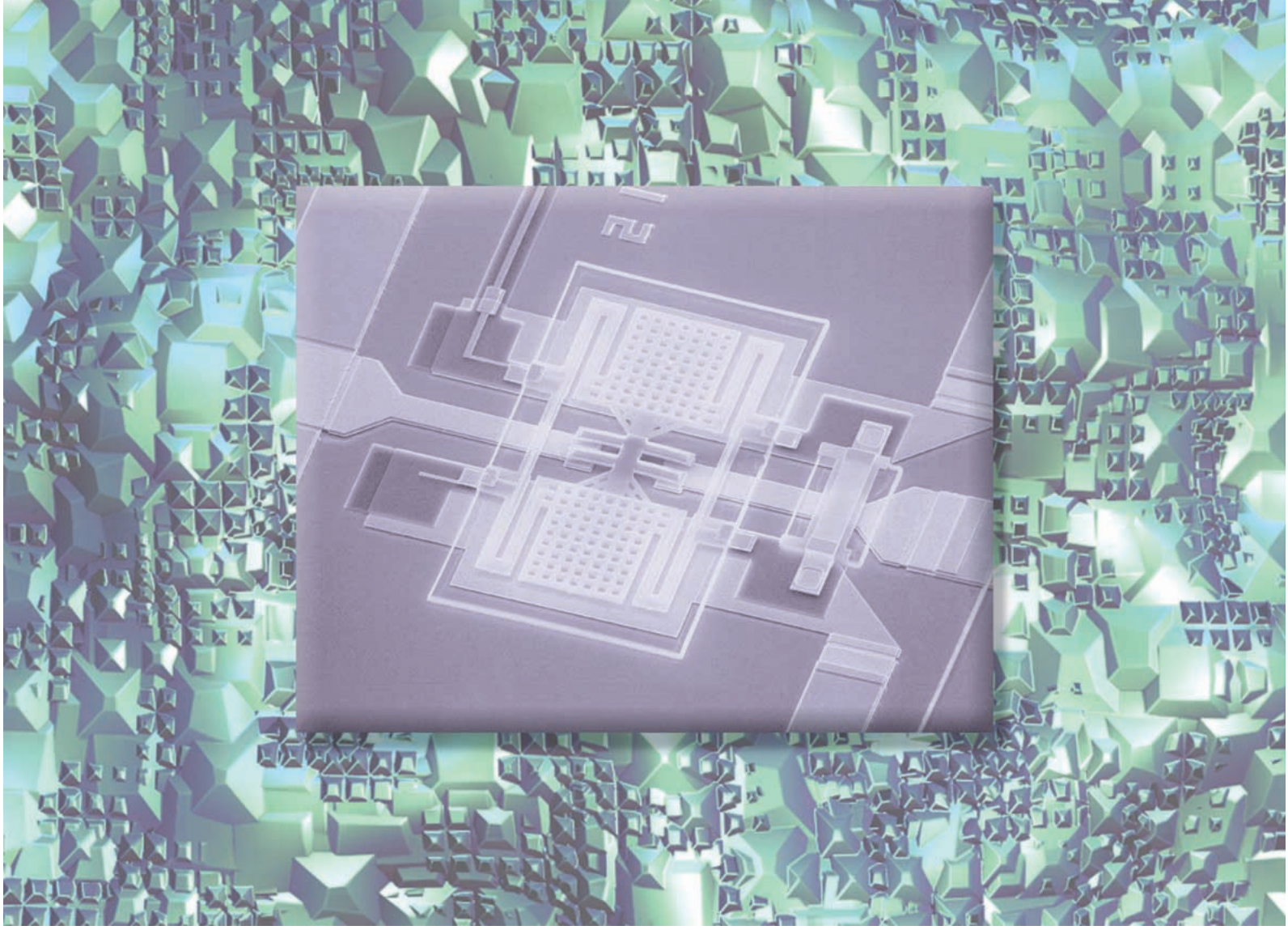

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RF MEMS Switches and Switch Circuits

Gabriel M. Rebeiz, Jeremy B. Muldavin

This article presents the latest development in RF microelectromechanical systems (MEMS) switches and high-isolation switch circuits. RF MEMS switches offer a substantially higher performance than p-i-n or field-effect transistor (FET) diode switches and have been used extensively in state-of-the-art MEMS phase shifters and switching networks up to 120 GHz. RF MEMS technology is now at a turning point; important issues, such as long and short-term reliability, packaging techniques and their effect on reliability, and production costs, are currently being addressed. RF MEMS application areas are in phased arrays and reconfigurable apertures for defense and telecommunication systems, switching networks for satellite

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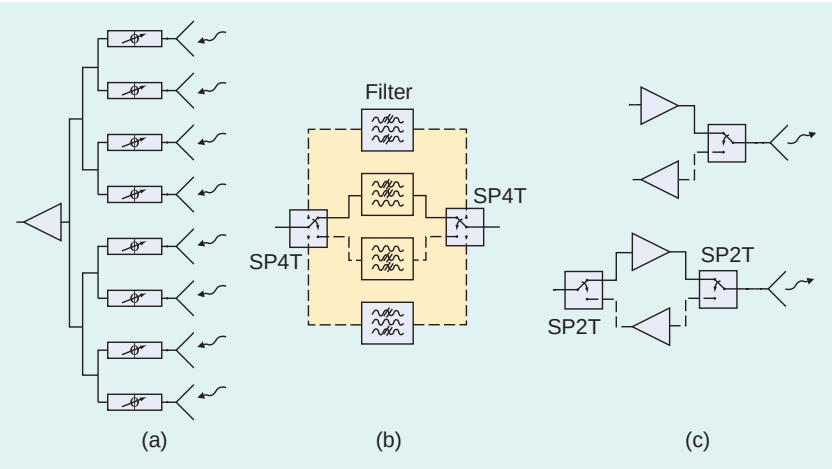

Figure 1. *Some application areas of MEMS switches: (a) phased arrays, (b) switched filter banks for wireless applications, and (c) SP2T T/R switches.*

communications, and single-pole N-throw switches for wireless applications (portable units and basestations).

Touch of Reality

MEMS switches are devices that use mechanical movement to achieve a short circuit or an open circuit in the RF transmission line. RF MEMS switches are the specific micromechanical switches that are designed to operate at RF-to-milimeter-wave frequencies (0.1 to 100 GHz). The forces required for the mechanical movement can be obtained using electrostatic, magnetostatic, piezoelectric, or thermal designs. To date, only electrostatic-type switches have been demonstrated at 0.1-100 GHz with high reliability (100 million to 10 billion cycles) and wafer-scale manufacturing techniques. It is for this reason that this article will concentrate on electrostatic switches.

The advantages of MEMS switches over p-i-n-diode or FET switches are:

- *Near-Zero Power Consumption:* Electrostatic actuation requires 20-80 V but does not consume any current, leading to a very low power dissipation (10-100 nJ per switching cycle).
- *Very High Isolation:* RF MEMS series switches are fabricated with air gaps, and therefore, have very low off-state capacitances (2-4 fF) resulting in excellent isolation at 0.1-40 GHz.
- *Very Low Insertion Loss:* RF MEMS series and shunt switches have an insertion loss of –0.1 dB up to 40 GHz.
- *Intermodulation Products:* MEMS switches are very linear devices and, therefore, result in very low intermodulation products. Their performance is around 30 dB better than p-i-n or FET switches.
- *Very Low Cost:* RF MEMS switches are fabricated using surface micromachining techniques and can be built on quartz, Pyrex, low-temperature cofired ceramic (LTCC), mechanical-grade high-resistivity silicon, or GaAs substrates.

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

- *Relatively Low Speed:* The switching speed of most MEMS switches is around 2-40 μs. Certain communication and radar systems require much faster switches.
- *Power Handling:* Most MEMS switches cannot handle more than 20-50 mW. MEMS switches that handle 0.2-10 W with high reliability simply do not exist today.
- *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.
- *Reliability:* The reliability of mature 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.
- *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 effect the reliability of the MEMS switch.
- *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 3-V p-i-n or FET switch, tested, packaged, and delivered.

The main application areas of MEMS switches (Figure 1) are:

- *Radar Systems for Defense Applications (5-94 GHz):* Phase shifters for satellite-based radars (20 billion cycles), missile systems (0.1-1 billion cycles), long range radars (20-200 billion cycles).
- *Automotive Radars:* 24, 60, and 77 GHz (1-4 billion cycles and 10 years).
- *Satellite Communication Systems (12-35 GHz):* Switching networks with 4×4 and 8×8 configurations and reconfigurable-Butler matrices for antenna applications (0.1 million cycles). Switched filter banks (0.1-100 million cycles, depending on the application). Also, phase shifters for multibeam satellite communication systems (1-20 billion cycles).
- *Wireless Communication Systems (0.8-6 GHz):* Switched filter banks for portable units (0.1-1 million cycles), switched filter banks for basestations (0.1-10 billion cycles), general SP2T to SP4T switches

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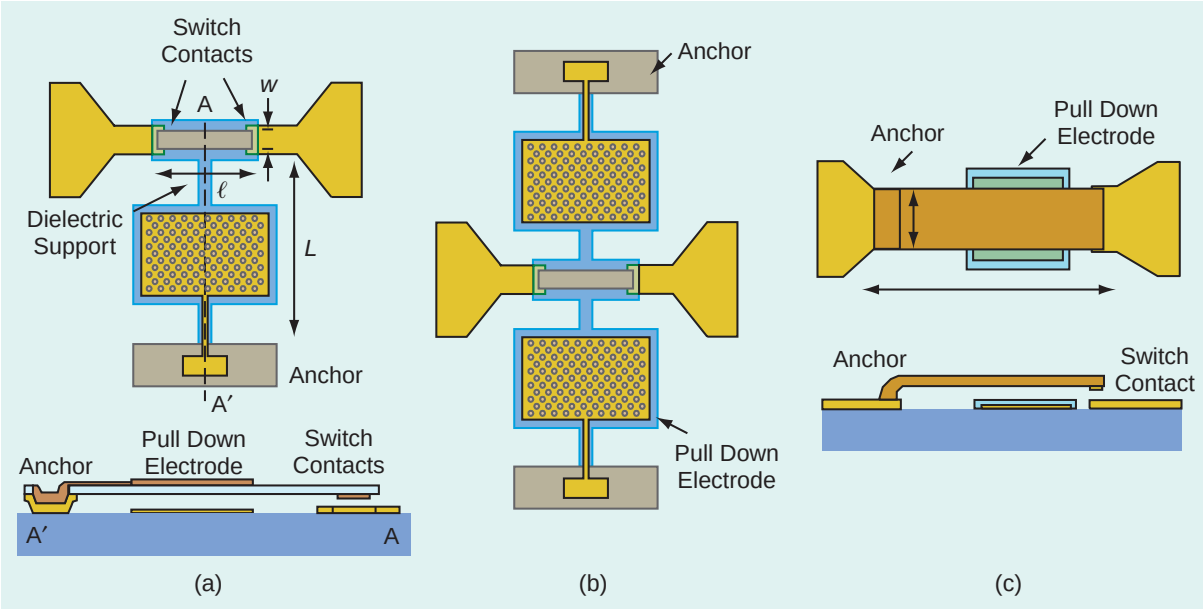

Figure 2. *Broadside MEMS-series switches with (a) one electrode, (b) two electrodes, and (c) inline MEMS-series switches.*

(0.1-10 billion cycles), transmit/receive switches (2-4 billion cycles and 5-20 µs switching time), and antenna diversity SP2T switches (10-100 million cycles).

- *Instrumentation Systems (0.01-50 GHz):* These require high-performance switches, programmable attenuators, SPNT networks, and phase shifters capable of at least 20-40 billion cycles and 10 years of operation, especially in industrial test benches.

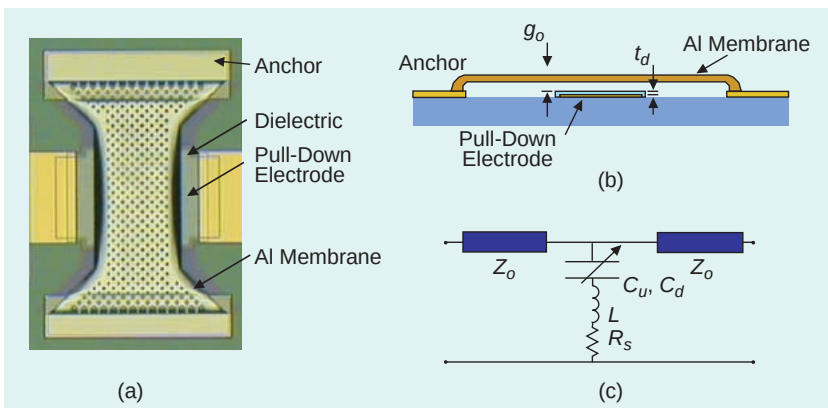

Figure 3. *Raytheon MEMS capacitive shunt switch: (a) cross-section view and (b) electrical CLR model.*

Electromechanical Considerations

The RF MEMS switches developed today, even if quite small, still follow the basic mechanical laws developed 200-400 years ago. However, the scale and relative importance of the forces acting on the switches are significantly different from the macro-world we experience daily. Surface forces and viscous air damping dominate over inertial and gravitational forces. The switches are either fabricated using a fixed-fixed membrane or a floating cantilever (diving-board design) and are modeled as mechanical springs with an equivalent spring constant, k [N/m] (Figures 2 and 3). The spring constant depends on the geometrical dimensions of the membrane or cantilever and on the Young's modulus of the material used (Au, Al, nitride, etc.) [1], [2] and is 5-40 N/m for most RF MEMS switch designs. The switches have very low mass, around 10^{-10}-10^{-11} kg and, therefore, are not sensitive to acceleration forces. Actually, for a spring constant of 10 N/m and an acceleration of 100 m/s^2 (10 g), the movement is of the order of nanometers. This is insignificant since the switches are suspended 1.5-4 µm above the transmission line.

The actuation mechanism is achieved using an electrostatic force between the top and bottom electrodes, and is given by

$$F = \frac{QE}{2} = \frac{CVE}{2} = \frac{CV^2}{2\left(g + \frac{t_d}{\varepsilon_r}\right)} = \frac{\varepsilon A V^2}{2\left(g + \frac{t_d}{\varepsilon_r}\right)^2}, \tag{1}$$

where V, g, and C are the voltage, gap distance, and capacitance between the lower and upper electrodes, respectively, and A is the area of the electrode (Figures 2 and 3). The bottom electrode is often covered by a dielectric layer with a thickness (t_d) of 100-200 nm and a relative dielectric constant (ε_r) between 3 and 8 to prevent a short circuit between the top and bottom plates (Figures 2 and 3). Consider a switch with an electrode area of 100

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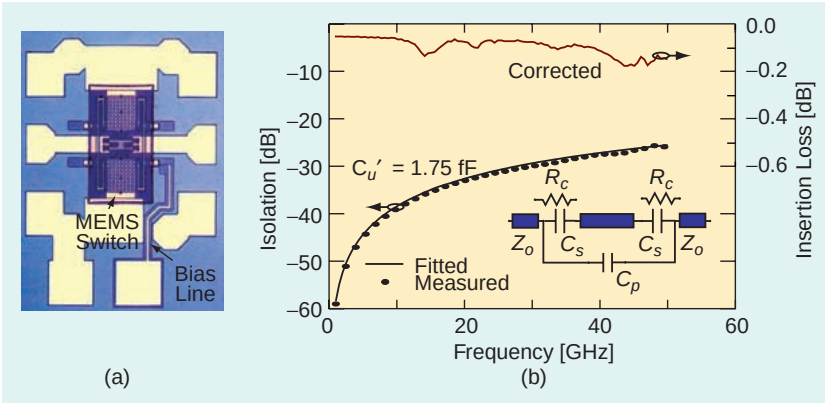

Figure 4. *(a) RSC MEMS-series switch and (b) the measured isolation and insertion loss. (Courtesy of Rockwell Science Center.)*

$\times$ 100 μm^2, an applied voltage of 40 V, and a gap of 2.5 μm, then the initial actuation force is only 11 μN. Electrostatic actuation results in very low forces, but this is enough for MEMS-switch actuation. The reason is that, as the switch is pulled down to the bottom electrode, the gap is reduced, and the pull-down force on the switch increases. On the other hand, there is a pull-up force due to the spring constant of the switch. The equilibrium is achieved when both forces are the same and

$$F = \frac{\varepsilon A V^2}{2\left(g + \frac{t_d}{\varepsilon_r}\right)^2} = k(g - g_0) \tag{2}$$

where g_0 is the initial height of the bridge. The solution of this cubic equation in g results in a stable position up to approximately $g_0/3$ and then a complete collapse of the switch to the down-state position. The voltage that causes this collapse is called the pull-down voltage and is

$$V_p \cong \sqrt{\frac{8kg_0^3}{27\varepsilon A}}. \tag{3}$$

For k = 10 N/m, A = 100 × 100 μm^2, g_0 = 2.5 μm, the pull-down voltage is V_p = 23 V. The applied voltage is typically 1.2-1.4 V_p so as to achieve fast operation of the switch. Once the switch is pulled down and g is reduced to 0 μm (capacitive switches) and 0.3-0.5 μm (most series-contact switches), the electrostatic voltage can be reduced to 8-15 V while still keeping the switch in the down-state position. This is done so as to reduce the electric field in the dielectric and the possibility of dielectric breakdown or charge injection into the dielectric.

The contact force on most metal-to-metal contact series switches should be around 50-200 μN [3]. This is needed to result in a low contact resistance (0.1-0.3 Ω). Remember that while the initial electrostatic force is 11 μN for a gap of 2.5 μm, the force increases to 400 μN for a gap of 0.4 μm (down-state position for most series switches) and a voltage of 40 V. Note that this force is exerted at the pull-down electrode and must be transferred to the contact point (see Figure 2) using the stiffness of the cantilever (or bridge). For capacitive switches where the gap is zero and an excellent contact must be achieved between the bridge and the dielectric layer, the contact force is 1.5 mN for a silicon-nitride dielectric thickness of 1,500 Å and ε_r = 7.6 and a hold-down voltage of 10 V. This contact force is distributed over the 100 μm^2-contact area. Once the bias voltage is removed, the pull-up force is approximately given by $F = kg_0$ since the displacement of the bridge is g_0. This results in a pull-up force of 30-60 μN for most switches and is quite small. It is for this reason that RF MEMS switches are very sensitive to surface physics, humidity, and contaminants and must be packaged in clean-room conditions.

MEMS switches also follow standard Newtonian's mechanics and, more specifically, d'Alembert's equation of motion [4]. The dynamic response is

$$mg'' + bg' + k(g_0 - g) = F_e, \tag{4}$$

where m and b are the mass and damping coefficient of the bridge or cantilever, and F_e is the electrical force given by (1). This is a second-order system with a resonant frequency

$$\omega_0 = \sqrt{k/m}.$$

It is seen that a switch with a low mass and a spring constant of 5-30 N/m does result in a resonant frequency of 30-100 kHz. The damping coefficient can also be written in terms of the quality factor (Q) defined as $Q = k/\omega_0 b$. The damping is limited by squeeze-film effects (removing of the air underneath the bridge or cantilever) and $0.2 < Q < 5$ for most designs. A low-Q system results in a slow switch, and its time-domain response is limited by the first pole at $Q\omega_0$. It is important to operate the switches around atmospheric pressures and to keep Q around 1 (squeeze-film damping is good). If the switch is operated in vacuum, the Q may be as high as 50-1,000 depending on the material of the cantilever (or bridge) and the anchor design. This results in long settling times for both the actuation and release mechanisms.

A simple equation, derived by Barker and Rebeiz, that accurately predicts the switching time can be obtained by setting $b = 0$ (no damping) in (4), and taking the electrical force as the initial force with $g = g_0$[1]. The switching time becomes

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$$t = 3.67\frac{V_p}{V_S\omega_0}, \tag{5}$$

where V_S is the applied voltage. Simulations done by Muldavin and Rebeiz using nonlinear differential equations, a varying force and b versus position indicate that (5) is accurate to within 10% for $Q > 1$ and $V_S > 1.3\ V_p$ [5]. For a switch with $\omega_0 = 50$ kHz and $V_S = 1.3\ V_p$, the switching time is 9 µs. Most MEMS switches have a switching/release time of 2-50 µs.

As indicated by (5), it is very hard to get a switching time of 0.3 µs. In this case, the resonant frequency must be 1 MHz, and $V_p/V_S \leq 3$. Since a high resonant frequency can only be achieved using a high spring constant (and a very low mass), the associated pull-down voltage is high; therefore, V_S must be indeed very high. The authors believe that the practical limit of switching time will be around 1 µs for high-reliability operation.

The beauty of MEMS switches is their near-ideal behavior and the relative ease of their circuit designs

MEMS-Series Switches: Fabrication and Performance

There are two types of MEMS series switches: The broadside series switch [Figure 2(a) and (b)] and the inline series switch [Figure 2(c)]. The actuation of the broadside switch occurs in a plane that is perpendicular to the transmission line, while the actuation of the inline switch occurs in the same plane as the transmission line. The main difference between the two designs is that the RF signal will pass by the entire inline switch. As a result, inline switches must be fabricated using a thick metal layer (Au, Al, Pt, etc.). On the other hand, only the contact portion of the broad-side switch needs to be fabricated using a metal layer, and the actuation portion can be composed of a dielectric or a dielectric/metal cantilever or fixed-fixed beam.

The electrical model of a MEMS series switch is a series capacitance in the up-state position and a small resistance in the down-state position. The isolation of a series switch in the up-state position is given by

$$|S_{21}|^2 = 4\omega^2 C_u^2 Z_0^2, \tag{6}$$

where C_u is the up-state capacitance and Z_0 is the transmission-line impedance. The insertion loss is

$$|S_{21}|^2 = 1 - R_s/Z_0, \tag{7}$$

where R_s is the contact resistance of the switch. It is seen that an up-state capacitance of 2-4 fF and a contact resistance of 1 Ω results in an isolation of –46 to –40 dB at 4 GHz and a –0.1 dB loss up to 40 GHz. This is a spectacular performance not attained by any solid-state device. The figure of merit cut-off frequency is

$$f_c = \frac{1}{2\pi C_u R_s} \tag{8}$$

and is an indication of the low-loss performance of the switch. The cut-off frequency of MEMS series switches is 30-80 THz, while it is only 1-2 THz for GaAs p-i-n diodes and 0.2-0.5 THz for FET switches.

The Rockwell Science Center MEMS-series switch is shown in Figure 4(a) [6]. This is a broadside switch with two pull-down electrodes on either side of the contact area. The switch membrane is composed of a nitride/gold layer and is suspended 2.5 µm above the substrate and pull-down electrode. The membrane is folded at the end and four anchors are used to fix the membrane to the substrate, resulting in a spring constant of 12-15 N/m. Also, $6 \times 6\text{-}\mu m^2$ holes are etched in the membrane to reduce the air damping, and the switch mechanical Q is 4. The pull-down electrodes are 75-µm square, and the pull-down voltage is 50-60 V. The actuation voltage is typically 1.3 V_p, and is 70-85 V. There are two contact points with dimensions of 3-µm square on either contact area. The small contact points are needed to reduce metal-to-metal stiction and increase the contact pressure. The resulting contact force is 100-150 µN per contact, and the total switch resistance is less than 1, for a 60% yield over the wafer (less than 2 for a 95% yield). The up-state capacitance of the switch is only

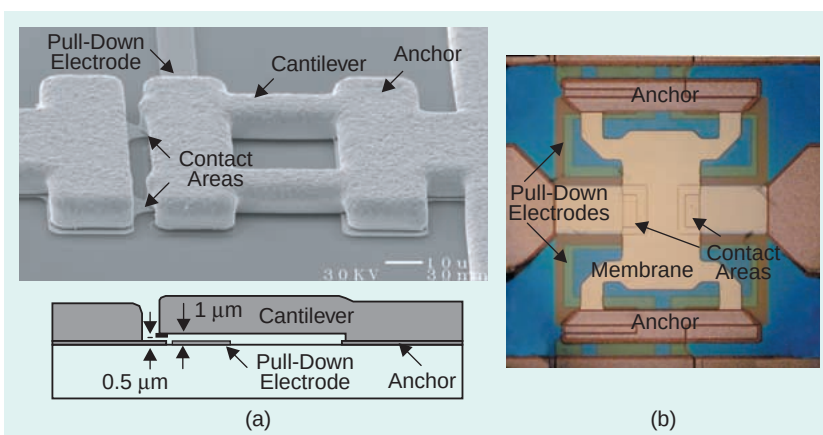

Figure 5. *(a) Analog Devices MEMS-series switch (Courtesy Analog Devices) and (b) the University of Michigan MEMS series switch.*

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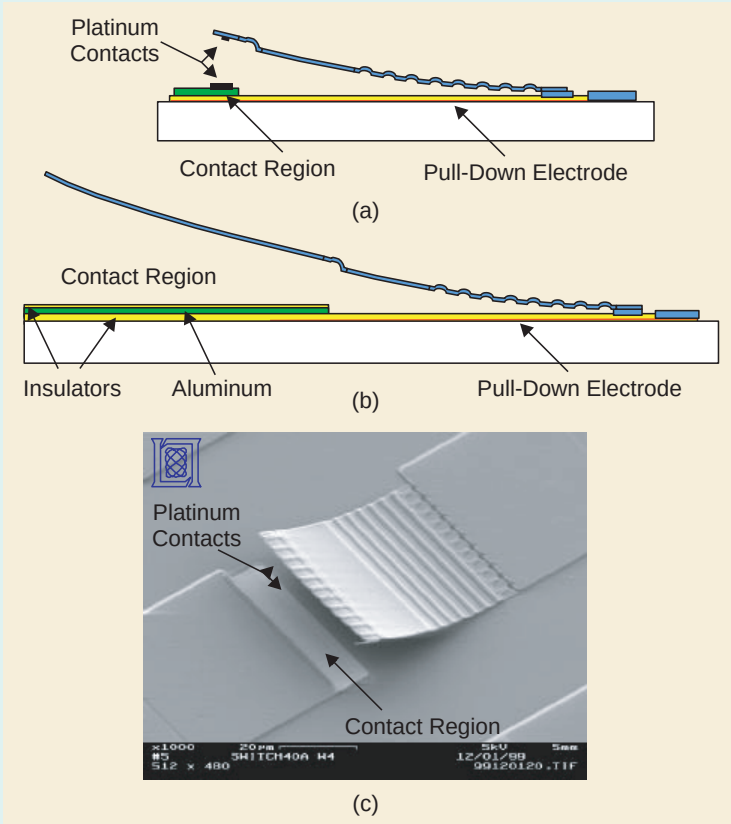
The Little Switch That Could

Lincoln Labs developed a miniature inline-series switch that could be configured as a dc-contact switch (8 × 45 μm^2 contact area), or as a capacitive switch with a large contact area (around 50 × 100 μm^2) and a down-state capacitance of 1-1.5 pF [13]. The Lincoln Lab switch is based on a cantilever arm, which curls in the up-state position. The cantilever is formed using a three-layer deposition process composed of 2000 Å of compressive PECVD SiO_2, 5000 Å of sputtered aluminum, and capped by a 2000-Å layer of tensile PECVD SiO_2. The polyimide-release layer is also patterned so as to result in corrugations in the cantilever surface. The corrugations are used to adjust the stiffness of the arm and the contact region. The curling motion of the cantilever arm results in a very compact switch (less than 50-μm long) with a large open-state separation distance (10-15 μm) and, thus, a very low up-state capacitance (4 fF). Also, notice that the pull-down electrode is quite large and extends all the way to the anchor of the cantilever. The pull-down voltage is 50-60 V, and an actuation voltage of 70-80 V is used. The switching time is very short (<1 μs) due to the small size and mass of the switch and the absence of the squeeze-film damping. The capacitive-series switch results in a high capacitance ratio of 200-300 and has been tested to more than nine billion cycles.



(a) SEM of Lincoln Laboratories inline MEMS-series switch in a dc-contact and (b) capacitive configuration, and (c) SEM of the dc-contact switch.

1.75 fF resulting in very high isolation up to 40 GHz. The measured S-parameters in the up-state (isolation) and down-state (insertion) are shown in Figure 4(b).

The Analog Devices MEMS-series inline switch is shown in Figure 5(a) [7]. The switch is fabricated using a 7-8-μm thick gold cantilever and is suspended 1 μm above the substrate. The switch is very compact and is around 75-μm long and 30-μm wide. The pull-down electrode is defined near the end of the cantilever and is 20 × 35 μm. There are two contact points, each with dimensions around 2-m square. The spring constant is 60-100 N/m, which results in a pull-down voltage of 60-80 V and a switching time of 2-3 μs. The mechanical Q is close to 1, therefore, the switch settles quickly upon actuation. The contact force is 100-150 μN, and the switch resistance is 0.5-1.0 . The up-state capacitance is 4-5 fF, and the measured isolation is –40 dB at 4 GHz and –26 dB at 20 GHz. The measured insertion loss is –0.15 dB up to 20 GHz.

The University of Michigan developed an all-metal broadside-series switch [Figure 5(b)] [8]. In this case, the pull-down electrodes are moved away from the center of the switch, and the switch is anchored on both sides of the transmission line. The switch is fabricated using a 0.8-μm thick gold layer and is suspended 1.7 μm above the t-line. The spring constant is given by the anchor design and the residual stress in the membrane and is 25-40 N/m for the switch of Figure 5(b). The resulting pull-down voltage is 35-50 V. As usual, 5-μm-square gold contact points are used, and the contact resistance is 1-2 . The up-state capacitance is 6-8 fF, which results in an isolation of –35 dB at 4 GHz. The University of Michigan switch is completely compatible with the shunt-capacitive switch-fabrication technique, therefore, it can be used in series/shunt designs.

There are other series switches, such as Motorola [9]; Hughes Research Labs [10], [11]; U.S. Air Force Research Labs [12]; University of California, Berkeley [14], [15]; Samsung, NEC [16]; Thompson-CSF, to name just

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a few. All have very low capacitances and low contact resistance, but none have attained the maturity of the Rockwell or the Analog Devices switches.

MEMS Capacitive Shunt Switches: Fabrication and Performance

Texas Instruments (now Raytheon) developed the first practical MEMS capacitive shunt switch (Figure 3) [18], [19]. The switch is based on a fixed-fixed metal (Al or Au) beam design. The anchors are connected to the coplanar-waveguide ground plane, and the membrane is, therefore, grounded. In a microstrip implementation, the switch anchors are either connected to the ground plane using via holes or using a $\lambda/4$ radial stub. In the Raytheon design, a center pull-down electrode is used, and a 1000-2000-Å silicon-nitride layer is used to isolate the metal membrane from the pull-down electrode. The membrane is typically 250-350 µm long, with a thickness of 0.5-1.2 µm and a width of 40-140 µm, depending on the required down-state capacitance (C_d). The spring constant can be made as low as 1 N/m or as high as 50 N/m, with a practical range of 6-30 N/m. The height of the membrane is 1.5-4 µm and results in a pull-down voltage of 10-60 V. A set of 3-6-µm-square holes are etched in the membrane to result in a mechanical Q of 1-2. For the Raytheon switch, the beam is aluminum with a spring constant of 8-12 N/m and, when coupled with the small mass of the membrane layer (0.5 µm Al), results in a 100-kHz resonant frequency and a switching time of around 3 µs. The Raytheon switch is very mature and can be fabricated on 6 in (15 cm) wafers with a standard deviation of 1.5 V in the pull-down voltage [22].

Notice that in the center electrode design of Figure 3, the electrode provides both the electrostatic actuation and the RF capacitance between the transmission line and the switch membrane (ground). When the switch is in the up-state position, it provides a low capacitance to ground, around 25-75 fF and does not affect the signal on the t-line. When the switch is actuated in the down-state position, the capacitance to ground becomes 1.2-3.6 pF, and this results in an excellent short circuit and high isolation at microwave frequencies (10 GHz and above). The capacitance ratio (C_d/C_u) is around 40-100 for most designs.

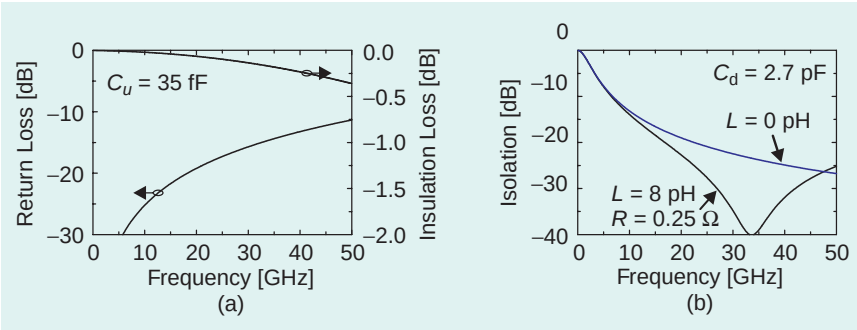

Figure 6. *S-parameters of a MEMS shunt switch in a CPW configuration with C_u = 35 fF, C_d = 2 .7 pF, L =8 pH R = 0.25, (a) up-state position and (b) down-state position. The*

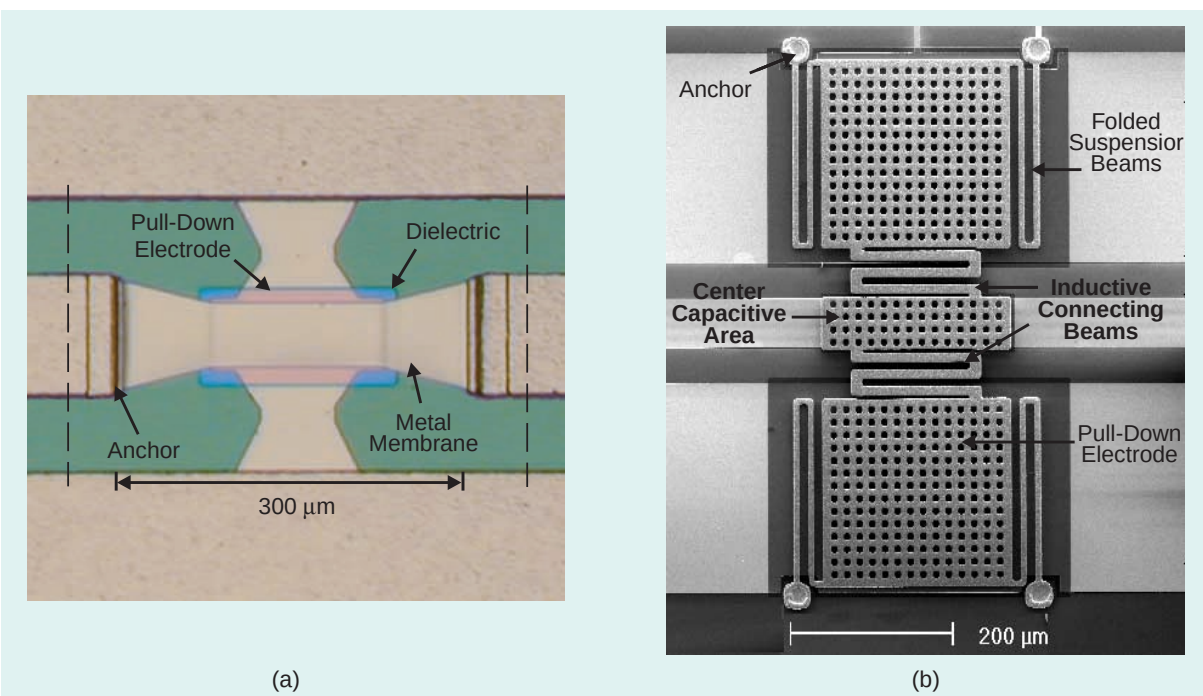

Figure 7. *(a) University of Michigan low-height high-spring-constant gold MEMS switch and (b) low spring-constant MEMS switch.*

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The up-state reflection coefficient of a shunt-capacitive switch is

$$|S_{11}|^2 = \frac{\omega^2 C_u^2 Z_0^2}{4}, \tag{9}$$

where C_u is the up-state capacitance of the switch. The down-state isolation is

$$|S_{21}|^2 \cong \begin{cases} \dfrac{4}{\omega^2 C_d^2 Z_0^2} & \text{for } f << f_0 \\ \dfrac{4R_s^2}{Z_0^2} & \text{for } f = f \\ \dfrac{4\omega^2 L^2}{Z_0^2} & \text{for } f >> f, \end{cases} \tag{10}$$

Performance of RF MEMS switches is truly spectacular when compared to p-i-n diode or FET switches

where

$$f_0 = 1/\left(2\pi\sqrt{LC_d}\right)$$

is the down-state resonant frequency of the capacitive switch. The loss of the shunt switch in the up-state position is nearly equal to the loss of the t-line and is around –0.03 to –0.05 dB at 10-30 GHz (not including the $1 - |S_{11}|^2$ return-loss component). The electrical performance of a capacitive switch with $C_u = 35$ fF and $C_d = 2.7$ pF, $L = 8$ pH and $R_s = 0.25\ \Omega$ is shown in Figure 6. This switch can be used up to 30 GHz without a matching network in the up-state position. The isolation is high above 15 GHz, and one can clearly see the LC_d resonance at 34 GHz. The LC_d resonance improves the performance of the switch as compared to the case with $L = 0$ pH. This has been used to obtain high isolation X-band switches using MEMS capacitive switches with $C_d = 1.5$-3 pF [20], [21].

Tha University of Michigan has developed two different capacitive switches. The first one is similar to the Raytheon switch and is shown in Figure 7(a) in an inline configuration (anchors attached to the center conductor and the electrode attached to ground) [24]. The membrane is composed of a 0.8-µm thick gold layer with a height of 1.7-2.2 µm. The spring constant is 25-35 N/m and results in a pull-down voltage of 25-30 V. The capacitance ratio is only 30-40, but excellent isolation can be obtained with this design. The second capacitive switch is based on a low spring-constant membrane [25]. The membrane is connected using a folded spring to the anchors, and the spring constant can be lowered to 1-3 N/m with the use of several turns [Figure 7(b)]. This results in a pull-down voltage of 8-15 V and a relatively low switching speed of 30-40 µs. Since the restoring forces are low for such a design, these switches are useful when integrated with a pull-up electrode placed 1-2 µm above the movable membrane. The pull-up electrode is used to fix the membrane in the up-state position when the switch is not being activated and to

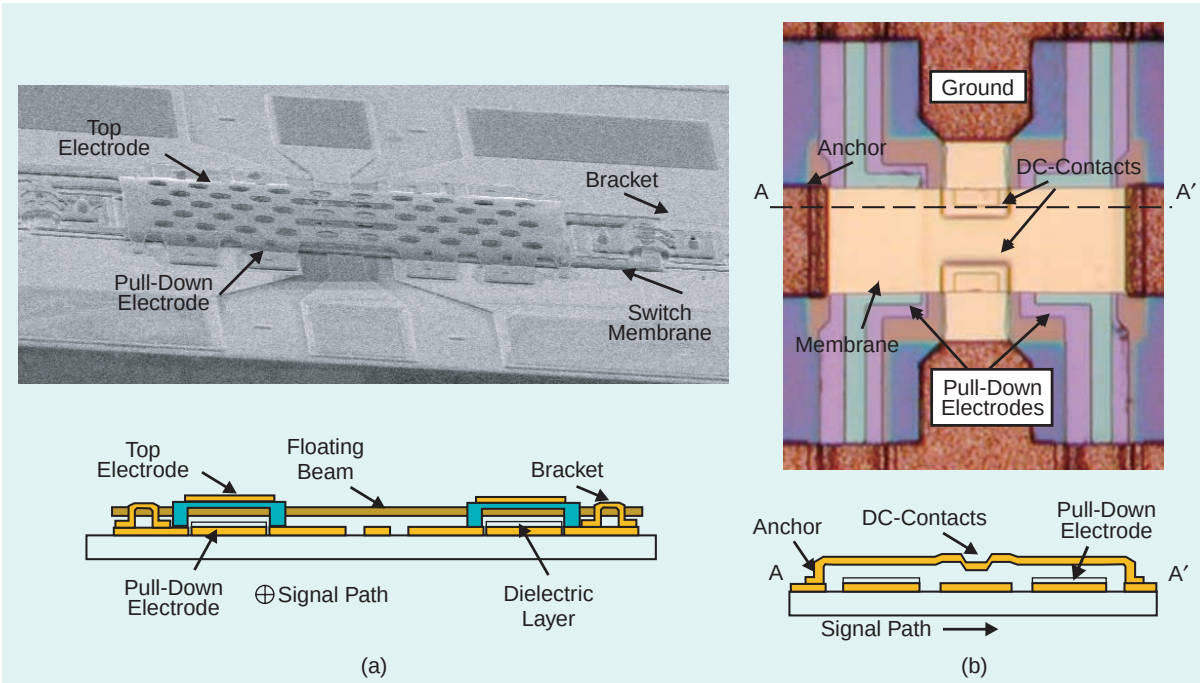

Figure 8. *(a) University of Illinois and the (b) University of Michigan dc-contact shunt switch.*

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Reliability of MEMS Switches

The reliability of MEMS switches is of major concern for long term applications and is currently the subject of an intense research effort. The *mechanical* failure (metal fatigue or fracture) of well-designed micromachined cantilever or fixed-fixed beams is not a problem since the beams are 75-350-μm long and are deflected by only 1-4 μm. Actually, many MEMS switches have been tested up to 100 billion cycles with no observed mechanical failure around the anchors (the location of maximum strain). For dc-contact switches, the failure mechanisms are resistive, and for capacitive switches, the failure mechanism is due to stiction.

The reliability of the dc-contact switch is limited by damage, pitting, and hardening of the contact area due to the impact force between the beam and the bottom metal. Other failure mechanisms are due to organic deposits and contamination around the contact area, but these can be mitigated with a clean packaging environment. The failure shows as an increase in the contact resistance from 1-2 to 4-10 and above. Resistive failure occurs quite suddenly, and, for a 100 million cycle switch, the failure occurs in the last 50,000-200,000 cycles. There is no specific definition for resistive failure, but a good assumption is when the contact resistance becomes greater than 4-5 Ω (which results in an insertion loss of 0.4-0.5 dB). The dc-contact switch reliability can be improved by tailoring the switch drive voltage and reducing the impact energy on the contact area as demonstrated by the University of Michigan and Rockwell Science Center [17]. In general, stiction is not a problem in series switches for low RF powers, since, for most designs, the pull-down electrode does not even need to touch the micromachined beam. However, microwelding can be a serious problem for 100-1000 mW of RF power. For a contact resistance of 1 Ω, the contact dissipates 2% of the incident power, which is 2 mW for an RF power of 100 mW. This results in microwelding of the contact area and a failure of the switch in the closed position.

The reliability of capacitive switches is dominated by stiction between the dielectric layer and the metal due to the large contact area of the switch (approximately 100 μm × 100 μm). The major stiction force is due to the charging effects in the silicon nitride dielectric layer, and, depending on the polarity of the injected charge, it can can cause the switch to either stick in the down-state position or results in an increase in the pull-down voltage so that the MEMS switch cannot be used anymore. The electric field can be as high as 3-5 MV/cm in the dielectric layer, which results in a FP-charge injection mechanism from the metal to the dielectric [23]. Charge injection is exponential with voltage, and a reduction in the pull-down voltage by 6 V can result in a 10× increase in the lifetime of the MEMS switch [23]. This does not automatically lead to the design of low-spring constant, low-voltage switches (5-10 V) since these switches have a low restoring (pull-up) force. A pull-down voltage of 25-30 V may be the best compromise. Also, it is well known that silicon dioxide has a much lower trap density than silicon nitride and may result in less charging when used in the RF MEMS capacitive switch. The penalty paid is a decrease in the down-state capacitance (or capacitance ratio) due to the lower dielectric constant of the oxide material. Once the charge injection is solved, the reliability is limited by stiction due to water vapor (humidity) and organic contaminants underneath and around the MEMS switch.

Most mature dc-contact series switches have been tested to 50-500 million cycles (Rockwell, Motorola, Samsung) with the notable exception of Analog Devices, which was demonstrated up to several billions of cycles. All tests are done on-wafer, at 1-5 mW of RF power, using a 1-10 KHz switching rate, under flowing nitrogen or dry-air environments and in clean room conditions. Analog Devices has shown that their switch can reliably handle amps of pulsed-current μs durations) which is interesting for industrial and medical ultrasonics applications. Analog Devices has also packaged its MEMS switch using standard hermetic-sealing techniques, and the packaged switch was tested to several billion cycles. The Raytheon switch and the Lincoln Lab capacitive switches were tested to more than 1 billion cycles with high repeatability (under the same conditions outlined above). These are the only capacitive switches that have crossed the 1 billion cycle mark (at least, public information). All RF MEMS switches (dc-contact and capacitive) show a marked reduction in reliability when tested at 50-100 mW. The failure mechanisms under medium power levels are still not well understood.

One of the major questions in communication systems concerns the reliability of the switch for long-term applications. That is, will the switch fail if actuated in the down-state position for hours, days, or months and 1-100 mW of RF power is flowing through the contact areas? Remember that the restoring force of the electrostatic MEMS switch is only 30-150 μN. Surprisingly, there are no long term reliability results for capacitive and dc-contact MEMS switches.

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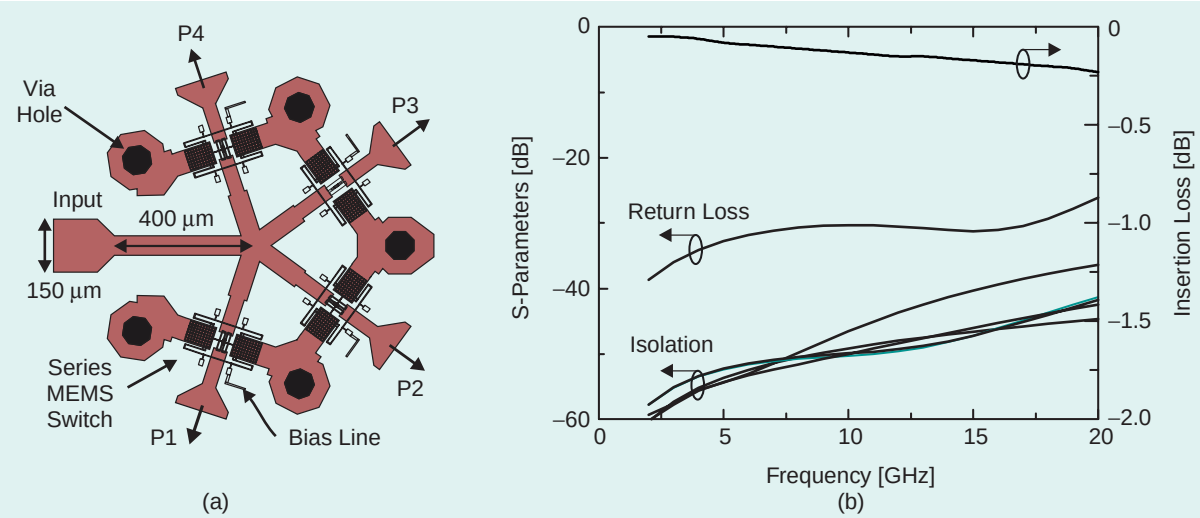

Figure 9. *(a) SP4T switch based on the RSC MEMS series switch and (b) simulated S-parameters.*

exert a pull-up force when the membrane is in the down-state position. A switch with a pull-up electrode was recently demonstrated by [26].

MEMS-Shunt Switches for 0.1-20 GHZ Applications

The capacitive switch (Figure 7) is excellent for 10-120 GHz, but does not provide enough capacitance for 0.1-20 GHz applications. Using the idea of Figure 7(b) (two pull-down electrodes on either side of the center area of the switch), one can build a dc-contact shunt switch by removing the dielectric layer in the center part of the switch. The dc-contact shunt switch results in high isolation at 0.1-20 GHz, which is useful for wireless applications. The performance of a dc-contact shunt switch is limited by the contact resistance (around 1) and by the inductance to ground. An isolation of –27 dB from 0.1-40 GHz using a CPW line with a narrow gap and a low inductance to ground [Figure 8(a)] was achieved in [27]. Also developed was an *inline* dc-contact shunt switch with an isolation of –30 dB at 0.1-5 GHz and –20 dB at 20 GHz (Figure 8(b)) [28]. The reliability of dc-contact shunt switches is the same as the dc-contact series switches.

Another way to build a low-frequency shunt switch is to increase the down-state capacitance to 40-60 pF. This was done at LG-Corporate Research using a strontium titanate oxide (STO) layer with a relative dielectric constant of 120 [29], [30]. The mechanical characteristics and pull-down voltage of the switch are very similar to the Raytheon or University of Michigan designs. The capacitance ratio is 500-600, with a measured isolation of –30 to –40 dB at 2-3 GHz. The only problem with STO (or similar high-K dielectric layers) is their relatively large trap density, which could seriously degrade the reliability of the MEMS switch.

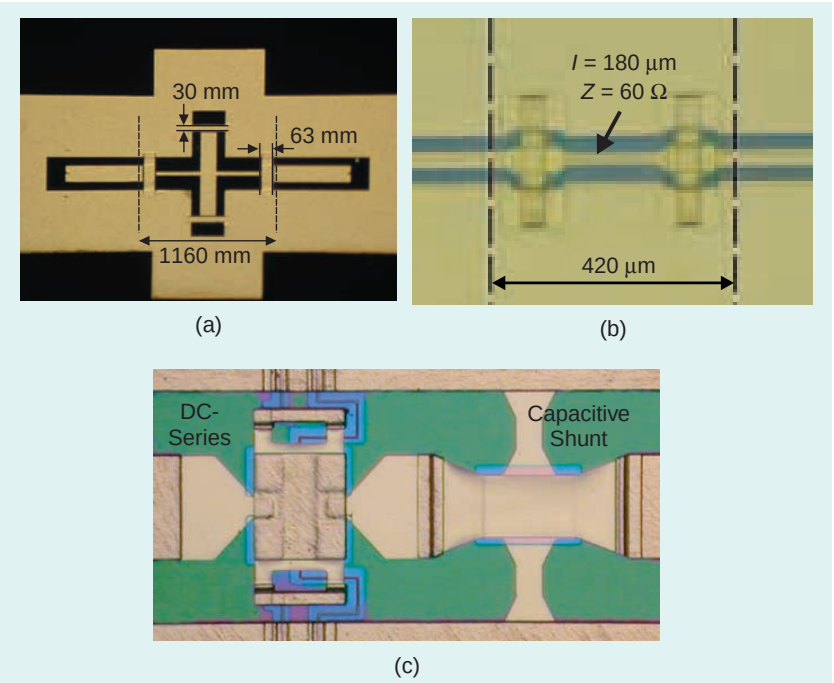

Figure 10. *Examples of high-isolation MEMS switch circuits: (a) cross-switch at Ka-Band, (b) W-band-tuned switch, and (c) series/shunt switch.*

High-Isolation MEMS Switch Circuits

MEMS switch circuits have been demonstrated from 0.1 to 120 GHz using series and capacitive switches. The beauty of MEMS switches is their near-ideal behavior and the relative ease of their circuit designs. A single MEMS series switch with C_u = 2-4 fF

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Packaging and Its Effects on Reliability

The most critical part of RF MEMS switches is the packaging technique used. It is the most expensive step in the production line and will ultimately determine the cost of the switch or switch network. MEMS switches are very sensitive to humidity and must be packaged in hermetic or near-hermetic seals in nitrogen environments.

It is always possible to package MEMS switches or switch networks in clean room conditions using proven hermetic packages and ceramic/glass feed-throughs. This is an expensive approach that is viable for satellite and high-performance defense systems. After all, the only competitor at 6-20 GHz is the space-qualified coaxial rotary switch, which costs $7-12K and weighs 300-400 g. This packaging approach is also applicable to telecommunication basestations requiring low-loss switches for signal routing, filter banks, and antenna sectoring (at least on the receive section, since power handling of RF MEMS switches is still a major problem). Many defense applications require that the entire transmit/receive (T/R) module for phased-array radars be hermetically sealed. In this case, the MEMS phase shifter becomes just one component in a complicated hermetic package consisting of amplifiers, switches, etc., and the additional packaging costs are virtually nil.

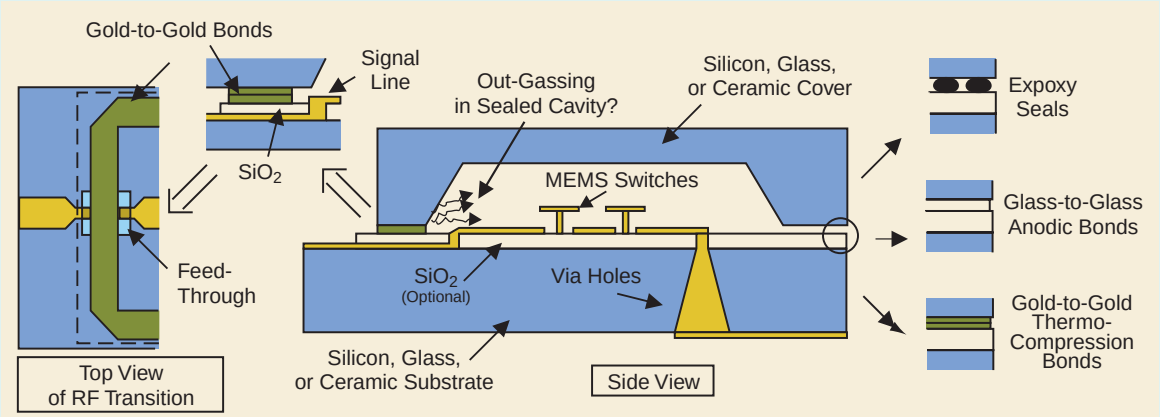
However, it is well recognized that the only way to reduce the cost of RF MEMS switches for applications requiring a large number of units is to develop a wafer-scale packaging solution. There are several techniques used by industry to package MEMS devices (accelerometers, gyros, etc.):

- *Epoxy seals*
- *Glass-to-glass anodic bonding*
- *Gold-to-gold bonding.*

There are two main problems with these techniques. First, they outgass organic materials inside the MEMS cavity during the bonding process due to wetting compounds in the glass, gold, or epoxy layers. This has a serious detrimental effect on the reliability of the MEMS switches, both dc-contact and capacitive switches. Second, most bonding processes require a temperature of 300-400 °C to achieve a good seal. This is not compatible with a released structure, which may be very thin (0.5-1.5 μm) and quite long (250-350 μm). The temperature may bow the membrane (or cantilever) by ±1-5 μm making the switch unusable. The reason why these factors do not affect standard MEMS devices is that MEMS-accelerometers, -gyros, -pressure and -temperature sensors, etc., do not have surfaces that touch each other, are generally fabricated using much thicker polysilicon layers, and are calibrated every time you turn on the device. These options do not exist for RF MEMS switches.

Another problem is the RF feedthroughs. Again, standard MEMS components require dc-50 kHz signals that can easily pass underneath the glass layer (anodic bonding) or use a thin nitride or oxide layer to isolate the input/output lines from the gold-seal ring (thermo-compression bonding). These designs can be pushed to 6 GHz using narrow lines around the seal ring and a short input matching network. However, for 6-100 GHz operation, it is best to use RF transitions based on via holes (wideband designs) or on electromagnetic coupling through the wafer (20-30% bandwidth). Alpha Inc. developed a via-hole transition covering dc-40 GHz and having an insertion loss of –0.1 dB at 20 GHz [36]. RF transitions are, therefore, not the major problem in RF MEMS packaging.

There is currently a large effort to develop wafer-scale packaging techniques that are compatible with MEMS switches (low-temperature hermetic glass bonding, minimal outgassing, gold-to-gold bonding with localized heating, etc.). Perhaps the only mistake in this field is that most RF MEMS switches available today were developed independent of the package. This necessitates the development of packaging techniques that must be compatible with an already mature RF MEMS switch technology at the wafer level. In hindsight, it would have been better to develop the RF MEMS switch together with the package, as a single unit, with perfect compatibility between the two areas. It is interesting that after 7-8 years of RF MEMS switch research and more than $100 million spent on this area there is not a single reliability test done on a hermeticaly packaged switch using wafer-scale techniques.



Current-packaging and interconnect schemes for MEMS switches. Feed-through or via technologies are needed to pass the RF signal through the sealed package.

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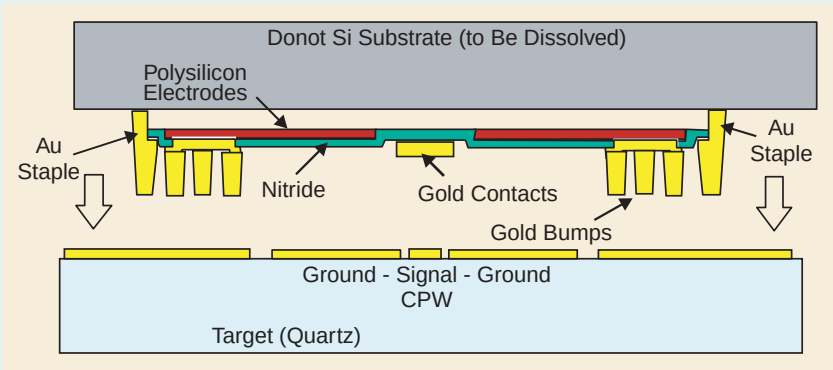
To Transfer or Not to Transfer

There are two schools of thought on the development of MEMS switches. The first one, outlined in detail in this article, is to fabricate the MEMS switches or switch circuits directly on the microwave substrate (quartz, pyrex, high-resistivity silicon, GaAs, etc.). Another possibility, developed by the University of California, Berkeley [14], and the University of Colorado, Boulder [34], [35], is to fabricate the MEMS switches on a low-resistivity silicon substrate using standard high-temperature polysilicon and nitride processing, release the switches, and then transfer them to the microwave-carrier substrate using substrate-dissolution techniques. The idea is to leverage the very low cost processing available for complimentary metal-oxide-semiconductor (CMOS)-type wafers and to develop a reliable and low-cost substrate-transfer process.

At Berkeley, dc-contact series and shunt switches and series/shunt see-saw designs using substrate transfer were fabricated [15]. A major problem with substrate transfer is the precise control of the air gap between the movable membrane (being transferred) and the bottom electrode (on the carrier substrate). Also, the substrate dissolution process may contaminate the contacts. This is currently an area of research, and there are no reliability results on this technique. Still, it offers an interesting possibility for applications requiring a very large number of switches. It is the opinion of the authors that the no-transfer process will dominate switch development for the next five years.



The Berkeley transfer process: Part of the switch is integrated on the carrier substrate and the movable part is integrated on the low-resistivity silicon substrate which will be dissolved after the switch membrane is transferred to the carrier substrate.

provides a very high isolation up to 20 GHz, and, if more isolation is desired, then two switches can be placed in series (200-400 μm apart). It is also trivial to design a single-pole double-throw using MEMS series switches below 10 GHz. Figure 9 shows a SP4T, designed by Tan et al., based on the Rockwell Science Center (RSC) MEMS switch [6]. The input reflection coefficient is better than –20 dB up to 20 GHz, with an insertion loss of only –0.15 dB and an isolation of –50 dB at 10 GHz. The SP4T is simulated using Momentum and includes inductive matching sections to result in the excellent match performance. It is the fundamental component in switched filter banks and switch matrices for telecommunication systems. RSC also designed SP2T switches with a –20 dB reflection coefficient up to 40 GHz using a similar technique.

Capacitive MEMS shunt switches with a nitride dielectric provide excellent isolation at 20-50 GHz, and if more isolation is desired, then two switches can be placed in series (200-400 μm apart). Also, one can build tuned capacitive switches with a relatively wideband response (±20-30%) and very low loss. Figure 10(a) shows a tuned cross-switch at 30 GHz using capacitive shunt switches with an isolation of –50 dB (limited by substrate leakage) and an insertion loss of –0.3 to –0.4 dB at 15-40 GHz [31]. Also, a 75-100 GHz π-match switch with an isolation of –40 dB (limited by substrate leakage) and an insertion loss of –0.3 dB was demonstrated using capacitive switches [Figure 10(b)] [32]. Barker et al. [33] and Peroulis et al. [21] have also developed distributed-capacitive switches with high isolation (–50 dB, limited by substrate leakage) and with –0.25 to –0.5 dB loss from 10-60 GHz. Muldavin et al. recently demonstrated a series/shunt MEMS switch with an isolation of better than –40 dB (limited by substrate leakage at $f < 10$ GHz) and an insertion loss of –0.1 to –0.2 dB over the 0.1-40 GHz range [Figure 10(c)] [8], and Tan et al. developed a 0.1-26 GHz MEMS absorptive switch using dc-contact series and shunt switches [28].

Future of MEMS Switches

This article presented an overview of MEMS switches and high-isolation switch circuits. The development of MEMS switches has been progressing at a relatively rapid rate since the first practical dc-contact (series) and capacitive (shunt) switches were published in 1995 by Rockwell and Texas Instruments, respectively. RF MEMS technology is currently quite mature at the wafer level, and the mechanics of the switch actuation is well understood. It is seen that there is a large variety of switches available today covering the 0.1-120 GHz range, and the performance of RF MEMS switches is

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truly spectacular when compared to p-i-n diode or FET switches. However, there are currently no high-power (0.1-10 W) RF MEMS switches, and this limits their use in many radar and telecommunication systems (transmit side). Several problems relating to long-term reliability, metal-to-metal contacts under low forces, packaging, and fabrication cost are currently being addressed, and it is expected that practical solutions will be available in the coming 3-5 years. Still, it is not yet clear if RF MEMS switches will be price competitive with p-i-n diode and FET switches at 0.1-6 GHz and may be first used in high-performance defense and satellite systems.

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