**Development of MEMS Microwave Switches with
Application to Reconfigurable Integrated Antennas**

by

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A thesis submitted to the Faculty of Graduate Studies and Research in
partial fulfillment of the requirements for the degree of

Master of Applied Science

Ottawa-Carleton Institute for Electrical Engineering

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**“Development of MEMS Microwave Switches
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submitted by Jason Rose, B.Sc.

in partial fulfillment of the requirements for the degree of
Master of Applied Science

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Dedication

Dedicated to Erin and to my family for their
unwavering support and encouragement.

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Abstract

In this thesis, a design methodology for microelectromechanical system (MEMS) shunt switches is presented and implemented. A four mask, surface-micromachining procedure for fabricating MEMS devices is demonstrated, as is the use of hexamethyldisilazane (HMDS) as an anti-stiction surface treatment when releasing suspended MEMS structures. It is shown that the use of HMDS significantly increasing the number of usable switches by reducing stiction and resulting in a process yield of 75%. As well, the performance of a MEMS shunt switch is presented and compared with simulated results. Agreement between simulation and measured results was found to be quite good. An insertion loss of 0.25 dB is observed in the off-state between 10-20 GHz. In the on-state, an isolation of 5 dB is demonstrated at 10 GHz, rising to 10 dB at 20 GHz. The shunt switches were designed to operate between 10-20 GHz in a coplanar waveguide (CPW) regime.

The MEMS switch capability developed herein is also applied to a novel coplanar patch antenna configuration in order to achieve adaptive radiation characteristics. The dimensions of the antenna are adjusted by selectively contacting adjacent islands using cantilevers, thereby altering the phase of the radiated signal. The final patch design shows a simulated phase shift of 70 degrees in the radiated signal between 28-32 GHz.

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List of Symbols

A - Contact Area.

C_s - Switch Capacitance.

E - Young's Modulus.

G - Line separation of coplanar waveguide.

GHz - Gigahertz.

GPa - GigaPascals.

I_{rms} - Root Mean Squared Current.

K - Spring Constant.

K(k) - Complete elliptic integral.

L - Length of coplanar waveguide or patch antenna.

L_{eff} - Effective Length of coplanar waveguide.

N - Newton(s).

N/m - Newtons per Meter.

P_{av} - Average Power.

V - Volt(s).

V_P - Pull-down voltage.

V_{rms} - Root Mean Squared Voltage.

W - Width of Air-bridge or Patch Antenna.

Z_0 - Characteristic Impedance.

dB - decibel(s).

f_0 - Frequency of Operation / Resonant Frequency.

g_0 - Initial bridge height.

h - Substrate thickness.

t - Metallization thickness.

w - width of coplanar waveguide center conductor.

ϵ_0 - Permittivity of free space.

ϵ_r - Relative permittivity.

ϵ_{re} - Effective, relative permittivity.

λ_0 - Operational wavelength.

μm - Micrometer(s).

ν - Poisson's Ratio.

σ - Residual internal stress.

ϕ - Power loss factor.

Ω - Ohm(s).

$^\circ$ - degree(s).

Acronyms

AC - Alternating Current.

ADS - Advanced Design System.

CPW - Coplanar Waveguide.

C-V - Capacitance-Voltage.

DC - Direct Current.

DI - deionized.

EM - Electro-Magnetic.

HFSS - High Frequency Simulation Software.

HMDS - Hexamethyldisilazane.

MEMS - Microelectromechanical system.

MIF - metal-ion-free.

RF - Radio Frequency.

RMS - Root Mean Squared.

rpm - Rotations Per Minute.

SEM - Scanning Electron Microscope.

TEM - Transverse Electro-Magnetic.

1.1 Introduction and Motivation

The origins of microelectromechanical systems (MEMS) can be traced to the silicon-based, thin-film research of the 1960s. Advancements in these bulk and surface micromachining techniques has resulted in the ability to create the microscopic, three-dimensional machines referred to as MEMS, a field that has emerged as an exciting and unique technology. With an ever-increasing demand for smaller and faster personal electronics and a growing infrastructure of researchers and facilities, MEMS are poised to become possibly one of the most commercially viable technologies of the twenty-first century. Especially promising is the impact of MEMS technology on the fields of sensors, switching circuits and other control components [1][2].

This document explores the development of MEMS switches and their uses in integrated antenna applications. Previous research has shown that MEMS switches have many desirable characteristics, including very high isolation, very low insertion loss and minimal intermodulation distortion. MEMS switches also use nearly zero power since the capacitive connections they employ result in no DC current being consumed [3].

There are several of draw-backs to MEMS switches as the technology stands now, not the least of which is the relatively poor reliability, breaking down after 0.1-10 billion cycles, when 20-200 billion cycles is required for many systems [3]. Another major problem is the packaging and surface treatment required to combat the unintentional bonding that can occur between surfaces in a MEMS device, commonly referred to as “stiction”. A number of surface treatments [4][5], and packaging methods [6], have been explored, but these process requirements add time and cost to the development to the otherwise inexpensive MEMS devices.

MEMS capacitive switches have been developed by Raytheon that show insertion loss and isolation of <0.07 dB and >35 dB respectively at 40 GHz. These switches actuate at a fairly high voltage however, switching between 30-50 V [7]. A group in Korea, using a more novel switch topology, demonstrated a switch using torsion springs and leverage which is actuated at only 6 V and has an isolation of more than 28 dB, though it is only tested up to 4 GHz and is more complex than a typical air-bridge shunt switch [8].

Another method of reducing the actuation voltage of capacitive switches is to utilize compliant folded suspensions in order to lower the spring constant of the device. An example of this method, developed at the University of Michigan in Ann Arbor, demonstrates an isolation of 26 dB at 40 GHz while being actuated by an applied voltage as low as 9 V [9].

Improving upon the reported performance of these switches is not the main goal of this thesis. The major motivation behind this project is to establish a repeatable surface micro-machining procedure that can be used in the Carleton University Microelectronics Fabrication Laboratory for developing multi-layer, MEMS devices.

1.2 Thesis Objectives

The focus of this thesis is the development of a repeatable process for creating multi-layer, MEMS structures, specifically, the fabrication of MEMS switches for use at microwave and radio frequencies (RF). Both air-bridge style and cantilever MEMS switches are designed and experimentally verified, and the use of MEMS switches in planar antenna applications is also explored.

1.3 Organization of the Thesis

This document contains six chapters organized as follows:

Chapter 2 outlines the various calculations and design considerations that went into modelling and designing the MEMS shunt switches prior to fabrication.

Chapter 3 describes the surface micro-machining process that was used to fabricate all the MEMS structures discussed in this document. Also included in this chapter are sections on the inherent processing problems associated with thin-film deposition and patterning and the methods used to counter-act these problems.

Chapter 4 details the testing methods used to characterize the devices and the corresponding results obtained.

Chapter 5 explores the use of MEMS switches in patch antenna applications and describes a novel approach to electronically steering a radiated signal from a patch antenna.

Chapter 6 presents the conclusions drawn from this research and proposes a number of research possibilities, based on this work, that may be pursued in the future.

Modelling and Design Considerations

2.1 Chapter Overview

This chapter deals extensively with the modelling, calculations, and design considerations that were addressed before the final switch set was fabricated. Two switch sets are described, corresponding to the devices created during two separate fabrication process iterations. The first set, referred to as the initial switch set, includes a number of test structures, various switch layouts, and a simple shunt-switch actuation method where the DC pull-down voltage is applied across the RF signal line. The purpose of the initial switch set was to test process tolerances, experiment with various layout geometries, and expose any design flaws.

The second set consists mainly of a number of optimized shunt switches. Switch actuation in the final design occurs when a voltage is applied to the air-bridge through a DC bias pad that is isolated from the signal line. Unlike the initial switch design, this final design would allow a number of CPW shunt switches, each capable of independent actuation, to be present along a single RF line.

The initial phase in the development of a MEMS shunt switch is to properly model the RF characteristics of the underlying coplanar line and create appropriate calibration

structures for the high frequency measurements. A frequency range of 10-20 GHz is used in all the simulations and measurements concerning the shunt switches. The upper limit of 20 GHz was defined by the test equipment available at Carleton University, though the switches are expected to perform well at all frequencies up to 40 GHz. The lower limit was established at 10 GHz in order to encompass existing and emerging applications such as satellite communication in the *Ku* band, with uplink and downlink frequencies of 14 GHz and 12 GHz respectively. Once a satisfactory geometry for the CPW line is decided upon the air-bridge switches may be designed. A number of calculations are performed to determine the pull-down voltage of the bridges. Then, after all the prefabrication design work is completed, the initial switch set can be fabricated in order to ascertain the best possible dimensions for the etch holes (Section 2.3.1) and finally, to optimize the fabrication process (Section 3.3).

2.2 RF/Microwave Modelling

All the RF/Microwave modelling was done using *Momentum*, an electromagnetic simulator included in Agilent Technologies Advanced Design System (ADS) [10]. The goal of the modelling process was to determine the geometry of the devices to be fabricated in order to achieve desirable characteristics in the fabricated switch. Essentially, a low loss CPW line having a characteristic impedance of $Z_0=50 \Omega$ is desired in order to match to the system impedance.

The 2.5-D *Momentum* package was chosen as the best possible tool for modelling the coplanar lines. The ability to lay-out a device topology, and identify parasitic coupling between components makes *Momentum* a more appropriate tool than 2-D circuit simula-

tors, such as the ADS circuit designer, which rely on more rigid models based on lumped components. Similarly, the ability of *Momentum* to calculate S-Parameters for thin-film, multi-layer devices and its ability to visualize 3-D displays of far-field radiation, makes a full 3-D EM simulation tool, such as Ansoft's HFSS, unnecessary even when designing the patch antenna described in Chapter 5.

Momentum was chosen over other so-called 2.5-D EM simulation tools because it met all the needs of the project and it was already licensed by Carleton University's Department of Electronics, making it readily available.

2.2.1 CPW Modelling

The first step in designing MEMS air-bridge switches is determining the proper dimensions of the underlying coplanar waveguide. Coplanar waveguides consist of three conducting lines laid out side-by-side as shown in Figure 2.1. The signal is applied to the center line and the two outer lines are set at ground potential. Having both the center and ground conductors in the same plane allows the signal line to be shunted to ground using an air-bridge, without the use of vias.

The geometry of the CPW structure affects its characteristic impedance and propagation constant in the desired quasi-TEM mode of operation. Changing the CPW's dimensions beyond certain limits may allow undesired higher order modes, (such as slot line mode), to exist. This is why an EM simulator, such as *Momentum*, is so useful in determining the proper dimensions for the lines. Referring to Figure 2.1, a coplanar waveguide is defined by W , the width of the center conductor, G , the width of the slots sep-

arating the center conductor and the ground plane, t , the thickness of the lines, h , the thickness of the dielectric, and ϵ_r , the relative dielectric constant of the substrate material.

Figure 2.1: Cross-section of a basic Coplanar Waveguide.

Momentum calculates the S-parameters of a device over a user defined range of frequencies by creating a grid-like array of cells made up of triangles and rectangles over the entire surface of the device to be modelled. The current and any coupling effects are then calculated for each individual cell of this mesh during simulation using the Method of Moments [11]. Modelling the coupling effects across the slots between the ground conductors and the signal line allowed a much smaller area of effects to be computed on the part of *Momentum*, resulting in fewer calculations and faster simulation times compared to modelling the conductors themselves.

The first consideration made was the choice of substrate. The MEMS devices were created on two-inch quartz wafers having a thickness of $300\ \mu\text{m}$. Quartz was chosen as a middle ground between alumina and Si wafers, quartz having better microwave properties than silicon and a smoother surface than alumina, thus allowing for a more even deposition. Quartz has a relative permittivity of $\epsilon_r = 3.9$ and a loss tangent of 0.0003.

The thickness of the metallization was the next factor chosen. The lines were to be etched out of a $0.5\ \mu\text{m}$ thick deposited aluminum layer. Aluminum was chosen for both

the CPW lines and the bridge because it was readily available and deposits evenly. A thickness of $0.5\ \mu m$ is sufficient because it is thick enough that slight variations in thickness become inconsequential but still thin enough that undercut during etching is not a major problem. Undercutting is described in Section 3.2.2. EM simulation will be required to verify that the RF signal losses for such a small metallization thickness are acceptable.

With the lines having such a small thickness, the slots between the ground conductors and the center conducting line were made as close as possible in order to maximize the edge-coupling effects across the gaps, (for a $50\ \Omega$ characteristic impedance), and thus, reduce the overall size of the device. Ideally, the fabrication equipment in the Carleton University Microelectronics Fabrication Laboratory can realize structures with a resolution of $2.5\ \mu m$. However, in order to reasonably safeguard against any imperfections which might occur as a result of process errors, the width of the gaps was chosen to be $G=10\ \mu m$.

The widths of the signal line and ground conductors were constrained by the dimensions of the three-pin probes that would be used with the network analyzer to test the microwave characteristics of the finished MEMS shunt switches. The pins of the probes are separated by $150\ \mu m$, measured from the tip of the center pin to the tip of each outer pin. Also taken into consideration was the fact that the ground-conductors would have to be sufficiently wide as to allow the ground plane to be considered infinite [12], common practice when designing coplanar waveguides. As such, the width of the ground-conductors was chosen to be $250\ \mu m$, leaving only the width of the center conductor to be determined.

Since it is the cross-sectional dimensions of a coplanar line that determine its characteristic impedance and all other cross-sectional dimensions have been determined, the width of the center conductor must be chosen so that the characteristic impedance of the waveguide is $Z_0=50 \Omega$. Knowing the substrate thickness is finite and assuming the ground plane and the width of the dielectric substrate are infinite, we can approximately determine the properties of the transmission line using Equation 2 . 1 and Equation 2 . 2, which are based on a quasi-static analysis. [13]

$$Z_0 = \frac{30\pi K(k')}{\sqrt{\epsilon_{re}} K(k)} \quad (2.1)$$

$$\epsilon_{re} = 1 + \frac{\epsilon_r - 1}{2} \frac{K(k') K(k_1)}{K(k) K(k_1')} \quad (2.2)$$

where:

$$k = a/b; \quad k' = \sqrt{1 - k^2} \quad (2.3)$$

$$k_1 = \sinh((\pi a)/(2h))/\sinh((\pi b)/(2h)); \quad k_1' = \sqrt{1 - k_1^2} \quad (2.4)$$

Z_0 is the characteristic impedance of the line, ϵ_{re} is the effective relative permittivity of the substrate and K is complete elliptic integral of the first kind. The terms described in Equation 2 . 3 and Equation 2 . 4 are determined by the cross-sectional dimensions of the CPW, illustrated in Figure 2.2.

Figure 2.2: CPW Cross-Section

Choosing a value of $W=100 \mu m$ for the width of the center conductor and having already chosen a value of $G=10 \mu m$ for the width of the slots, we get $a=50 \mu m$ and $b=60 \mu m$. The thickness of the lines is assumed to be infinitesimal. Thus, $k = 0.83$, $k' = 0.56$, $k_1 = 0.83$, and $k_1' = 0.56$. Again, if the impedance is not sufficiently close to 50Ω , a new value for the width of the center conductor will have to be chosen. As mentioned above, K is the complete elliptic integral of the first kind. The relation $(K(k))/(K(k'))$ however, can be approximated by Equation 2 . 5 or Equation 2 . 6 depending on the value of k^2 .

$$\frac{K(k)}{K(k')} = \frac{1}{\pi} \ln \left(2 \frac{1 + \sqrt{k}}{1 - \sqrt{k}} \right) \quad 0.5 \leq k^2 \leq 1 \quad (2.5)$$

$$\frac{K(k)}{K(k')} = \frac{\pi}{\ln \left(2 \frac{1 + \sqrt{k'}}{1 - \sqrt{k'}} \right)} \quad 0 \leq k^2 \leq 0.5 \quad (2.6)$$

Since $k^2 = k_1'^2 = 0.69$, Equation 2 . 5 is used in both cases. Solving and inverting Equation 2 . 5 for k and solving Equation 2 . 5 for k_1 :

$$\frac{K(k')}{K(k)} = 0.84 \quad \frac{K(k_1)}{K(k_1')} = 1.19 \quad (2.7)$$

Knowing the values in Equation 2 . 7, the effective, relative permittivity, ϵ_{re} , can be found using Equation 2 . 2.

$$\epsilon_{re} = 1 + \frac{3.9 - 1}{2}(0.84)(1.19) = 2.45 \quad (2.8)$$

Now, using the values found in both Equation 2 . 7 and Equation 2 . 8, and substituting these calculated values into Equation 2 . 1, the characteristic impedance of the CPW can be found. Solving yields an impedance of $Z_0 = 50.42 \, \Omega$, which is very close to the desired result.

With the widths of the center conductor, ground conductors, and line spacings known, the line length may now be determined. Typically, the length of a CPW would be chosen by a number of wavelengths or quarter-wavelengths so that the phase change from one end to the other is known. However, since the maximum size of a die is 4mm x 4mm and the wavelength of the signal at 40 GHz is 7.5 mm and since the phase of the signal is of limited importance when measuring the S-parameters of the shunt switches, a line length of 500 μm on either side of the switch was arbitrarily chosen to conserve space on the die and the structure was modelled in *Momentum*. Should these switches be used in a phase-shifter or similar device, then the length of the CPW becomes more important and would have to be determined based on the requirements of the application.

Figure 2.3: CPW line simulation layout modelling the CPW line spacings, using *Momentum*.

Figure 2.3 illustrates the CPW line simulation layout in *Momentum*, which models the magnetic current within the CPW slots. Unlike the previous calculations for the characteristic impedance of a CPW, when using *Momentum* the thickness of the lines is taken into account. The horizontal lines represent where the S-parameter plane is established, the vertical lines are the CPW slots, and the arrows represent the coupled ports that excite the structure. It was determined through this simulation that the dimensions calculated above were satisfactory as can be seen in the results shown in Figure 2.4.

Figure 2.4: CPW Simulation Results. (a) Magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

The reflection coefficient, S_{11} , represents the voltage reflected back to the input after being excited at the input. Similarly, S_{22} represents the voltage reflected back to the output after being excited at the output. The magnitude of the reflection coefficients in Figure 2.4 are the same for both the input and the output, which is expected when dealing with a symmetrical structure since the device *looks* the same from either perspective. Typically, a reflection coefficient of better than -20 dB is sought, meaning the device is matched to better than 1% or in this case, between 49-51 Ω . In the above results, the

impedance of the coplanar line has a reflection coefficient of approximately -55 dB at 20 GHz, corresponding to a near perfect impedance match.

Similarly, the results of the simulation show nearly perfect power transfer. The square of transmission coefficients, $|S_{12}|$ and $|S_{21}|$ represent the amount of power that is transmitted from the input to the output or vice-versa. The values of the transmission coefficients, $|S_{12}|$ and $|S_{22}|$ are very nearly 0 dB, corresponding to basically zero loss.

2.2.2 Calibration Structures

A set of TRL calibration structures was included in both designs in order to establish the S-parameter reference plane when testing the microwave characteristics of the shunt switches and to remove any effects associated with the probe-CPW line transition. These structures were also designed using ADS *Momentum* prior to fabrication and included two shorts of length 0.5 mm, a 50 Ω line of length 1 mm, and a through of length 2.1 mm.

The 50 Ω line shown in Figure 2.5 was also used to verify the fact that the equipment had been properly calibrated and approximated the behavior and characteristics of the switch when the bridge was in the up-state. The shorts, similarly, approximated the behavior of the switch when the bridge was in the down-state further verifying the calibration of the test equipment was satisfactory. An image of the fabricated shorted-line structure is shown in Figure 2.6.

Figure 2.5: Image of fabricated CPW 50 Ω line under microscope, length 1 mm.

Figure 2.6: Image of fabricated CPW shorted line under microscope, length 0.5 mm.

The calibration structures were also modelled in Momentum in order to verify their S-parameters.

Figure 2.7: *Momentum* simulation results for 50 Ω calibration structure. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

Figure 2.7 shows the results of modelling the 50 Ω calibration structure. The line is nearly perfectly matched, evident by the extremely low reflection coefficients. Similarly, there is basically zero loss according to the results obtained for the transmission coefficients.

Modelling the short resulted in only a single reflection coefficient since it is a single port device. Still the reflection coefficient for the short shown in Figure 2.8 shows a perfect reflection of voltage with no loss, which is expected.

Figure 2.8: Momentum simulation results for shorted line calibration structure, showing the magnitude of the input reflection coefficient.

2.3 Quasi-Static Design Considerations

This section covers methods used to determine optimal bridge dimensions and examines a number of peripheral structures included in both the initial and final designs in order to evaluate the fabrication process and any adverse effects the process steps may have on the MEMS switches.

2.3.1 Etch Holes

MEMS bridges, cantilevers, and other devices that are suspended in air, are created by laying down a layer of material that acts as a spacer while the layer that is to become the suspended structure is deposited on top of it. Once the suspended structure is fully realized, the spacer is removed and the device remains suspended above the lower layers

and substrate due to the rigidity of the material used to create the device. Since the spacing layer is ultimately sacrificed, it is often referred to as a *sacrificial layer*.

All the suspended structures described in this project are etched out of aluminum. The sacrificial layer used is HPR-504 photoresist, deposited by spin coating the wafers at 2000 rpm. This method of depositing the sacrificial layer results in a device height of approximately $2.2\text{ }\mu\text{m}$. A number of methods can be used to dissolve and remove the sacrificial layer, and several of these *release* methods, as well as a process summary, can be found in Chapter 3.

Regardless of the release method used, a $2.2\text{ }\mu\text{m}$ gap leaves very little room for the etch to remove the sacrificial layer from under a $110\text{ }\mu\text{m}$ wide suspended structure, as is the case with the MEMS air-bridges described in this document. Therefore, a number of *etch-holes* are patterned into the bridge, increasing the surface area of the spacer that is open to the release agent and vastly reducing the amount of time required to release the devices. The more etch-holes in an air-bridge, or the larger they are, the faster the sacrificial layer will be removed. If the holes are too large or too numerous though, the strength and stability of the device is sacrificed and it may break or collapse during the release process or testing. Therefore, a balance must be struck between a reasonable etch time and the rigidity of the suspended structure being fabricated.

The best possible etch hole size and spacing was determined by laying out and fabricating a number of switches with various hole sizes and spacings as part of the initial switch set and then visually checking what dimensions resulted in large clear holes while leaving a sufficiently sturdy bridge lattice. Fabricated devices from the initial switch set, with a range of hole sizes and spacings, are shown in Figure 2.9 - Figure 2.12.

Figure 2.9: SEM image of bridge lattice. Etch Holes - Diameter = $5\ \mu m$, Separation = $10\ \mu m$.

Figure 2.10: SEM image of bridge lattice. Etch Holes - Diameter = $5\ \mu m$, Separation = $5\ \mu m$.

Figure 2.11: SEM image of bridge lattice. Etch Holes - Diameter = $10\ \mu m$,
Separation = $20\ \mu m$.

Figure 2.12: SEM image of bridge lattice. Etch Holes - Diameter = $10\ \mu m$,
Separation = $10\ \mu m$.

The bridge that has the clearest holes while maintaining a sufficiently thick spacing of aluminum and reasonable etch time is the $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ hole size, separated by $10\text{ }\mu\text{m}$ of aluminum shown in Figure 2.12. These were the dimensions used in the final switch set design.

2.3.2 Design Structures

Included in both the initial and final designs were arrays of cantilever switches. These cantilevers were used to verify how effective the release process had been. Since they are simpler than shunt switches and their microwave characteristics are not being examined, it is possible to make them much smaller than the bridge-style switches.

Figure 2.13: SEM image of Cantilevers.

The cantilevers shown in Figure 2.13 are used to determine the yield of the process, (Section 3.4).

2.3.3 DC Biasing

Though MEMS research is only a few decades old, the tiny electromechanical structures under study still adhere to the same basic mechanical laws that were developed centuries ago. The only difference between modelling MEMS structures and their macroscopic counterparts is the relative significance of the forces acting on the devices. [14]

In order to find the applied voltage required for electrostatic actuation of the switch, the device is modelled as a mechanical spring with an electrostatic force applied. Therefore, the spring constant of the aluminum bridge must be found and a force balance equation must be solved in order to find the minimum voltage that will cause the bridge to collapse. [14]

The spring constant can be found if the dimensions of the structure, and the Young's modulus and Poisson's ratio of the aluminum used to fabricate the bridges are known. The value of the spring constant is given by:

$$K = \frac{32Et^3w}{L^3} + \frac{8\sigma(1-\nu)tw}{L} (N/m) \quad (2.9)$$

where E is the Young's modulus of the bridge material, t is the bridge thickness, L is the bridge length, w is the bridge width, ν is Poisson's ratio of the bridge material, and σ is the residual internal stress of the bridge. [3]

Assuming that the residual internal stress on the bridges is negligible, the above equation simplifies to:

$$K = \frac{32Et^3w}{L^3}(N/m) \quad (2.10)$$

Where Young's modulus for aluminum is $E = 70 \text{ GPa} = 70 \times 10^9 \text{ N/m}^2$, the bridge thickness is $t = 1 \text{ } \mu\text{m}$, and the bridge width is $110 \text{ } \mu\text{m}$.

The length of the bridges in the initial switch set are $140 \text{ } \mu\text{m}$. Substituting these values into Equation 2.10 gives a spring constant of:

$$K = 89.93(N/m) \quad (2.11)$$

The force acting on the switch due to an applied voltage on the center conducting line of the CPW is given by:

$$F = \frac{\epsilon_0 A}{2g^2} V_{bias}^2 (N) \quad (2.12)$$

where ϵ_0 is the permittivity of free space, A is the contact area of the top and bottom electrode, given by the width of the bridge and the width of the CPW center conductor, g is the height of the bridge above the bottom electrode, and V_{bias} is the applied, DC potential. Figure 2.14 shows a cross-section of a MEMS shunt switch, illustrating the location of the pull-down voltage for the air-bridges included in the initial switch set.

Figure 2.14: Cross-section of MEMS shunt switch showing the location of the pull-down voltage when applied to center conductor.

Setting up the force-balance equation between the restoring force of the bridge and the electrostatic force resulting from the applied voltage, shows that instability occurs at $2g_0/3$, where g_0 is the height of the bridge above the ground plane with no potential applied to the CPW center conductor [1]. The voltage required to reach this instability, V_p , is given by:

$$V_p = \sqrt{\frac{8Kg_0^3}{27\epsilon_0 A}} (V) \quad (2.13)$$

The height of the bridge with no electrostatic force acting on it is, $g_0 = 2.2 \mu m$. Solving this equation for the pull-down voltage of the switches created initially gives:

$$V_p = 57.69 (V) \quad (2.14)$$

This is a large value for the pull-down voltage and we wish to reduce it to less than 10 V by increasing the length of the bridges when designing the shunt switches to be included in the final switch set.

Figure 2.15: Cross-section of CPW shunt switch showing pull-down voltage being applied between bridge and ground conductors.

Determining the pull-down voltage of the final switch set requires slightly more work than the initial set because the electrostatic force acting on the bridge is between the

ground plane and the bridge as opposed to the CPW center conductor and the bridge, as was the case in the above calculations. Figure 2.15 shows a cross-section of a CPW shunt switch with the pull-down voltage being applied between the bridge and the ground conductors. Still, with a few adjustments, the procedure for calculating the pull-down voltage is basically the same. [3]

The physical length of the bridges in the final switch design was increased to $L=500 \mu m$ in order to reduce the pull-down voltage required to actuate the switches. However, to use the equations given above, the effective length, L_{eff} , must be considered. This can be done by assuming that the ground conductors are at the center of the bridge and ignoring the section of bridge material that stretches between the inner edges of the outer lines, over the center conductor and slots of the CPW. The final switch design still uses a center conductor width of $W=100 \mu m$ and a gap spacing between the center conductor and the ground-lines of $G=10 \mu m$. We are thus left with an effective length of:

$$L_{eff} = L - (W + 2G)(\mu m) \quad (2.15)$$

$$L_{eff} = 380(\mu m) \quad (2.16)$$

Using the effective length, L_{eff} , in place of the physical length in Equation 2.10, we find the spring constant of the bridges in the final switch set to be:

$$K = 4.49(N/m) \quad (2.17)$$

which is a dramatic reduction in the rigidity of the bridge compared to the initial switch set.

The other variable that is different compared to the initial switch set design is the contact area of the top and bottom electrode. Since the bottom electrode is the ground-

lines and not the center conductor, the contact area is given by the width of the bridge and the width of the ground planes directly below the bridge. In this case:

$$A = 3.63 \times 10^{-8} \quad (m^2) \quad (2.18)$$

Substituting our new values of A and K into the pull-down voltage equation reported previously, (Equation 2.13), we are left with:

$$V_p = 6.63(V) \quad (2.19)$$

This is a much lower pull-down voltage than was achieved by the shunt switches included in the initial switch set.

2.4 Self Actuation/Power Handling

Finding the DC actuation voltage of the final MEMS switch using the method described for the center conductor biasing layout, (Figure 2.14), we can then calculate the maximum AC power the device can handle before the RMS of the AC signal exceeds the pull-down voltage, causing the switch to actuate without a DC bias being applied.

$$V_p = V_{rms} = 7.97(V) \quad (2.20)$$

Knowing the maximum RMS value of a signal that can be applied to the CPW center-conductor, Equation 2.20, we can then determine the maximum average power of the signal, Equation 2.21[15].

$$P_{av} = I_{rms} V_{rms} \cos \phi(W) \quad (2.21)$$

Where I_{rms} is the current of the signal and $\cos(\phi)$ is the power loss factor. We can simplify the equation by assuming a purely resistive load, thus making $\phi = 0$ and $\cos(\phi) = 1$, and leaving Equation 2 . 22 [15].

$$P_{av} = I_{rms} V_{rms} = \frac{V_{rms}^2}{R} (W) \quad (2.22)$$

Substituting the RMS value from Equation 2 . 20 and a value of $R=50 \Omega$ line into Equation 2 . 22, a maximum average power can be determined:

$$P_{av} = 1.27(W) = 31(dBm) \quad (2.23)$$

The switching speed of the shunt switches was not measured due to time constraints.

2.5 Switch design

Finally, after all the design considerations and calculations, the up-state and down-state characteristics can be simulated in *Momentum*. Figure 2.16 shows the layout as it appears in *Momentum*. The arrows are indicative of the coupled ports that excited the coplanar waveguide and the horizontal lines represent where the S-parameter plane is established. The vertical lines are the waveguide gaps between the center conductor and ground conductors and the large rectangle in the center is the bridge.

Figure 2.16: Momentum Layout - Final Switch Design

The up-state and down-state of this structure were modelled by adjusting the substrate layers. Figure 2.17 shows a cross-sectional illustration of the up-state layer map and Figure 2.18 shows the down-state layer map. The up-state layer map shows an additional layer named *FreeSpace_2* that has a thickness of $2\text{ }\mu\text{m}$, approximating the device height above the dielectric layer when no actuation voltage is applied. When the switch is actuated, the bridge collapses and makes electro-static contact with the underlying conductor, shunting it to ground. This is approximated by removing the *FreeSpace_2* layer mentioned above.

Figure 2.17: *Momentum* Simulation - device layers for up-state model.

Figure 2.18: *Momentum* Simulation - device layers for down-state model.

Simulating the up-state and down-state characteristics using these layer maps results in more realistic S-parameter values compared to the approximations made simulating the original CPW 50 Ω line with no air-bridge, (representing the up-state), and the CPW shorted line structures, (representing the down-state.)

The results for the up-state behavior using this simulation method are shown in Figure 2.19.

Figure 2.19: *Momentum* Simulation Results - Final switch, up-state. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

The reflection coefficient now rises from -24 dB at 10 GHz to -17 dB at 20 GHz. This is not quite the perfect line demonstrated in the previous, 50 Ω line simulations (Figure 2.7), but acceptable nonetheless. Typically, it is desirable to have a device matched to better than -20 dB, however, the results shown above at 20 GHz are still close to this goal and should yield good results when testing.

Figure 2.20 presents the results of the *Momentum* simulation using the down-state layer map shown in Figure 2.18 and again using the layout shown in Figure 2.16.

Figure 2.20: Momentum Simulation Results - Final switch, down-state. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficients, (d) magnitude of reverse transmission coefficient.

The reflection coefficients for the actuated switch, ranging from -0.25 dB at 10 GHz to -0.1 dB at 20 GHz, show less perfect values than approximated using the short model in Section 2.2.2. Still, the reflection coefficients are very good and the isolation shown by the transmission coefficients, ranging from -13 dB at 10 GHz to -20 dB at 20 GHz, is better than -13 dB for all frequencies, which is acceptable.

Figure 2.21 depicts the equivalent circuit model of the MEMS CPW shunt switch where Z_0 is the characteristic impedance of the ports and C_s represents the capacitance of the bridge.

Figure 2.21: Equivalent circuit model for MEMS CPW shunt switch.

The isolation is given by:

$$I = \frac{1}{|S_{21}|} \quad (2.24)$$

which in the case of the circuit model shown in Figure 2.21 can be approximated as:

$$I = \left(1 + \left(\frac{\omega C_s Z_0}{2} \right)^2 \right)^{1/2} \quad (2.25)$$

where I is the isolation, Z_0 is the characteristic impedance, C_s is the switch capacitance and ω is the frequency. Equation 2.25 shows that the isolation increases as the frequency increases, as is shown by the transmission coefficients in Figure 2.20.

Based on the assumptions, calculations, simulations and tests described in this chapter, Figure 2.22 shows the final switch set die design as a Cadence layout.

Figure 2.22: Final Switch Design - Cadence Layout. (a) shorts, (b) 50 Ω line, (c) thru, (d) alignment markers, (e) switch, (f) cantilevers.

This layout will be used to create the masks used in the fabrication process described in Chapter 3. Two shorted lines were included so that both probes could be calibrated simultaneously when testing.

The initial switch set was a major influence in shaping the final layout shown in Figure 2.22. The final etch-hole spacing and size were determined by examining fabricated bridges with variations on these dimensions in the initial switch set. The electrical characteristics of the TRL calibration structures and the CPW lines beneath the bridges were measured and showed the expected characteristics, therefore it was unnecessary to alter their dimensions.

Surface Micromachining Fabrication Process

3.1 Chapter Overview

This chapter provides a summary of the surface micromachining process used to fabricate the MEMS devices described throughout this document. Also provided in this chapter are detailed descriptions of release processes and yield results. For a complete and in-depth process description, refer to Appendix A.

3.2 Surface Micromachining Process Summary.

The four-layer fabrication process described in this section is a modified version of a fabrication process developed by Dr. Niall Tait.

3.2.1 Starting Material

The switch sets were fabricated on both two-inch quartz and two-inch silicon wafers with gate oxide. Quartz wafers were chosen because they demonstrate superior microwave properties compared to silicon and yet have a smoother surface than alumina. The silicon wafers were used as an inexpensive way of testing process methods and DC characteristics.

Figure 3.1: Cross-section of completed, four mask shunt switch.

Figure 3.1 shows a cross-section of a completed shunt switch. The following sections will detail the development of this switch layer by layer.

3.2.2 Metal Layer 1

The first deposition was of a $0.5\ \mu\text{m}$ layer of aluminum, deposited using an E-beam evaporator. This layer was patterned using mask number CU-220-01, (Figure 3.2), a light-field mask, drawn in Cadence, which outlines the CPW lines, as well as the base pads for a number of other structures. The term *light-field* means the boxes shown in Figure 3.2 outline the metal structures that will remain once the etch is performed.

Figure 3.2: Mask number CU-220-01

The mask making equipment used at Carleton University does not recognize polygonal shapes or diagonal angles, meaning all structures must be laid out as a series of overlapping rectangles.

Figure 3.3: Cross-Section of CPW line showing the progression of the fabrication process (proportions and dimensions are not to scale). (a) aluminum is deposited; (b) HPR 504 photoresist is spun on; (c) photoresist is patterned and developed; (d) aluminum is etched using phosphoric acid; (e) remaining photoresist is stripped using Microstrip 2001.

The first layer was patterned and developed using HPR 504 photoresist and etched in phosphoric acid at 60° . The photoresist remaining after the aluminum etch is removed using Microstrip 2001. Figure 3.3 shows the sequence of progressing steps involved.

One of the problems associated with this method of patterning and etching the aluminum is undercutting. Undercutting occurs when the etching agent begins dissolving the material beneath the photoresist, affecting the actual dimensions of the pattern as shown in Figure 3.4. Thus, etching time must be properly timed in order to limit the amount of undercutting that occurs.

Figure 3.4: Undercutting.

In the case of the CPW lines being etched, the effect of undercutting is negligible since the dimensions are on the order of $100\ \mu\text{m}$ and undercutting on a $0.5\ \mu\text{m}$ thick layer of aluminum would be on the order of $1\ \mu\text{m}$ for properly timed etches. However, undercutting does become a problem when trying to realize smaller structures, such as the bridge lattice that is created in the final process step, (Section 3.2.5).

3.2.3 Dielectric Insulator

The next layer deposited is a layer of dielectric. This insulator is used as a buffer between the CPW and the bridges, forming the capacitor dielectric when the switch is actuated. This layer is also deposited by E-beam evaporation, using a quartz source and resulting in a layer of SiO_x , (mostly SiO_2), $0.1\ \mu\text{m}$ thick. Mask number CU-220-02, a dark-field mask, is used to pattern the dielectric layer. The term *dark-field* means the boxes shown in Figure 3.5 outline the areas where the dielectric layer will be removed.

The mask shown in Figure 3.5 opens holes in the dielectric allowing subsequent metal layers to anchor themselves on the substrate or the first metallization layer, as well as leaving openings for probes to make contact with the initial metallization.

The dielectric is patterned and developed using HPR 504 photoresist, and etched in siloxide etch, (a buffered hydrofluoric acid solution). The remaining photoresist is removed using Microstrip 2001.

Figure 3.5: Mask number CU-220-02.

Figure 3.6 describes the sequence of processing steps involved in the application and patterning of the dielectric layer.

Figure 3.6: Layer 2 process flow, (proportions and dimensions are not to scale). (a) dielectric is deposited. (b) HPR 504 photoresist is spun on. (c) photoresist is patterned and developed. (d) dielectric is etched using siloxide etch. (e) remaining photoresist is stripped using Microstrip 2001.

3.2.4 Sacrificial Layer (HPR 504)

This layer is deposited by spin-coating the HPR 504 at 2000 rpm for 30 seconds. This corresponds to a measured thickness of $1.9 \mu m$, (average measurement), which defines the height of suspended structures above previous layers. The sacrificial layer is patterned using mask number CU-220-03, a dark-field mask shown in Figure 3.7. This mask is used to open holes in the sacrificial layer allowing the bridges, cantilevers and other suspended devices to be anchored on previous layers.

Figure 3.7: Mask number CU-220-03

The holes are etched using metal-ion-free (MIF) photoresist developer. This layer is not removed until after the final metal layer has been deposited, patterned and etched. The removal of this layer, known as the release process, is described in detail in Section 3.3. The sequence of steps for this layer is shown in Figure 3.8.

Figure 3.8: Layer 3 process flow, (proportions and dimensions are not to scale) (a) HPR 504 is spun on; (b) photoresist is patterned and developed.

3.2.5 Metal Layer 2

A 1 μm layer of aluminum is deposited using E-beam evaporation. Mask number CU-220-04, shown in Figure 3.9, is a light-field mask used to pattern this layer, which will become the air bridges and cantilevers.

Metal layer 2 is patterned and etched as described in Section 3.2.2, though the HPR 504 photoresist used to pattern the aluminum is not removed immediately since that would also affect the sacrificial layer.

Figure 3.9: Mask number CU-220-04

Figure 3.10 shows the process progression through the deposition of the fourth and final layer. However, an additional step remains, that of etching holes in the aluminum bridge in order to remove the sacrificial layer beneath it. The top photoresist is patterned and developed and the aluminum is etched using phosphoric acid, creating the holes shown in the SEM figures in Section 2.3.1. This patterning is difficult to show in the cross-sectional example and has thus been omitted.

Figure 3.10: Layer 4 process flow, (proportions and dimensions are not to scale.)
(a) aluminum is deposited; (b) HPR 504 is spun on.

3.3 Release Process

This section examines the problem of stiction as it relates to MEMS and proposes methods for combatting the various causes. Also in this section, various methods for removing the sacrificial layer and releasing the bridges are described as well as the success of each one.

3.3.1 Stiction

The term stiction refers to the unintentional bonding of MEMS surfaces when the interfacial forces exceed the restoring force of the device. Due to the enormous surface area compared to a relatively small volume, capillary, electrostatic, and van der Waals forces become a major concern.

There are generally two types of stiction that must be addressed: release stiction and in-use stiction. Release stiction occurs as a result of the sacrificial layer removal process and is dominated by the capillary forces prevalent when removing the chemical agent used to dissolve the sacrificial layer. Capillary forces are only a concern when removing the spacer using a liquid agent. Should a dry release method be used, capillary forces are not a concern but the surfaces can still become charged due to excited plasma particles and become bonded nonetheless. For this thesis, only liquid release methods are used.

In-use stiction occurs when a surface of a successfully released structure comes in contact with another surface, either intentionally or unintentionally, and becomes bonded to it. Figure 3.11 shows an example of stiction, where an air-bridge has bonded to the underlying CPW-line during the release process.

Figure 3.11: Stiction example. SEM image of air-bridge bonded to the underlying CPW-line.

In order to minimize the release stiction problem when releasing a MEMS with a liquid agent, rinsing the device in chemicals with progressively lower surface tensions can decrease the number of devices that become bonded as a result of being pulled into another surface due to capillary forces.

Minimizing in-use stiction requires the surfaces of the MEMS devices be treated in some fashion in order to minimize interfacial forces. This is especially true in cases where the surfaces are intentionally contacted. The concern when dealing with in-use stiction is typically van der Waals or intermolecular forces, (not to be confused with *intramolecular* forces). These forces encompass all dipole-dipole or dipole-forced-dipole interactions. The major catalyst for in-use stiction is usually water, which is abundant in the atmosphere and has a relatively strong inherent dipole due to its V-like shape. Figure 3.12 shows the atomic structure of H_2O and how two molecules can attract and combine as a result of intermolecular forces. Therefore, MEMS surfaces are usually treated in some fashion in order to make them hydrophobic and thus, reduce in-use stiction.

Figure 3.12: Atomic Structure of a Water Molecule and their interaction.

3.3.2 Anti-Stiction Coating - Hexamethyldisilazane, (HMDS)

HMDS is a chemical used in the Carleton University fabrication facility primarily as an adhesion promoter when spinning photoresist. However, since this chemical works by making the surface of the wafers hydrophobic, it can also be used to coat the surfaces

of the MEMS structures, making them hydrophobic and thus drastically reducing interfacial forces. It is believed that this is the first time HMDS has been used specifically as an anti-stiction coating for MEMS devices. The HMDS is applied as part of the release processes described in subsequent sections.

3.3.3 Acetone Release Method

The MEMS were first placed into an acetone bath in order to dissolve the photoresist and release the suspended structures. Various lengths of time ranging from 5 to 45 minutes were used in an effort to find the greatest yield of usable switches. However, the use of acetone as the release agent resulted in a thin residue of photoresist being left across the surface of the wafer, regardless of the etch time.

The MEMS were then submersed in an isopropyl alcohol bath for various lengths of time ranging from 30 seconds to 2 minutes. This was used to rinse the dissolving agent from the MEMS.

Next, the MEMS were placed in a HMDS bath for various lengths of time ranging from 1 to 15 minutes. This step is used to make the surfaces of the devices hydrophobic in an effort to combat stiction.

Finally, the MEMS were put into a methyl alcohol bath for between 30 seconds and 2 minutes. This final step is used in order to reduce the surface tension of the chemical beneath the bridges in an effort to reduce release stiction and increase yields.

The greatest yield of reusable switches using acetone as the release agent was only 40%. Therefore, an alternative was needed.

3.3.4 Microstrip 2001 Release Method

Microstrip 2001 was used as an alternative to acetone and proved to be much better. The devices were immersed in consecutive Microstrip 2001 baths at 70-80°C for 10 minutes each, followed by an 8 minute rinse in deionized (DI) water. After the DI rinse, the process proceeded as described in the previous section, with times of 1 minute for the isopropyl alcohol, 8 minutes in the HMDS, and 1 minute in the methyl alcohol showing the best results.

The use of Microstrip 2001 as the release agent proved more effective than the acetone release process, showing no signs of the photoresist residue that previously affected the performance of the switches and resulting in a process yield of 75%. Figure 3.13 shows a cross-sectional illustration of the completed MEMS shunt switch.

Figure 3.13: Microstrip 2001 is used to remove the photoresist.

3.4 Process Yield

As described in the previous section, several methods of releasing the suspended MEMS structures were tried before a suitable method was found. A number of cantilever switches were included in the die in order to determine the process yield. The testing

method for determining the process yield using the cantilever switches is explained in Section 4.2. Table 3.1 reports the number of switches tested, the number of working switches, and the subsequent process yield for each release method.

TABLE 3.1: Release Process Yields

<i>Release Process</i>	<i>Number of working switches</i>	<i>Number of switches tested</i>	<i>Yield Percentage</i>
Acetone Release (No HMDS)	2	11	18%
Acetone Release	6	15	40%
Microstrip 2001 Release	6	8	75%

It is very important to have a high process yield when considering the applications for these switches. For example, fabricating a one-bit phase shifter would require four working switches. Using the Microstrip 2001 release method, with a process yield of 75%, the probability of having all four switches working is 32%, meaning two out of every three phase shifters fabricated are likely to have at least one switch which doesn't work. The acetone releases with and without HMDS are much worse, resulting in the probability of having four working switches only 2.6% and 0.1% respectively.

4.1 Chapter Overview

This chapter contains a description of the testing methods, the equipment used to characterize the fabricated switches, and the corresponding results obtained from testing.

4.2 Cantilever Testing Procedure

The cantilever measurements were used to determine the process yield of various release methods, (Section 3.4).

Figure 4.1: SEM image of Cantilever switch. (a) signal-input pad, (b) actuation voltage pad, (c) signal-output pad.

Figure 4.1 shows an image of a fabricated cantilever switch taken using a scanning electron microscope. This structure is set-up so that resistance measurements can be

taken, when the switch is actuated, between pad (a) and pad (c), with an actuation voltage being applied to pad (b), though no resistance measurements were taken. Figure 4.2 shows a cross-sectional representation of the cantilever actuation. Capacitance measurements were taken of the cantilever switches in the unactuated and actuated states. Again, the actuation voltage is applied between pads (a) and (b).

Figure 4.2: Cross-section of cantilever actuation. (a) cantilever in unactuated, up-state. (b) cantilever in actuated, down-state.

A number of cantilever switches were tested for each release method to establish a percentage yield. A cantilever that was actuated and restored at least five times without becoming bonded to the bias pad was considered a working switch. While a greater number of switch cycles would be more desirable, the switches were being tested in air and thus, the lifetime was limited by the ambient humidity. A cantilever which failed to work the minimum five repetitions was deemed stuck and counted against the yield. In a final application, these devices would be placed in a hermetically sealed package.

A common way to assess the MEMS switch behavior is to measure the capacitance variation between pads (a) and (b) as a function of the applied pull-down voltage.

Figure 4.3: Hysteresis curve of a working cantilever switch.

Figure 4.3 shows the resulting C-V curve response of a working MEMS cantilever switch, which exhibits the expected hysteresis due to the fact that it requires less voltage to hold the switch down than to pull the switch down. Actuation of the switch occurs at approximately 12 V for this switch, as is evident from the lower curve's sharp increase in capacitance at that voltage. As the voltage is reduced, the restoring force of the metal causes the cantilever to return to its original state. Notice the sharp decrease in the top

curve's capacitance between 6-8 V and another at approximately 4 V. Between these two jumps, there is a gradual reduction in the capacitance of the switch.

Figure 4.4: Progression of MEMS Cantilever actuation. (a) voltage applied to actuation pad; (b) cantilever switch is actuated; (c) cantilever switch is partially restored as voltage is reduced; (d) cantilever switch is completely restored.

This is caused by the switch being partially stuck as the voltage is stepped down and then completely restored as the actuation potential reaches 0 V. Figure 4.4 shows the progression of a cantilever's full switching cycle.

Figure 4.5 gives a more dramatic example of a cantilever being momentarily bonded at the end and released in the center, evident by the intermediate capacitance achieved during the test cycle between 2-6V.

Figure 4.5: Hysteresis curve of a working MEMS cantilever switch, highlighting a partial restoration between 2-6V.

It is possible, however, for a cantilever to be actuated and then only be partially restored, as is the case in Figure 4.6 which shows that the top curve has not returned to its initial value after the commencement of the second cycle. Switches behaving in this manner were considered to be unreleased and counted against the process yield.

Figure 4.6: Hysteresis curve for non-working MEMS cantilever switch.

4.3 Shunt Switch Testing Procedure

The microwave characteristics of the MEMS shunt switches were measured using an 8720ES analyzer from Agilent Technologies. The switches were excited by the network analyzer through a pair of ground-signal-ground, three-pin probes.

The equipment was calibrated using a picoprobe-model CS-5, ground-signal-ground calibration substrate by GGB Industries Inc. Using this method of calibration establishes the S-parameter plane at the probe tips, located at the end of the CPW line as is illustrated in Figure 4.7.

Figure 4.7: S-parameter reference plane for probe-tip calibration.

Measurements were taken using this method since all the modelling in *Momentum* was done using the ends of the coplanar line as the reference plane. However, it is possible to calibrate the network analyzer using the TRL calibration structures included on the die. This yields results purely for the device without including the length of waveguide leading into it as well as accounting for probe-metal interaction effects. The reference plane in this case is illustrated in Figure 4.8.

Figure 4.8: S-parameter reference plane for on-chip calibration.

4.3.1 Signal Line DC Biasing

When measuring the S-parameters of MEMS air bridges created during the initial fabrication run, a voltage supply was connected to the switch through a bias-tee inserted on the second port of the network analyzer. Several problems were made evident during the testing phase of these switches, the first of which being a design flaw which made the bridges actuate at a higher voltage than anticipated. The dimensions were modified according to the calculations in Chapter 2 to ensure a pull-down voltage less than 10 V. In spite of the high pull-down voltage, a number of useful measurements could still be taken, including measuring the TRL calibration structures and the switches in the bridge-up state.

The results obtained for the initial switch set showed the characteristic behavior anticipated by the *Momentum* simulation results shown in Figure 2.7, Figure 2.8, and Figure 2.19, and thus, no changes to the dimensions of the CPW lines or calibration structures were required before fabricating the final switch set. The results obtained were very

similar to the measurements taken using the final switch set and have therefore been omitted to prevent redundancy.

4.3.2 Independent DC Biasing

The MEMS switches fabricated during the final process run were created using the masks presented in Section 3.2 and the surface micro-machining process described in detail in Appendix A.

Before the switches were tested, measurements of the on-chip calibration structures were taken in an effort to verify the fact that the underlying CPW lines performed satisfactorily.

Figure 4.9: Measurement of on-chip 50 Ω line - Final Switch Set. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

Figure 4.9 shows the measured S-parameters of the 50 Ω line, where the insertion loss is near 0 dB and the return loss is on the order of 30 dB. A comparison with the simulated results for this line reported in Figure 2.7 shows the fabricated structure indeed exhibits low loss and 50 Ω characteristic impedance. In addition, the results obtained measuring this structure are expected to approximate the S-parameters that will be measured when testing the shunt switches in the bridge-up state despite the fact that the switch lines are 100 μm longer than the 50 Ω calibration line due to the device width. Such a change in length would affect the transmission phase, but is of little importance for these measurements.

Similarly, the results from measuring the shorted line calibration structures should approximate the results that will be obtained when measuring the switches in the bridge-down state. The $|S_{11}|$ measurement of the shorted CPW line is given in Figure 4.10 showing an $|S_{11}|$ value of better than 0.5 dB for all frequencies between 10-20 GHz. Comparing with the simulated results in Figure 2.8 shows that the fabricated shorts behave as expected, exhibiting nearly total power reflection.

Figure 4.10: Measured magnitude of input reflection coefficient for on-chip shorted line calibration structure - Final Switch Set.

Having obtained reasonable results from the calibration structures, we can then look at the measurements taken of the switch in both the unactuated, (bridge-up), and actuated, (bridge-down), states. These results are presented in Figure 4.11 through Figure 4.17 .

Figure 4.11: Measured results for switch - Bridge-Up - Final Switch Set. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

The measurements obtained for the switch in the unactuated state are shown in Figure 4.11. The reflection coefficients, $|S_{11}|$ and $|S_{22}|$, show that the device is matched to better than -20dB for all frequencies, while the transmission coefficients, $|S_{12}|$ and $|S_{21}|$, never drop below -0.5dB between 10-20 GHz. The values obtained in Figure 4.11 are representative of the 3 working switches that were tested.

Comparing these results to the simulations performed using Momentum, (Figure 2.19), shows that the switches in the up-state do not significantly load the CPW line and therefore, are behaving as expected.

Figure 4.12: Comparison of simulation and measured results for shunt-switch in unactuated state. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

This is further confirmed in Figure 4.12, where the measured results (Figure 4.11) and the simulated results (Figure 2.19) are superimposed. The tested switch actually matched better than the model as is shown by the better reflection coefficient results. The insertion loss depicted by the transmission coefficients, however, is not quite as good as the simulated results. This is a result of an approximation made when modelling the switches in *Momentum*. The up-state S-parameters shown were calculated by assuming the bridge was a solid strip of aluminum as opposed to the perforated bridges that were

fabricated. The resulting larger bridge shunting the CPW line corresponds to the larger magnitude of reflection coefficient observed in simulation. Scaling the size of the bridge in *Momentum* to better approximate the actual capacitance of the device yields the results shown in Figure 4.13.

Figure 4.13: Comparison of simulation and test results for shunt-switch in unactuated state after scaling to match actual bridge area. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

A comparison of the measured and resimulated $|S_{11}|$ results show a far better agreement. As for $|S_{21}|$ being approximately 0.25 dB higher in simulation than in mea-

surement, it is believed that momentum slightly underestimates the transmission loss of the line.

Once measurements for the up-state were taken, the switch was then biased using a 20 V DC supply applied through a third probe contacted at the DC bias pad. Figure 4.14 shows an overview of the final switch design, featuring an independant DC bias pad that allows the voltage to be applied between the bridge and the ground conductors.

Figure 4.14: Overview of final switch design with independant DC bias voltage applied between the bridge and the ground conductors.

The switches tested actuated with an applied voltage between 6-10 V. This corresponds well to the pull-down voltage previously calculated in Section 2.3.3.

Figure 4.15: Measured results of switch - Bridge-Down - Final Switch Set. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

Figure 4.15 shows the results of testing the switch in the bridge-down state. The general characteristics are as expected, but not at the level of performance that was anticipated by the original simulation results shown in Figure 2.20. The isolation of the switch at 10 GHz is only 5 dB. Though this improves with frequency, an isolation of at least 13 dB for all frequencies was anticipated.

A comparison of the tested results with the simulated results obtained from *Momentum* is shown in Figure 4.16. Here, it is more apparent that the fabricated switch underperforms compared to the expected results.

Figure 4.16: Comparison of simulation and test results for shunt-switch in actuated state. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

The magnitude of reflection coefficients are at least 2.5 dB worse for all frequencies than the values obtained using *Momentum*. A small portion of this discrepancy can be attributed to losses in the CPW metallization, however the majority of this is attributed to the MEMS air-bridge not shunting the RF signal to ground as effectively as anticipated. Again, this is due to the original approximation for the bridge size being too large. The reason that this approximation affects the isolation is effectively demonstrated by Equation 2.25, derived from the equivalent circuit model shown in Figure 2.21.

Figure 4.17: Comparison of simulation and test results for shunt-switch in actuated state after scaling to match actual bridge area. (a) magnitude of input reflection coefficient, (b) magnitude of output reflection coefficient, (c) magnitude of forward transmission coefficient, (d) magnitude of reverse transmission coefficient.

As shown in Equation 2.25, an increase in the capacitance would increase the isolation of the device. Thus, overestimating the capacitance of the bridge caused an overestimation of the isolation of the switch in the down state.

Re-simulating the down-state using the effective area of the scaled down bridge yields results that agree much better with the measured S-parameters as is shown in Figure 4.17.

Figure 4.18: Comparison of expected isolation characteristics and measured isolation characteristics after scaling bridge size. (a) simulated magnitude of transmission coefficients, (b) measured magnitude of transmission coefficients.

Figure 4.18 shows a comparison of the isolation characteristics of the fabricated switches and the simulated switches once the bridges were reduced to represent the effective area of the bridge. The simulated results in this case, show an isolation of 7 dB at 10 GHz. This is 2 dB better than the 5 dB isolation obtained for the fabricated switches at 10 GHz. To improve the isolation, the capacitance between the signal line and shunt to ground would have to be increased. This could be done simply by increasing the width of

the switches. This would have a trade-off of greater insertion loss of the device in the up-state.

Figure 4.19: *Momentum* simulation for switch in the up-state and down-state with larger bridge.

Figure 4.19 reports the isolation achieved in *Momentum* when the capacitance was over-estimated. This figure demonstrates that increasing the size of the air-bridge and thus increasing the capacitive loading that occurs, will improve the isolation of the device in the down-state.

The switches fabricated during the final process run showed a number of deformations on the air-bridges and other suspended structures. Since these impurities are only evident on the final metallization layer, it is most likely a result of bubbling or shifting of the sacrificial layer. It is quite possible that these deformations affected the isolation of the fabricated switches, inhibiting the bridges from making good contact with the underlying layers when actuated.

Figure 4.20: (a) Cross-section of MEMS shunt switch in the intended down-state; (b) Cross-section of MEMS shunt switch in down-state with deformation.

Figure 4.20 shows a representative cross-section of a possible cause for the poorer isolation shown by the fabricated switch compared to simulated results.

Figure 4.21: Fabricated switch with independent DC bias pad from final switch set.

Figure 4.21 shows a fabricated switch from the final switch set. Small dark spots can be seen on the bridge lattice and it is believed that these spots are depressions in the

air-bridge like those illustrated in Figure 4.20. Comparing the results of these switches to those achieved by other groups, we see that the pull-down voltage of between 6-10 V compares favorably with other reported results. A group from Raytheon [7] reports a pull-down voltage of between 30-50 V for a shunt switch of similar dimensions. However, the isolation reported by said group was better than 35 dB, far better than the isolation reported in this project. Still, the work in this chapter has shown that it is a relatively simple matter to improve isolation. By increasing the size and capacitance of the switch, the isolation would improve.

Design of an Adaptive Antenna using MEMS

5.1 Chapter Overview

As an application example of the MEMS capability developed herein, this chapter proposes an adaptive patch antenna that uses MEMS switches to control the phase of the radiated fields. Rather than using a conventional external switched line phase shifter or loaded line phase shifter [17] to achieve this effect, a more novel and integrated approach, using switching elements within the antenna element itself, was adopted instead.

5.2 Introduction

A typical microstrip patch antenna usually consists of a metallic patch placed on an electrically thin, though large grounded substrate, where the radiating patch and the ground plane are on opposite sides of the substrate. In this work, the ground plane will be established on the same layer as the patch antenna. This topology is referred to as a coplanar patch antenna and is compatible with the CPW regime employed in the MEMS switch development. Figure 5.1 illustrates the geometries of both microstrip and CPW patch antennas.

Patch antennas have a number of advantages over other types of antennas. Their very low profile and conformability allow them to be used in a variety of applications without taking up much space and they are light weight. This also makes them amenable to arrays. Patch antennas can also be designed to produce either linear or circular polarization and are generally employed in the frequency range 1-40 GHz. [18]

Figure 5.1: Comparison of patch antenna geometries. (a) Microstrip patch antenna; (b) CPW patch antenna.

The major disadvantage of patch antennas is their very narrow bandwidth. Using conventional designs, a patch antenna typically has a bandwidth of around 1-2% of the resonant frequency. [18] A potential drawback of the CPW antenna versus microstrip antennas is its bidirectional radiation characteristics. However, several techniques exist to obtain unidirectional radiation using external components.

An enormous body of research already exists in the field of antennas [19] though only a relatively small amount of that research has been conducted on coplanar patch antenna configurations [20][21]. The use of MEMS switching elements in reconfigurable integrated circuit applications has also been explored [16], but it is believed this is the first

work done where a MEMS switch is implemented directly into the main radiating element of a coplanar patch antenna.

In this work, all CPW patch antenna simulations were performed using *Momentum* from Agilent technologies ADS. *Momentum* was chosen as the simulation tool because it was used to design the MEMS shunt switches described previously, and because it has the ability to present 3-D far-field radiation patterns. Therefore, it contains all the tools required for simulating patch antennas while maintaining a level of continuity with the work done previously.

5.3 Antenna Design

A basic CPW patch is shown in Figure 5.2. The antenna's resonant frequency is dependant mainly upon the length (L) of the antenna, whereas the width of the patch (W) is usually adjusted in order to achieve a certain input impedance, though altering the shape or width of the patch can still affect the resonant frequency. Typically, the length and width of a patch antenna are on the same order. Equation 5 . 1 gives an approximation of the antenna half-wave resonant length based on the wavelength of operation, λ_0 , and the effective permittivity of the substrate, ϵ_{reff} .

$$L = \frac{\lambda_0}{2\sqrt{\epsilon_{\text{reff}}}} \quad (5.1)$$

It is clear that the patch antenna's frequency of operation is inversely proportional to its size. Here an operating frequency between 20 and 40 GHz is desired, allowing the patch antenna to be designed using MEMS switches having comparable dimensions to those designed previously.

Figure 5.2: *Momentum* layout - coplanar patch antenna.

Figure 5.2 also shows the basic antenna layout as it was simulated in *Momentum*. Much like the simulations described for the coplanar lines and shunt switches in Chapter 2, the gaps between the patch antenna and ground plane are modelled instead of the metalization. This is done in an effort to reduce simulation time. *Momentum* works by laying an array of cells over the device and calculating the currents and coupling effects in each using the Method of Moments. Since the area covered by the gap spacings is much smaller than the area covered by the aluminum, there are fewer cells in the mesh and thus, fewer calculations for *Momentum* to perform.

The patch antenna modelling is approached assuming that it would be fabricated using the four-layer, surface micromachining process described in Chapter 3. The patch

would be fabricated on a $300\text{ }\mu\text{m}$ thick quartz substrate with a relative permittivity of $\epsilon_r = 3.9$, and a loss tangent of 0.0003. The patch itself would be etched out of a $0.5\text{ }\mu\text{m}$ layer of aluminum.

Figure 5.3: Performance of patch antenna. Magnitude of reflection coefficient shows a resonant frequency of approximately 33GHz.

The first step is to design an antenna that resonates near 30 GHz. This was achieved with a CPW patch having $L = 1.4\text{ mm}$ and $W = 2.7\text{ mm}$. Figure 5.3 shows the results of the momentum simulation. A resonant frequency of approximately 33 GHz is obtained, with a reflection coefficient of better than -10 dB, which is a sufficient match to the $50\text{ }\Omega$ system. The radiation patterns at 33 GHz are shown in Figure 5.4.

Figure 5.4: Far-field E cuts of basic patch antenna. (a) $\phi = 0$, (b) $\phi = 90$

These radiation patterns are planar cuts through the far-field E radiation pattern.

The angles of $\phi = 0$ and $\phi = 90$ are taken as shown in Figure 5.5.

Figure 5.5: Basic patch antenna showing the direction of the radiation cuts.

The next step is to affect the antenna in some way in order to induce a phase shift in the radiated far-field. Viewing the patch as a resonant structure, it is well known that its phase characteristic changes rapidly with frequency when operating near resonance. Therefore, it is necessary to slightly affect the antenna's resonant frequency with a MEMS switch. Islands of metallization are positioned adjacent to the patch antenna, as shown in Figure 5.6, and MEMS cantilever switches are used to make a connection between the patch and the islands, effectively widening the patch. It is expected that altering the width of the patch will cause a substantial phase change in the radiated field while affecting the resonant frequency of the patch only marginally. The goal is to obtain a significant phase shift, (several tens of degrees), without degrading the impedance match to $50\ \Omega$, ($|S_{11}|$ below -10 dB).

Figure 5.6: Momentum layout - coplanar patch antenna with adjacent islands.

Figure 5.6 shows the coplanar patch antenna with $150\text{ }\mu\text{m}$ wide islands positioned on either side of it, separated by a gap of $200\text{ }\mu\text{m}$. While the islands are not yet connected to the patch, their proximity to the main radiating element will slightly alter its characteristics.

Notice also the small DC connections between the islands and the surrounding ground-plane of width $25\text{ }\mu\text{m}$. These connections are used in order to set the islands at ground potential so that a DC voltage applied through the CPW feedline, (as described in Section 2.3.3 for the shunt switches), to the cantilever switches, (Figure 2.13), anchored on the patch will cause these to be pulled down, creating an electrical connection between the patch and the islands.

Figure 5.7 shows the simulated behavior of the patch antenna when the adjacent islands are considered in *Momentum*.

Figure 5.7: Performance of patch antenna with islands not connected.

In Figure 5.7 we still see a resonant frequency between 30-40GHz, though now it has shifted to approximately 36 GHz. We also see that a second resonance has been induced, by the presence of the islands, at 22GHz.

Figure 5.8: *Momentum* layout - Coplanar patch antenna with adjacent islands connected, approximated by physical connection between main antenna element and adjacent islands.

Now, the behavior of the patch must be determined when the islands are connected to it via cantilever switches. In *Momentum*, this is approximated by placing a break in the gap spacing between the island and the patch as shown in Figure 5.8. This method of approximating the connection assumes the main antenna element and the islands are con-

nected physically as opposed to being connected capacitively across a dielectric spacer, as would be the case in the fabricated antenna.

Figure 5.9: Performance of patch antenna with islands connected.

The magnitude of the input reflection coefficient is shown in Figure 5.9. The resonant frequency is slightly altered by changing the width of the antenna. The resonant frequency of the antenna is now nearly 40 GHz. Comparing the reflection coefficients of the patch with the islands both connected and not connected, as shown in Figure 5.10, we see that the optimal frequency of operation for this patch antenna for minimal perturbation of its input impedance is approximately 37 GHz.

Figure 5.10: Comparison of input reflection coefficients for patch antenna with islands connected and not connected.

Having shown that the shape of the patch antenna can be changed without drastically changing the resonant frequency, a simulation can now be conducted to determine the phase of the radiated signal in the far-field. This will be done by inserting a probe a considerable distance above the patch and treating the antenna-probe combination as a two port circuit. Thus, the S21 phase characteristic obtained should represent the phase of the radiated signal.

Figure 5.11: Momentum layout - coplanar patch antenna with islands and secondary wire antenna for measuring phase in far-field.

Figure 5.11 shows the complete assembly as simulated in *Momentum*. The coplanar antenna shown has the cantilever switches actuated and thus, the islands connected to the main antenna element. The probe strip, located 15mm above the patch, has a width of $20\ \mu\text{m}$ and leads to port 2 at the top of the figure.

Figure 5.12 shows a comparison of the reflection coefficients as well as a comparison of the phase of the radiated signal when the switches are actuated and unactuated. The results show that the phase of the radiated signal is unchanged between 30-40GHz regardless of the state of the switch.

Figure 5.12: Comparison of Antenna characteristics with islands connected and not connected. (a) Magnitude of input reflection coefficients; (b) phase of forward transmission coefficients.

A number of simulations were performed using various dimensions for the island widths and gap spacings, as well as adjusting the position of the switches. All of these simulations yielded similar results as those shown in Figure 5.12. Also considered was using only one adjacent island, thereby affecting the width of the patch and the position of the input signal feed, though those simulations were similarly unsuccessful in achieving a change in radiated signal phase.

Finally, it was conceded that in order to see an appreciable change in the phase of the radiated signal, the length of the patch would have to be changed, thereby altering the resonant frequency more directly.

Figure 5.13: Patch antenna layout using a single island to adjust the antenna's length.

Figure 5.13 shows the layout of the patch antenna, using a MEMS cantilever switch to connect it to an adjacent island so as to change the length of the patch.

Figure 5.14: Comparison of patch antenna characteristics with island connected and not connected. (a) Magnitude of input reflection coefficient; (b) Phase of forward transmission coefficient.

Figure 5.14 shows the results from simulating the patch antenna with the length-altering island connected and not connected. While there is no phase change at the resonant frequency of 35 GHz, there is a substantial phase change of approximately 70 degrees between 28-32 GHz. This result shows that it is possible to induce a phase shift in the radiated signal by connecting the patch antenna to an adjacent island of metallization via a MEMS cantilever switch. However, the impedance match to 50Ω has not been simulta-

neously maintained, ($|S_{11}|$ is between -3 dB and -6 dB). Further Optimization of this structure is therefore required.

Figure 5.15: Gain of antenna with adjacent island connected.

Figure 5.15 shows the gain of the final patch antenna when the adjacent island of metallization is connected to the main antenna element via cantilever switch. As expected, the antenna shows the characteristics that we would expect in a single CPW patch antenna element, demonstrating the highest gain 0° and 180° , or directly perpendicular to the face of the antenna both above and below the patch.

Figure 5.16: Gain of antenna with adjacent island unconnected.

Figure 5.16 shows the gain of the final patch antenna when the adjacent island of metallization is not connected to the main antenna element. In this figure, we see a drop in the gain at 0° and 180° . This is due to coupling between the main radiating element and the island. This destructive interference could be eliminated by adjusting the size and separation of the two elements.

Conclusions and Future Work

6.1 Chapter Overview

This chapter summarizes the work done, the problems encountered, and proposes possibilities for future research.

6.2 Conclusions

In this thesis, the design methodology for MEMS shunt switches is presented. The devices were fabricated in the Carleton University Microelectronics Fabrication Facility using a four-layer, surface-micromachining process. In the final stages of the fabrication process, HMDS is used as an anti-stiction surface treatment, resulting in a greatly superior process yield and a dramatic reduction in permanent interfacial bonding.

Also in this thesis, the testing and corresponding performance results of the MEMS shunt switches is described. These results show that the switches behave as expected, showing very low insertion loss in the unactuated state, (better than 0.25 dB between 10-20 GHz), and poor isolation in the actuated state, (better than 5 dB between 10-20 GHz).

Finally, a novel topology is presented for a patch antenna using a MEMS cantilever to connect an adjacent island and thereby adjusting the length of the patch. This CPW patch antenna produces a 70 degree phase shift at 30 GHz when switching between its two states, and is a potential candidate for adaptive array applications.

The finite lifespan of the HMDS surface treatment requires immediate testing to be done subsequent to the release of a MEMS switch. In production, this would probably not create serious problems, provided the device was hermetically sealed within a few hours of release.

The fabricated MEMS shunt switch did not perform as well as anticipated. It is possible that slight deformities in the bridge are keeping it from making clean contact with the underlying layers. This explanation is proposed in Chapter 4.

6.3 Future Research

Some ideas for continuing this work include:

- Another process run using the masks developed for the final switch set. This would be done in order to verify whether the poorer-than-expected isolation was due to a process flaw or a design flaw.
- Further simulations of the antenna design proposed in Chapter 5 in order to achieve more optimal performance. This could include changing the dimensions of the island, changing the location of the switches and adjusting the spacing between the island and the main antenna element.

-
- Fabrication and testing of the patch antenna design proposed at the end of Chapter 5, should the above suggestions yield better performance, (significant phase shift while maintaining -10 dB match to 50 Ω system and eliminating the destructive interference in radiated fields when cantilever switch is unactuated).

Detailed Surface Micromachining Process Description

A.1 Mask Making

Mask layouts were designed using Cadence Custom IC Design Tools - Front to Back Design Environment 4.4.6.100.29, exported as stream files, and converted to *.man format.

The pattern is transferred via a program called pgen1600, (from H&L associates), to two-inch high resolution UF plates, with type 1A emulsion, from Microchrome Technology Inc. The plates were generated using a Flash Unit Photo repeater from the David W. Mann Company, controlled by a Zenith Data Systems Data-640K personal computer. The plate developing procedure is described in Section A.1.1. The reticles image is then reversed, from light-field to dark-field, and transferred to a second two-inch photographic plate using an Oriel Corporation of America Photo mask Printer powered by an Oriel 68810 Arc Lamp Power Supply, (200-500WATT, Hg).

The pattern is then reduced and transferred to a four-inch high resolution UF plate, with type 1A emulsion, using a Model 4M 10AXYL Step and Repeat Camera from the

Jade corporation. Should the process require a dark-field mask, the image is reversed and transferred to a second four-inch plate via the previously mentioned photo mask printer.

A.1.1 Emulsion Plate Developing Procedure

- Developer - 4 minutes - 4:1, deionized water (DI): Kodak Professional HRP Developer.
- Stop Bath - 30 seconds - 54:2, DI water: Acetic Acid, (965ml:35ml).
- Fixer - 45 seconds - DI water: Kodak Professional Fixer, (solution A): Kodak Professional Hardener, (solution B).
- DI water cascade rinse - 5 minutes.
- Methanol bath 1 - 30 seconds, 2" plates, (45 seconds, 4" plates) - 1:1, SEMI Grade Methyl Alcohol: DI water.
- Methanol bath 2 - 30 seconds, 2" plates, (45 seconds, 4" plates) - 95:5, SEMI Grade Methyl Alcohol: DI water.
- Blow dry using nitrogen, (N_2), blower.

A.2 Surface Micromachining Process

This section describes the thin-film deposition and etch procedures used to fabricate the MEMS devices described within this document.

A.2.1 Starting Materials

- 2" +/- 0.015" Standard Quartz wafers from Silicon Quest International Inc., having a thickness of 0.011 +/- 0.001".
- 2" Silicon wafers, orientation - 100, dopant - Bo, type - P, from Addison.

A.2.2 Glassware Cleaning

A glassware cleaning was performed on the wafers prior to processing in order to remove any particles from the surface of the wafers.

- Ammonium hydroxide solution - 10 minutes - 80° C - 20:1:4, DI water: Ammonium hydroxide: Hydrogen peroxide.
- DI water cascade rinse - 10 minutes.
- Hydrochloric acid solution - 10 minutes - 80° C - 6:1:1, DI water: Hydrochloric acid: Hydrogen peroxide.
- DI water cascade rinse - 10 minutes.
- Buffered Hydrofluoric acid, (1%) - 30 seconds - (Silicon wafers only since the buffered HF would etch the quartz, pitting the surface).
- DI water cascade rinse - 10 minutes.
- Spin dry.

A.2.3 Metal Layer 1

- E-beam deposition 0.5 μ m of aluminum, (Al), using Balzers Systems - BA 510 - Vacuum Evaporator, controlled by an Airco Temescal FDC - 8000 Film Deposition Controller. Vacuum pressure - 2x10⁻⁶ Torr, temperature - 12.5° C.
- Spin-coat wafer with Hexamethyldisilazane, (HMDS) - 30 seconds - 4000 rpm, using a Solitec spinner.
- Hotplate soft-bake - 1 minute - 105-110° C
- Spin-coat wafer with HPR 504 Photoresist - 30 seconds - 4000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C

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- Expose wafer - 8 seconds - Mask number CU-220-01-B, using Karl Suss MA 6 Mask Aligner.
 - Develop wafer - 1 minute - 1:1, DI water: MIF Developer.
 - DI water cascade rinse - 5-10 minutes
 - Blow dry - Nitrogen, (N₂), blower.
 - Hard bake - 1 minute - 125-130° C
 - Photoresist, (PR), descum - 1 minute - O₂ plasma - 0.3Torr - 100W, using Technics PEIIA Plasma Etcher.
 - Phosphoric acid etch - 2 minutes, 30 seconds - 60° C.
 - DI water cascade rinse - 10 minutes.
 - PR removal, Microstrip 2001 bath 1 - 70-80° C - 10 minutes.
 - PR removal, Microstrip 2001 bath 2 - 70-80° C - 10 minutes.
 - DI water cascade rinse - 10 minutes.
 - Blow dry - N₂ blower.

A.2.4 Dielectric

- E-beam deposition 0.1 μm of dielectric insulator using quartz source, (SiO_x) - Vacuum pressure - 2x10⁻⁶ Torr, temperature - 12.5° C.
- Spin-coat wafer with HMDS - 30 seconds - 4000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C
- Spin-coat wafer with HPR 504 Photoresist - 30 seconds - 4000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C

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- Expose wafer - 8 seconds - Mask number CU-220-02
 - Develop wafer - 1 minute - 1:1, DI water: MIF Developer.
 - DI water cascade rinse - 5-10 minutes
 - Blow dry - Nitrogen, (N₂), blower.
 - Hard bake - 1 minute - 125-130° C
 - PR descum - 1 minute - O₂ plasma - 0.3Torr - 100W.
 - Siloxide etch, (buffered HF) - 1 minute, 20 seconds.
 - DI water cascade rinse - 10 minutes.
 - PR removal, Microstrip 2001 bath 1 - 70-80° C - 10 minutes.
 - PR removal, Microstrip 2001 bath 2 - 70-80° C - 10 minutes.
 - DI water cascade rinse - 10 minutes.
 - Blow dry - N₂ blower.

A.2.5 Sacrificial Layer, HPR 504

- Bake - 2 hours, 45 minutes - 165° C. This was done in order to remove any water vapor from the surface of the wafer.
- Spin-coat wafer with Hexamethyldisilazane, (HMDS) - 30 seconds - 2000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C
- Spin-coat wafer with HPR 504 Photoresist - 30 seconds - 2000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C
- Expose wafer - 8 seconds - Mask number CU-220-03.
- Develop wafer - 1 minute - 1:1, DI water: MIF Developer.

- DI water cascade rinse - 5-10 minutes
- Blow dry - N₂ blower.
- No hard bake
- Photoresist, (PR), descum - 1 minute - O₂ plasma - 0.3Torr - 100W.

A.2.6 Metal Layer 2

- E-beam deposition 1 μm of Al - Vacuum pressure - 2×10^{-6} Torr, temperature - 12.5° C.
- Spin-coat wafer with HMDS - 30 seconds - 4000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C
- Spin-coat wafer with HPR 504 Photoresist - 30 seconds - 4000 rpm.
- Hotplate soft-bake - 1 minute - 105-110° C
- Expose wafer - 8 seconds - Mask number CU-220-04.
- Develop wafer - 1 minute - 1:1, DI water: MIF Developer.
- DI water cascade rinse - 5-10 minutes
- Blow dry - Nitrogen, (N₂), blower.
- No hard bake
- PR descum - 2 minutes, 30 seconds - O₂ plasma - 0.3Torr - 100W.
- Phosphoric acid etch - 2-4 minutes - 60° C.
- DI water cascade rinse - 10 minutes.
- Blow dry - N₂ blower.

A.3 Release Process

- Microstrip 2001 bath 1 - 10 minutes - 70-80° C.

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- Microstrip 2001 bath 2 - 10 minutes - 70-80° C.
 - DI water cascade rinse - 8 minutes.
 - Isopropyl alcohol bath - 1 minute.
 - HMDS - 8 minutes.
 - Methanol bath - 1 minutes.
 - Dry on hotplate - 105-110° C.

References

1. Goldsmith, C. et al., "Characteristics of micromachined switches at microwave frequencies.", IEEE MTT-S Digest, 1996, pp. 1141-1144.
2. Lee, Joong W. et al., "The impact of micromachine technology on mobile communications.", Special Paper, LG Electronics Institute of Technology, Seoul, Korea.
3. Rebeiz, G. M., Muldavin, J. B., "RF MEMS Switches and Switch Circuits.", IEEE Microwave Magazine, December 2001, pp. 59-71.
4. Wallace, R. M. et al., "adsorption of perfluorinated n-alkoic acids on native oxide surfaces.", J. Vac. Sci. Technol. A, Vol. 13, No. 3, May/June 1995, pp.1345-1350.
5. Ashurst, Robert W. et al., "Dichlorodimethylsilane as an anti-stiction monolayer for MEMS: A comparison to the Octadecyltrichlorosilane self-assembled monolayer.", Journal of Microelectromechanical Systems, Vol. 10, No. 1, March 2001, pp.41-49.
6. Reichl, H., Grosser, V., "Overview and Development Trends in the Field of MEMS Packaging.", IEEE Press, ISBN 0-7803-5998-4, 2001, pp.1-3.
7. Goldsmith, C., "Development and application of RF MEMS technology.", special presentation, 7th World Micromachine Summit, Freiburg, Germany, 1-2 May, 2001.
8. Hah, Dooyoung et al., "A Low Voltage Actuated Micromachined Microwave Switch using Torsion Springs and Leverage.", IEEE MTT-S Digest, 2000, pp. 157-160.
9. Pacheco, Sergio P. et al., "Design of a low actuation voltage RF MEMS Switch.", IEEE MTT-S Digest, 2000, pp. 1165-1168.
10. Agilent Technologies, 395 Page Mill Road, Palo Alto, CA 94304 USA.

11. Agilent Technologies, Advanced Design System 2001 - Momentum Manual, Agilent Technologies 2001.
12. Muldavin, J. B., Rebeiz, G. M., "High-Isolation CPW MEMS Shunt Switches. 2. Design.", IEEE Transactions on Microwave Theory and Techniques, Vol. 48: Issue 6, June 2000, pp. 1053-1056.
13. Mongia, R., Bahl, I., Bhartia, P., "RF and Microwave Coupled-Line Circuits", Artech House, INC., 1999.
14. Barker, N. S., Rebeiz, G. M., "Distributed MEMS true-time delay phase shifters and wide-band switches.", IEEE transactions on Microwave Theory and Techniques, Vol. 46, No. 11, November 1998, pp. 1881-1890.
15. Serway, R. A., "Physics for Scientists and Engineers: With Modern Physics. Third Edition." Harcourt and Brace College Publishers, 1992.
16. Brown, Elliot, "RF MEMS switches for reconfigurable Integrated Circuits.", IEEE Transactions on Microwave Theory and Techniques, November 1998, Volume 46, pp. 1868-1880.
17. Hayden, J. S., Rebeiz, G. M., "One and Two-Bit Low-Loss Cascadable MEMS Distributed X-Band Phase Shifters.", IEEE MTT-S Digest, 2000, pp. 161-164.
18. Petosa, A., "Classnotes 97.567 - Antennas and Arrays", Carleton University, 2001.
19. Qian, Y., Itoh, T., "Progress in Active Integrated Antennas and their Applications.", IEEE transactions on Microwave Theory and Techniques, Vol. 44: Issue 11: Part 2, November 1998, pp. 1891-1899.
20. Murata, T., Fujita, M., "A Self-Steering Planar Array Antenna for Satellite Broadcast Reception.", IEEE transactions on Broadcasting, March 1994, Vol. 40: Issue 1, pp. 1-6.
21. Davis, G., "An Expression for the Mutual Impedances of Coplanar, Orthogonal Surface Patches.", IEEE transactions on Antennas and Propagation, December 1990, Vol. 38: Issue 12, pp. 1975-1978.