Reconfigurable Microwave Circuits

By

Georgina Guadalupe Rosas Guevara

A Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor on Science with Major on Electronics at the National Institute for Astrophysics, Optics and Electronics

Thesis Advisors:
Dr. Roberto Murphy Stack Arteaga – INAOE, Mexico
Dr. Wilfrido Moreno – USF, USA

July 2011
Tonantzintla, Puebla, Mexico

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Dedications

To my dear love José

To my dear parents Lupita and Jorge for their unconditional love and support

To my sisters Copis, Yetlita and Dulcecita

To my sweet princess Alexandra
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CRLH</td>
<td>Composite Right Left Handed</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical Systems</td>
</tr>
<tr>
<td>MTM</td>
<td>Metamaterial</td>
</tr>
<tr>
<td>CPW</td>
<td>Coplanar Waveguide</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission Line</td>
</tr>
<tr>
<td>LH</td>
<td>Left Handed</td>
</tr>
<tr>
<td>RH</td>
<td>Right Handed</td>
</tr>
<tr>
<td>PBG</td>
<td>Photonic Band Gap</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic Waves</td>
</tr>
<tr>
<td>ZOR</td>
<td>Zeroth Order Resonance</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuits</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADS</td>
<td>Advanced Design System</td>
</tr>
<tr>
<td>HFSS</td>
<td>High Frequency Structure Simulator</td>
</tr>
<tr>
<td>SUMMIT</td>
<td>Sandia Ultra-planar Multi-level MEMS Technology</td>
</tr>
<tr>
<td>TEM</td>
<td>Transverse Electromagnetic</td>
</tr>
<tr>
<td>LIGA</td>
<td>Lithographie Galvanoformung Abformung (German)</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>PR+</td>
<td>Positive Photoresist</td>
</tr>
<tr>
<td>CPD</td>
<td>Critical Point Drying</td>
</tr>
<tr>
<td>PNA</td>
<td>Power Network Analyzer</td>
</tr>
<tr>
<td>ISS</td>
<td>Impedance Standard Substrate</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
</tr>
<tr>
<td>SMA</td>
<td>SubMiniature version A</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
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Reconfigurable Microwave Circuits

Georgina Rosas Guevara

Abstract

The research presented in this doctoral thesis introduces a developmental path focused on a design methodology and a fabrication process of a Metamaterial - Micro Electro Mechanical Systems (MTM-MEMS) antenna for reconfigurable microwave circuits. The MTM-MEMS antenna is conceptualized in this research as a three-dimensional device using the fusion of emerging technologies such as Metamaterials (MTM) and Micro Electro Mechanical Systems (MEMS). Together, they can provide very small (with respect to the size of the conventional RF devices) and reliable “smart circuits” at a minimal cost.

The design of antennas using Metamaterial Technology implies a new concept in creating artificial materials that present unique electromagnetic properties, which are controllable and are not present in any known natural environment. Metamaterials open up new ways for innovation in communications systems, based on original designs that exploit singular properties, especially for microwave devices.

The antenna presented here is based on Coplanar Waveguide (CPW) technology; therefore, the signal and ground are in the same plane, presenting high signal integrity (lower dielectric losses and lower conductive losses). The antenna developed in this research has been successfully integrated with RF-MEMS by embedding a parallel plates MEMS capacitor, capable of achieving a capacitance from 0.69 to 6.29 pF in a gap of up to 30 microns between the plates of the capacitor, with an actuation voltage of 20 to 40 V, and thus to achieve reconfiguration in frequency. This is, when the capacitance is varied, the resonant frequency of the antenna is tuned. This versatile antenna can be tuned in the 5.3 to 8.6 GHz range by varying the MEMS capacitors. Additionally, T bias line has been integrated in the same design.
MTM-MEMS antenna was fabricated using surface micromachining technique, and it is integrated in a CMOS chip. The process is composed of five materials and four levels of masks on a silicon wafer of high resistivity acting as the mechanical support. Titanium (Ti) and aluminum (Al) are used as structural materials, with one suspended level for the mechanical structures, and AZ-P4260 was used as the sacrificial material. Silicon dioxide SiO₂ and SU8 were used as dielectrics. In this case, SU8 was used as a dimple for the high frequency device. This fabrication process was planned, implemented and characterized, especially for microwave devices.

Metamaterials-MEMS have had a great impact and constitute a new field in microwave devices by showing a strong performance in RF systems due to the ability to change their physical (electric) and mechanical properties.

These devices have many applications in wireless communications systems; however they also have applications in Nano-RF systems since they can present much smaller sizes than conventional systems.

This thesis is structured as follows: Chapter 1 presents a general introduction to the field; in Chapter 2 the use of metamaterials in RF circuits is discussed. The design of the metamaterial-MEMS antenna is presented in Chapter 3, followed by a description of the experimental procedures in Chapter 4. Chapter 5 presents the experimental results, analyzes them and discuss the principal conclusions, which are presented in a nutshell in Chapter 6.
Circuitos de Microondas Reconfigurables

Georgina Rosas Guevara

Resumen

El trabajo de investigación presentada en ésta tesis doctoral introduce un camino novedoso en el diseño y la fabricación de circuitos de microondas reconfigurables usando las tecnologías emergentes MTM (Metamateriales) y MEMS (Sistemas Micro-Electro-Mecánicos). Este trabajo está enfocado en el desarrollo de una antena MTM-MEMS reconfigurable. La antena es conceptualizada en un dispositivo tridimensional basadas en las tecnologías Metamateriales y MEMS. La combinación de estas dos tecnologías permite desarrollar dispositivos inteligentes, más pequeños, más confiable y a un menor costo.

El diseño de la antena usando la tecnología metamaterial implica un nuevo concepto. Los metamateriales son materiales artificiales con propiedades electromagnéticas inusuales, únicas no encontradas en la naturaleza. En un enfoque óptico los metamateriales se refieren a una serie de elementos dieléctricos y metálicos con cierta distribución y un tamaño definido con respecto a la longitud de onda. En circuitos de microondas o de radio frecuencia son una serie de inductores y capacitores conectados en serie y una serie de inductores y capacitores conectados en paralelo. La tecnología metamaterial abre nuevas vías para la innovación en los sistemas de comunicaciones inalámbricos, basados en diseños originales que explotan las propiedades singulares, especialmente para circuitos de microondas.

La antena presentada aquí es basada sobre una tecnología coplanar, es decir, la señal y el plano de tierra se encuentran en el mismo plano, teniendo bajas pérdidas por dieléctrico y buena integridad de la señal. La antena desarrollada ha sido integrada exitosamente con un dispositivo RF-MEMS a través de un elemento embebido por un capacitor MEMS que consiste de dos placas paralelas, donde una placa es fija y la otra es móvil.
El capacitor MEMS es activado por el principio electrostático capaz de obtener una capacitancia de 0.69 a 6.29 pF, teniendo un rango de desplazamiento entre las placas del capacitor MEMS hasta de 30 micrómetros con un voltaje de actuación de DC de 20 a 40 V, logrando así reconfigurar en frecuencia de 5.3 a 8.64 GHz., es decir, una variación capacitivo del capacitor MEMS resulta una variación en la frecuencia de resonancia de la antena. La línea de polarización o de control de la antena ha sido integrada en el mismo diseño a través de una línea tipo T, conocida comúnmente RF-Choke.

El desarrollo e implementación de la antena MTM-MEMS fue basada mediante la técnica de micromaquinado superficial, es decir, el proceso de fabricación es realizado capa por capa para lograr un dispositivo en 3D que tiene movimiento, el cual puede ser integrada en un chip con tecnología de circuitos integrados CMOS. El proceso de fabricación consiste de cinco materiales y cuatro niveles de mascarillas sobre un substrato de silicio de alta resistividad (orientación 100, \( \rho > 4000 \, \Omega \cdot \text{cm} \)), actuando como soporte mecánico. El titanio (Ti) y el aluminio (Al) son usados como materiales estructurales, con un nivel suspendido para la estructura mecánica. AZ-P4260 es usado como material se sacrificio. El óxido de silicio es usado como aislante térmico y SU8-2002 es utilizado como dieléctrico para definir los dimples, con el objetivo de que la placa móvil del capacitor MEMS regrese a su forma original de forma fácil. Los dimples evitan un corto circuito y las capacitancias parasitas. Todos los materiales usados en el proceso de fabricación fueron analizados y caracterizados especialmente para dispositivos de microondas.

La tecnología de los metamateriales y MEMS han tenido un gran impacto en el desarrollo de alta tecnología y contribuyen fuertemente en el desarrollo de los dispositivos de microondas, mostrando un excelente desempeño en sistemas de radio de frecuencias debido a la habilidad de cambiar sus propiedades físicas, eléctricas y mecánicas.

Estos dispositivos tienen aplicaciones en los sistemas de comunicaciones inalámbricas, así como en muchas aplicaciones biomédicas y en nano-sistemas, ya que
por medio de los metamateriales se pueden hacer los dispositivos tan pequeños como la tecnología lo permita.

La organización de la tesis es de la siguiente forma: el capítulo primero presenta una introducción general en el campo de investigación. En el capítulo segundo se presenta una discusión de los metamateriales en los circuitos de radiofrecuencia, en el tercer capítulo se muestra la metodología de diseño de la antena MTM-MEMS. En el capítulo cuarto se hace una descripción detallada del proceso de fabricación y los procedimientos experimentales llevados a cabo. En el capítulo quinto se dan los resultados, se analizan y se discuten para obtener las conclusiones principales. Por último, en el capítulo sexto se presentan las conclusiones generales y las contribuciones de éste trabajo.
Chapter 1 Introduction

This chapter gives a perspective of RF devices in terms of the emerging technologies of Metamaterials (MTM) and Microelectromechanical Systems (MEMS). It also presents a brief description of the novel RF MTM-MEMS device under study. It presents the objectives and goals of this research work. Finally, it concludes with the organization of the thesis.

1.1 Overview

Nowadays, following the fast development of Radio Frequency (RF) technology, electronic products demand more functions and higher performance, reduced dimensions and higher speeds, and higher output at lower cost. The state-of-the-art in edge technology requires the fusion of emerging technologies such Metamaterial (MTM) and Microelectromechanical Systems (MEMS). Together, they can revolutionize electronics by providing very small and reliable “smart circuits” at a minimal cost.
Metamaterials are structures created in an artificial form from natural materials such as metals (copper, aluminum, and gold, among others) or semiconductors such as silicon. There are essential differences between ordinary materials and metamaterials. The properties of ordinary materials depend fundamentally on their composition (molecules and atoms), whereas those of metamaterials depend principally on their structure; that is, they depend on the form and distribution of the elements. Research in this field opens up new ways for innovation in communications, based on original designs that exploit singular properties such as their simultaneously negative permittivity ($\varepsilon$) and permeability ($\mu$), antiparallel group and phase velocities, and negative refractive index ($n$) [1] - [5].

On the other hand, MEMS or Microsystems or Micromachined devices technology allows for miniaturized structures in 3D, which can be mobile, and are made using micro-fabrication techniques, such as surface micromachining, bulk micromachining, and LIGA, among others.

MEMS have had a great impact in RF systems/Microwave applications and are on top of the wireless communication revolution since they present essential characteristics such as low power consumption, reconfigurability and portability. For these reasons, RF-MEMS can be a key technology to enable universal wireless connectivity.

The main motivation behind this work is twofold: innovating RF-MTM-MEMS circuits through an original design method and a novel fabrication process, and developing ad-hoc RF-MEMS circuits using micromachining technology, which is fully compatible with integrated circuit fabrication processes and which achieves high performance, low cost and compact element size. In this work, the design, fabrication and characterization of a novel MTM-MEMS antenna using a CRLH-TL structure and a two parallel-plate MEMS capacitor as a 3D element for tuning the antenna in frequency is presented.

This work is focused on wireless communications applications with the aim to increase the performance and functionality of the wireless platforms, and to improve the quality of service, as displayed in Table 1.1. The implementation of reconfigurable
antennas in platforms for smart wireless communications reduces the complexity and increases the capacity of antenna systems. In addition, these types of antennas can be widely used in biomedical applications due to their small size and compatibility with materials used in the fabrication process. In this case, aluminum is used to reduce the fabrication cost. However, aluminum can be easily replaced by gold without affecting system performance.

Table 1.1 Frequency bands for wireless services and current number of antennas required [6].

<table>
<thead>
<tr>
<th>Wireless Service</th>
<th>Frequency Bands</th>
<th>Number of Antennas</th>
</tr>
</thead>
</table>
| WiFi             | IEEE 802.11b/g/n: 2.4 - 2.48 GHz  
IEEE 802.11a/n: 5.15-5.85 GHz | 3 x 3 MIMO |
| WiMax            | IEEE 802.16: 2.3-2.4 GHz, 2.5-2.7 GHz, 3.3-3.8 GHz, 5.15-5.85 GHz  
Diversity: main and aux (1 x Tx, 2 x Rx) |
| 3G               | GSM 850: 0.824-0.894 GHz  
GSM 900: 0.88-0.96 GHz  
DCS 1800: 1.71-1.88 GHz  
PCS 1900: 1.85-1.99 GHz  
UMTS: 1.92-2.17 GHz  
Diversity: main and aux (1 x Tx, 2 x Rx) |
| Bluetooth        | IEEE 802.15: 2.4-2.48 GHz | Single |
| GPS              | 1.575 GHz | Single |
| UWM              | 3-10 GHZ | Single |

1.2 Objective and Goals

The principal goal of this research is to design and fabricate reconfigurable microwave devices using Metamaterials and MEMS, implemented on a surface micromachined silicon wafer to obtain moving elements such as a variable capacitor for wireless communication applications.
The research is aimed to establish the following key points are:

a) To propose a novel design technique for reconfigurable antennas using metamaterials and MEMS, considering new and superior aspects (compact size, widely bandwidth, higher gain and higher efficiency) to the state-of-the-art in these fields.

b) To develop a fabrication process through superficial micromachining techniques based on high resistivity silicon wafers for high frequency devices.

c) To add, both in the design and in the fabrication process, elements that give to the structures a more robust mechanical stability such as dimples and holes.

d) To fabricate a MEMS variable parallel plates capacitor as a mobil element for the frequency tuning.

e) To characterize the MTM-MEMS device for system design validation.

1.3 Organization of the Thesis

The thesis is organized as follows. Chapter 2 presents a basic introduction to metamaterials in RF circuits, a description of the Composite Right/Left Handed-Transmission Line (CRLH-TL) model and a brief survey of the available literature for MTM antenna design. Chapter 3 provides a design methodology for the MTM-MEMS antenna, establishes an equivalent circuit model of the antenna, and describes the design and characteristic of the MEMS variable capacitor as a 3D element for tuning the antenna in frequency. Chapter 4 presents the fabrication process and a discussion focused on the experimental procedures. Chapter 5 presents the measurements, results and analysis for the MTM-MEMS antennas in threes aspects: as a radio frequency structure, as a metamaterial structure and as a MEMS structure, obtaining the dispersion parameters, radiation pattern, and other figures of merit such as the dispersion diagram.
associated to a metamaterial structure, and a 3D MEMS dynamic and topography analysis of the MTM-MEMS antenna. Finally, Chapter 6 exposes a comprehensive summary and recommendations for future work.
Chapter 2  Metamaterials in RF circuits

This chapter discusses the fundamental concepts of metamaterials in RF circuits at high frequency. It draws into context MTM devices with a Composite Right Left Handed - Transmission Line (CRLH-TL) approach model for the design. It then presents a study of the state-of-the-art focused on MTM Antennas.

2.1  Fundamentals of the Metamaterials

Metamaterials are broadly defined as effectively homogeneous artificial structures exhibiting unusual properties, for instance, an index of refraction ($n$) that may be negative (left-handedness), simultaneous negative permittivity ($\varepsilon$) and permeability ($\mu$), antiparallel group velocity ($v_g$) and phase velocity ($v_p$). Therefore, metamaterials have spurred considerable interest and led to numerous applications in microwave circuits, especially in antennas. [1-5].
The following figures display some examples of the physical phenomena occurring in or in association with LH media as predicted by Vesalago [1]; for example, reversal of Snell’s law, invisibility, perfect lenses, and miniaturization of devices, among others.

Metamaterials may be equivalently described in terms of physical properties (electric/magnetic dipole moments, electric/magnetic susceptibilities, permittivity, permeability), or in terms of transmission-line (TL) parameters (inductance/capacitance, impedance/admittance, propagation constant/characteristic impedance) [8].
Figure 2.2 shows a classification of materials with respect to permittivity and permeability, which depend on the nature of the unit cell. The diagram presents four possible sign combinations in the pair $(\varepsilon, \mu)$, which are $(\varepsilon > 0, \mu > 0)$, $(\varepsilon > 0, \mu < 0)$, $(\varepsilon < 0, \mu > 0)$ and $(\varepsilon < 0, \mu < 0)$. Whereas the first three combinations are well known in conventional materials, the last one (third quadrant) corresponds to the new class of left handed (LH) materials, also called **metamaterials**.

Metamaterials can be used in different applications, for example: photonic crystals or photonic band gap (PBG), resonant structures and transmission lines, (see Table 2.1). In this work, the focus is on **transmission lines**. The principal difference between them is that the photonic crystal or PBG (photonic band gap) structures are usually operated at the frequencies where the lattice period $p$ is multiple of half of a guided wavelength, $p \approx \lambda_g/2$, (it is operated in the Bragg regime), as illustrated in Figure 2.3 (a), where...
periodicity plays a crucial role. Thus, the properties of photonic crystals are essentially determined by the lattice, whereas in transmission lines the lattice period \( p \) is much smaller than wavelength \( p/\lambda_g \ll 1 \), (it is operated in the long wavelength regime). Therefore the properties of the metamaterials are determined by the nature of the unit cell [5], as detailed in figure 2.3 (b).

Table 2.1 Different modalities of the metamaterials [9] and [10].

<table>
<thead>
<tr>
<th>Photonic Cristal or PBG (Photonic Band Gap)</th>
<th>Resonant Structure Approach</th>
<th>Transmission Line Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>It is a periodic structure. Photonic crystals are composed of periodic dielectric or metallo-dielectric nano-structures that affect the propagation of electromagnetic waves (EM).</td>
<td>It is a resonant structure, lossy, narrow bandwidth and highly dispersive. The analysis is not simple, rigorous and no design method.</td>
<td>It is not a resonant structure, low loss, broad bandwidth and moderate dispersion. The analysis is like Transmission Line and circuits design methods.</td>
</tr>
</tbody>
</table>

Figure 2.3 Difference between the Bragg scattering and long wavelength regimes (a) Bragg regime, \( p \approx \lambda_g /2 \) and (b) Long wavelength regime, \( p \ll \lambda_g /2 \), where \( \lambda_g \) is guided wavelength and \( p \) is cell size.
2.2 CRLH Transmission Line

A specific metamaterial structure can be made for the microwave regime by a Composite Right/Left Handed (CRLH) Transmission Line (TL) consisting of a dual transmission line accomplished by conventional Right Handed Transmission Line (RH-TL) theory, with given $L_R$ and $C_R$, and series capacitors and shunt inductors given by $C_L$ and $L_L$, which constitute a Left Handed Transmission Line (LH-TL), as illustrated in Figure 2.4.

![Figure 2.4 Equivalent Circuit Model of a CRLH TL-MTM cell.](image)

The parameters for a composite Right/Left handed Metamaterial CRLH-MTM structure ($L_R$, $C_R$, $L_L$ and $C_L$) are obtained with the following equations, developed by Caloz and Itoh [5]. (These equations, however, have undergone modifications in sign and phase.) Once determining the central frequency ($\omega_0$), coupling impedance ($Z_C$), number of cells ($N$) and phase RH/LH ($\phi_{RH}, \phi_{LH}$), one gets:

\begin{equation}
L_R = -\frac{Z_C[\phi_{RH} - \phi_{LH}]}{2NW_c}
\end{equation} (2.1)
Chapter 2 Metamaterials in RF circuits

The series resonant frequency and shunt resonant frequency are given by [5]:

\[
\omega_{se} = \frac{1}{\sqrt{L_L C_L}} \quad (2.6)
\]

\[
\omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \quad (2.7)
\]

The fundamental characteristic of the CRLH-TL is the propagation constant or phase propagation or wave vector \( \beta = nk_0 \) \((k_0 = \omega/c: \) free space wavenumber, \( \omega \) angular frequency, \( c \): speed of light). Theoretically, a CRLH TL has two operating regions, corresponding to the RH mode \((\beta > 0)\) and to the LH mode \((\beta < 0)\), respectively. Notice that these two regions are bound by a bandgap and two cutoff frequencies determined by the RH circuit elements within the unit cell (low-pass filter) and LH circuit elements within the unit cell (high-pass filter). These two regions can be easily identified in a dispersion diagram, as shown in Figure 2.5.
The CRLH-TL exhibits interesting properties in the particular case where the series and shunt resonant frequencies are equal. This case is called the *balanced case*, as opposed to the general unbalanced case, where series and shunt resonances are different. Figure 2.6 illustrates a dispersion diagram in terms of frequency ($f$) versus propagation constant ($\beta$), where the resonant frequencies or transition frequencies when $\beta$ is equal to zero ($\beta = 0$) can be appreciated.

Balanced \[ \omega_0 = \omega_{se} = \omega_{sh}, \quad Z_c = Z_L = \sqrt{\frac{L_L}{C_L}} = \sqrt{\frac{L_R}{C_R}} \] (2.8)

Unbalanced \[ \omega_{se} \neq \omega_{sh}, \quad Z_c \neq Z_L = \sqrt{\frac{L_L}{C_L}} \neq Z_R = \sqrt{\frac{L_R}{C_R}} \] (2.9)
Figure 2.6 Dispersion Diagram of a structure CRLH-TL for the balance system and unbalance system.

2.3 Emerging Metamaterial Antennas

Recently, research into novel CRLH metamaterial concepts has led to a wealth of practical antennas with unprecedented features, this is, with unconventional electromagnetic characteristic, such as a negative $\varepsilon$ and $\mu$, and the use of a CRLH structure as the radiating element or feeding element, and the Poynting vector being antiparallel with the phase velocity or propagation constant [9] and [11].

The applications of metamaterials may be classified in three categories [5]:

1. Guided-wave components: multiband, enhanced-bandwidth, and miniaturized components; tight broadband couplers, compact resonators; uniform power combiners and splitters; UWB filters; agile distributed amplifiers; impulse delay lines and circuits.
2. Refracted-wave systems: focusing slabs, super resolution imagers, reflection-less curved refractors, coordinate-transformation-based graded-index structure for electromagnetic manipulations.


This research is focused on the third category. It presents a selected number of the most practical CRLH metamaterial leaky-wave and resonant antennas.

The main advantages of a CRLH-TL structure are:

✓ The resonant frequencies depend only on the reactive loadings ($C_L$ and $L_L$) of the unit cell and not on the physical length, which provides additional degrees of freedom in the design compared to conventional resonant antennas; the propagation constant $\beta$ is non-linear with respect to frequency and can be designed by changing the values for $C_L$ and $L_L$.

✓ CRLH supports both leaky-waves and guided-waves; a CRLH structure can support backward (LH) and forward (RH) waves, so that when it is used in a beam scanning system, it can scan at angles both negative and positive with respect to broadside.

✓ Of particular interest is the so called Zeroth Order Resonance (ZOR) mode, which occurs at the transition frequency between the LH and RH bands and corresponds to a perfectly uniform wave ($\lambda_g = \infty$) across the structure; this mode either provides higher directivity (due to higher effective aperture) and possible higher efficiency (due to lower current crowding) than a conventional resonant antenna of the same physical size,
or smaller size compared to a conventional resonant antenna of the same gain.

The following table displays a comparison between the state-of-the-art and the research proposed of the characteristic design and implementation of the antenna. In summary, all the works found in the literature are focused on devices that are fabricated with planar technology to exploit the advantageous properties of metamaterials, in this case to achieve dual-band properties, but not reconfigurability. Also, the fabrication process presented is not compatible with Integrated Circuits (IC) fabrication processes. This research aims at innovating RF-MTM-MEMS circuits through the use of an original design and novel fabrication process using surface micromachining technology, which is fully compatible with integrated circuit fabrication process. Furthermore, aside from begin a metamaterial structure, it is a radiant and configurable element. It can be used for wireless communication applications, but due to its smaller size, it also has potential bio-medical applications.
Table 2.2  Comparison between state-of-the-art and proposed of the design and the implementation of the MTM antennas.

<table>
<thead>
<tr>
<th>Reference Articles</th>
<th>Layout</th>
<th>Characteristic</th>
</tr>
</thead>
</table>
| Zeroth Order Resonator (ZOR) Antenna [7]                | ![Circuit Diagram](image1) | Planar Technology  
|                                                         |        | $f_0 = 4.90$ GHz  
|                                                         |        | Substrate: Rogers RT/Duroid 5880  
|                                                         |        | $\varepsilon_r = 2.2$  |
| Leaky-wave Antenna [7]                                  | ![Circuit Diagram](image2) | Planar Technology  
|                                                         |        | $f_0 = 3.18$ GHz  
|                                                         |        | Substrate: Rogers RT/Duroid 5880  
|                                                         |        | $\varepsilon_r = 2.2$  |
| Left Handed Mushroom Structure [12]                     | ![Circuit Diagram](image3) | Parallel-Plate Waveguide Structure  
|                                                         |        | $f_1 = 5.0$ GHz  
|                                                         |        | Multi-Layer Technology Metal-Insulator-Metal (MIM)  
|                                                         |        | $f_1 = 1.9$ GHz and $f_2 = 2.4$ GHz  |
| Dual Band CRLH Antenna [13]                             | ![Circuit Diagram](image4) | Planar Technology  
|                                                         |        | $f_0 = 3.58$ GHz  
|                                                         |        | Substrate: Rogers RT/Duroid 5880  
|                                                         |        | $\varepsilon_r = 2.2$  |
| Infinite Wavelength Resonant Antenna [14]               | ![Circuit Diagram](image5) | Planar Technology  
|                                                         |        | $f_0 = 5.3$ to 5.8 GHz  
|                                                         |        | Substrate: Silicon High Resistivity  
|                                                         |        | Reconfigurable  |
| This work MTM-MEMS Antenna [15]-[18]                    | ![Circuit Diagram](image6) | MEMS Technology  
|                                                         |        | $f_0 = 5.3$ to 5.8 GHz  
|                                                         |        | Substrate: Silicon High Resistivity  
|                                                         |        | Reconfigurable  |
2.4 Conclusions

This chapter has presented a perspective of RF-MTM circuits and contextualized a comprehensive background on the present state-of-the-art for MTM-Antennas. A literature survey was presented to document the antennas developed in this work. The merits and demerits of each type of design have been tabulated, including technology, ease of integration, and reconfigurability.
Chapter 3  Metamaterial-MEMS Antenna Design

This chapter establishes a design methodology for a metamaterial structure antenna, followed by the design of an RF-MEMS variable capacitor to be used as a tunable element for the antenna, considering micromachining techniques and the use of dimples and holes and some other aspects that support functional stability, and allow for the proper release of the structure. Finally, the complete design of the antenna is presented, including a T-Bias Line controlled by a DC voltage.

3.1  Design Methodology

The design methodology for the MTM-MEMS antenna consists of a mixed approach using the developed CRLH-TL circuit model and full wave simulations (Frequency-Domain Analysis-FDA). In this work, FDA is used for evaluating the scattering parameters behavior, specifically the return loss $S_{11}$ and the insertion loss $S_{21}$. In general, the S-parameters or scattering parameters tell us how much power "comes back" or
"comes out" when we "throw power at" a network. They also contain phase shift information. The return loss $S_{11}$ provides information about the impedance match of the device to a 50 Ω system, while the insertion loss $S_{21}$ provides information about the signal quality of the transmitted signal and the bandwidth of the device. The bandwidth, of course, is a rough indication of the highest data rate that can be transmitted through the structure. Return and insertion loss can be used to characterize a device and provide an immediate estimate for the performance of the device under test.

The design details are presented as follows:

Step 1) Obtain the values for $L_R$, $C_R$, $L_L$, and $C_L$ of a basic CRLH-MTM cell (see Figure 3.1(a)) using equations (2.1) to (2.7) (described in the previous chapter) developed by C. Caloz and T. Itoh [5], once the correct modifications is sign and phase have been performance, as displayed in table 3.1. For the circuit implementation of a basic metamaterial cell, the left-handed elements are formed by MEMS capacitors ($2C_L$) and inductor ($L_L$), whereas those of the right-handed portion are conventional transmission line elements ($C_R$ and $L_R$), as shown in Figure 3.1(b). This structure is simulated using Advanced Design System (ADS), as shown in Figure 3.2(a).

![Figure 3.1](image-url)
Table 3.1 Parameters of a basic CRLH-TL MTM cell

<table>
<thead>
<tr>
<th>Equations</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_R = -\frac{Z_C[\phi_{RH} - \phi_{LH}]}{2N\omega_0} )</td>
<td>( L_R = 1.437 \text{ nH} )</td>
</tr>
<tr>
<td>( C_R = -\frac{[\phi_{RH} - \phi_{LH}]}{2NZ_C\omega_0} )</td>
<td>( C_R = 0.574 \text{ pF} )</td>
</tr>
<tr>
<td>( L_L = -\frac{2NZ_C}{\omega_0[\phi_{RH} - \phi_{LH}]} )</td>
<td>( L_L = 1.31 \text{ nH} )</td>
</tr>
<tr>
<td>( C_L = -\frac{2N}{\omega_0Z_C[\phi_{RH} - \phi_{LH}]} )</td>
<td>( C_L = 0.524 \text{ pF} )</td>
</tr>
<tr>
<td>( \omega_{se} = \frac{1}{\sqrt{L_RC_L}} = \omega_{sh} = \frac{1}{\sqrt{L_RC_R}} )</td>
<td>( \omega_{se} = 3.64 \times 10^{10} \text{ rad/s} )</td>
</tr>
</tbody>
</table>

Where: the center angular frequency is \( \omega_0 = 3.64 \times 10^{10} \text{ rad/s} \) (\( f_0 = 5.8 \text{ GHz} \)); the coupling impedance is \( Z_C = 50 \text{ \Omega} \); the number of cells is \( N = 1 \), and the RH/LH phases are \( \phi_{RH} = -60 \text{ degrees} (-1.0472 \text{ rad/s}) \) and \( \phi_{LH} = 60 \text{ degrees} (1.0472 \text{ rad/s}) \).

Figure 3.2(b) and (c) show an ADS simulation of a CRLH-TL basic cell and scattering parameters of the return loss \( S_{11} \) and of the insertion loss \( S_{21} \) and phase \( S_{21} \).

The most noteworthy points to be observed are large bandwidth (band-pass response), as shown in Figure 3.2(b) and phase response when there is a transition frequency, the phase (\( S_{21} \)) is zero; in this case at a transition frequency of 5.8 GHz, the phase (\( S_{21} \)) is zero, as displayed in Figure 3.2 (c).
Figure 3.2. Simulations of a CRLH-TL at 5.8 GHz in ADS. (a) CRLH-TL cell basic, (b) $S_{11}$ and $S_{21}$ responses at a central frequency of 5.8 GHz and (c) Phase response at 5.8 GHz.

Step 2) Determine the circuit implementation, as illustrated in Figure 3.1(b). In this case $C=2C_L$, and each element of this structure is independently simulated using ADS and Ansoft HFSS, as displayed in Figures 3.3 through 3.4.

Every element of the CRLH-TL structure is simulated independently with the aim to verify that the elements do not have resonant frequencies at the device’s operating frequency, and therefore, they do not affect to performance of device. The simulations are done considering each element as lumped and distributed, and the results are compared verifying the responses such as response behavior, cutoff frequency and phase in the dispersion parameters, as seen in figures 3.3 and 3.4.
Figure 3.3(a) shows the lumped inductor model, the response in scattering parameters $S_{11}$ and $S_{21}$ of the inductor using ADS as displayed in Figure 3.3(b), Phase response of the inductor is depicted in Figure 3.3(c). Figure 3.3(d) illustrates the lumped inductor model type square spiral using ADS, the HFSS simulation of the distributed inductor model as is displayed in Figure 3.3(e), and finally, as Figure 3.3(f) presents a comparison of the responses between lumped and distributed models. In the distributed model response using HFSS, this is a complete analysis because it evaluates the effects that occur in high frequency. For example, it can be seen in Figure 3.3(f) a resonance peak in the $S_{11}$ and $S_{21}$ response at frequency of 11 GHz.
The same procedure is developed for capacitor analysis. Figure 3.4(a) shows the capacitor model, the response in scattering parameters $S_{11}$ and $S_{21}$ of the capacitor using ADS as displayed in Figure 3.4(b), Phase response of the capacitor is depicted in Figure 3.4(c). Figure 3.4(d) illustrates the lumped parallel plates capacitor model using ADS, the HFSS simulation of the distributed capacitor model as is displayed in Figure 3.4(e), and finally, as Figure 3.4(f) presents a comparison of the responses between lumped and distributed models. Likewise, we can see that the $S_{11}$ response displays several effects in the frequency, but $S_{21}$ has no effect. Hence, the MEMS capacitor response no presents resonance peaks.
Figure 3.4  Simulations of the capacitor with value of 2C_L at 5.8 GHz in ADS and HFSS. (a) Lumped capacitor model, (b) S_11 and S_21 simulated responses in ADS, (c) S_21 phase response, (d) Lumped parallel plates capacitor model, (e) Distributed capacitor model in HFSS and (f) Comparison of the responses between in lumped (ADS) and distributed models (HFSS).
Step 3) The complete CRLH structure is simulated with distributed models and to find the best values with respect to these parameters using ADS and Ansoft HFSS, as shown in Figure 3.5.

Figure 3.5(a) shows the CRLH-TL model, the response in scattering parameters $S_{11}$ and $S_{21}$ of the CRLH-TL using ADS as displayed in Figure 3.5(b). Phase response of the CRLH_TL is depicted in Figure 3.5(c). The response of HFSS simulation of the distributed CRLH-TL model presents a high-pass behavior that corresponds to a structure purely left handed, as is displayed in Figure 3.5(d) and finally, as Figure 3.5(e) presents a comparison of the responses between lumped and distributed models.
Step 4) Finally, iterations of the TL simulation are made in order to update the loading elements so they match the required equivalent circuit values, as obtained in step 3.

At this point, a methodology for the MTM structure design based on a CRLH-TL structure has been defined. This methodology has been previously described in [15] and [18]. Therefore, a basic cell is formed by double variable capacitors and an inductor connected to ground, where each MEMS capacitor has a value of 1.048 pF and each inductor has a value of 1.31 nH, as displayed in Figure 3.6. However, using the CRLH-TL structure many RF-MTM devices can be implemented, such as filters, resonators and multiplexors, among others.
3.2 MEMS Capacitor

The MEMS capacitor consists of two parallel plates (two electrodes, one mobile-positive charge and one fixed-negative charge), whose capacitance can be varied using the electrostatic principle.

The MEMS capacitor is fabricated using the surface micromachining technique, and it can be integrated in a CMOS chip. The process under consideration here is composed of four materials and five levels of masks on a high resistivity silicon wafer (100 orientation, $\rho>4000 \ \Omega\cdot\text{cm}$) acting as the mechanical support. Titanium (Ti) and Aluminum (Al) are used as structural materials, with one suspended level for mechanical structures, and AZ-4620 is used as the sacrificial material. Silicon dioxide SiO$_2$ and SU8-2002 are used as dielectrics, as displayed Figure 3.6.

The micromachined variable capacitor offers two advantages with respect to the varactors. The first one is the integration on chip to maintain a high quality factor $Q$. The second one is that it presents excellent linearity, which means, the C-V response is linear at operation frequency of the capacitor. The main disadvantages are the limited actuation margin because of the pull in effect, which means, the limitation on the tuning range and the difficulty of encapsulation; last one a common problem to all MEMS devices [19].

The capacitance between parallel plates is determined from:

\[
C = \frac{\varepsilon_0 \varepsilon_r WL}{g}
\]  

(3.1)

Where: $\varepsilon_0$ is the free space permittivity, $\varepsilon_r$ is the relative permittivity, $W$ is the design width ($W=596 \ \mu\text{m}$), $L$ the length ($L=596 \ \mu\text{m}$) and $g$ is the gap between electrodes ($g=1\rightarrow 5 \ \mu\text{m}$, theoretically).

Using these values in Equation (3.1), the capacitance varies from 0.629 to 6.29 pF, while the gap between the plates can vary up to 5 micrometers. The following figure shows the variation of capacitance with respect to the distance $g$, which represents the gap between electrodes of a variable capacitor. Here $g$ ranges from 1 to 5 micrometers.
The mechanism of actuation of the capacitor is electrostatic. The actuation is achieved using an electrostatic force between the top and the bottom electrodes. This electrostatic force is offset by the mechanical force due to the suspensions of the mobile electrode, which opposes movement.

In a real MEMS capacitor structure, the situation is more complicated than a simple lumped design. It should consider all possibilities of the instability points determined by the “pull-in” voltage, the “modes of vibration” and the mechanic-elastic aspects of the structure.

The “pull-in” voltage indicates the voltage that causes a total collapse between the two electrodes or plates; in fact this is called the pull in instability. Accordingly, capacitors are required to operate below the pull-in tension, this being the limiting factor of tuning range of the micromachined variable capacitor. Theoretically, this implies a limit in the separation between plates of $g/3$ [19].
The pull in voltage equation can be defined as [20]:

\[
V_{\text{pull}} = \sqrt{\frac{8K_{\text{eff}} g_0^3}{27\varepsilon_0 WL}}
\]  

(3.2)

Where: \(K_{\text{eff}}\) is the effective stiffness and \(g_0\) is the initial gap, and all the other variables have been previously defined.

The effective stiffness \(K_{\text{eff}} = 24\ \text{N/m}\) was obtained from mechanic-electrostatic analysis, for aluminum and titanium from mobile plate and calculated by an effective overlap area of 480 x 480 \(\mu\text{m}^2\) and considering that the displacement of the spring is only in the vertical direction (\(z\) axis). Using Coventorware simulations and it was also calculated following [20] and [21]. Figure 3.7 shows the displacement of the mobile electrode (Note: The displacement of the mobile electrode, it is not the gap between electrodes) and the associated capacitance variation as a function of applied voltage, as given by (3.2). However, Coventorware simulations have been performed in detail to consider the material properties; in this case, for titanium and aluminum, which are listed in Table 3.2.

![Figure 3.7](image-url)

**Figure 3.7** Displacement of mobile electrode and capacitance as a function of applied voltage (\(V_{\text{pull in}}=16.5\ \text{V}\)).
Table 3.2  Summary of electrical and mechanical properties of the different metals can be used in the fabrication process.

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity $\mu$Ω-m</th>
<th>Young’s Modulus GPa</th>
<th>Temperature Melting point $^\circ$C</th>
<th>Poisson ratio</th>
<th>Tensile Stress MPa</th>
<th>Effective Stiffness N/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>0.02214</td>
<td>79-109</td>
<td>1064</td>
<td>0.42-0.44</td>
<td>124-170</td>
<td>-</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.42</td>
<td>116-120</td>
<td>1668</td>
<td>0.32</td>
<td>240-370</td>
<td>48</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.0282</td>
<td>70-79</td>
<td>660.4</td>
<td>0.35</td>
<td>40-50</td>
<td>24</td>
</tr>
</tbody>
</table>

On the other hand, the structures can be analyzed in two ways static and dynamic. The static analysis is used here to solve for “vibration modes”, these is natural frequencies and modes shapes. For example, could find the four basic modes: 1) in torsion, 2) in a flexural motion wherein the whole MEMS capacitor goes up and down, 3) in cross flexure and 4) in flapping or flying motion.

3.2.1 Dimples and Holes

The design techniques for MEMS devices have to consider stiction and collapse of the structure. Thus, in this work, dimples and holes are considered in the MEMS device design which prevent its final release and thus correct device operation.

To avoid collapse, dimples were defined using SU8-2002. Furthermore, these give the structure a more robust mechanical stability. The dimples were designed using the criteria for SUMMIT V [22] and 3D full-wave electromagnetic field simulations for radio frequency (RF), to obtain better results. The dimples size is of 15 x 15 μm, and they are isolated to avoid parasitic capacitance, as displayed in Figure 3.8. Moreover, a series of ten holes for each MEMS capacitor were defined in order to insure the proper release of the structure without affecting the microwave performance of the device. The hole size is of 15 x 15 μm.
Table 3.3 shows a summary of the capacitance variations with respect to displacement according to Equation 3.1. Simulations in HFSS are shown in Figure 3.9 of the MEMS capacitor response, when the gap between electrodes is decreased.

<table>
<thead>
<tr>
<th>Cutoff Frequency GHz</th>
<th>Displacement μm</th>
<th>Capacitance pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>m₁</td>
<td>0.5</td>
<td>0.629</td>
</tr>
<tr>
<td>m₂</td>
<td>1.0</td>
<td>0.786</td>
</tr>
<tr>
<td>m₃</td>
<td>1.53</td>
<td>1.05</td>
</tr>
<tr>
<td>m₄</td>
<td>2.02</td>
<td>1.57</td>
</tr>
<tr>
<td>m₅</td>
<td>2.58</td>
<td>3.15</td>
</tr>
</tbody>
</table>
Figure 3.9  $S_{11}$ and $S_{12}$ HFSS simulations of a variable capacitor as a function of displacement. The cutoff frequencies are: $m_1=0.5$ GHz, $m_2=1.0$ GHz, $m_3=1.53$ GHz, $m_4=2.02$ GHz and $m_5=2.58$ GHz.

Figure 3.10(a) illustrates a schematic view of the MEMS capacitor with all its integrated elements (dimples and holes). The different shades in Figure 3.10(b) indicate the distribution of mechanical stresses along the length of the positive (mobile) electrode. The MEMS capacitor was simulated under electrostatic actuation, as is shown in Figure 3.10(c). The electrostatic analysis was performed sweeping the applied voltage from 0 to 24 V, obtaining a variation of 0 to 3 $\mu$m approximately. Figure 3.10(d) displays stress simulations in the anchor. Figure 3.10(e) shows a mechanical simulation using Comsol Multiphysics, indicating the distribution of the mechanical deformations when a force is applied along the z axis [23]. All modes and shapes of the structure can be determined using Comsol Multiphysics. Hence it is necessary to define a mechanical model for the device. This aspect will be considered in the near future.
Figure 3.10  Coventorware and Comsol Multiphysics simulations (a) Sketch of the MEMS capacitor with dimples and holes, (b) MEMS capacitor stress simulations along the $y$ axis, (c) Electrostatic simulations with an applied voltage of 24V, (d) Anchor stress simulations and (e) Total Displacement: deformation (meters) when apply a force of 60 $\mu$N.
3.3 Description of the MTM-MEMS Antenna

In this section the description of a novel and compact coplanar antenna using MTM and MEMS is presented.

3.3.1 Coplanar Waveguide (CPW) Technology

The antenna is based on Coplanar Waveguide (CPW) technology. This is a true alternative to the microstrip line especially for applications in modern microwave integrated circuit design. It is a three-conductor line, which can carry one fundamental mode with zero cutoff frequency, the so called “even mode”, which has equal ground planes potentials, as shown Figure 3.11(a). Figure 3.11(b) shows the electric and the magnetic field distribution for the even mode (coplanar waveguide mode). The even mode is a quasi-TEM mode with even symmetry with respect to the symmetry plane, its dispersion is very low and it is normally used for applications in circuit design. The electric field lines begin at the center conductor and end on the two surrounding ground planes. The magnetic field lines enclose the center conductor. If current is transported in the center conductor, the current densities in the ground planes have the opposite direction. Because of the low dispersion of the fundamental “even mode”, very broadband applications are possible, making this mode of propagation applicable in microwave integrated circuits [24]. Therefore, the principal advantages are that the signal and ground are on the same plane, presenting lower dielectric losses and higher signal integrity. In addition, simple on-wafer measurement techniques are available to characterize coplanar circuits. On-wafer measurement results may be directly interpreted and attributed to component or circuit properties.
Figure 3.11  (a) Coplanar Structure and (b) Electric and Magnetic field distributions in the even mode.

The MTM-MEMS antenna feed is electromagnetically coupled with a coplanar waveguide (CPW), designed for a central frequency of 5.8 GHz and a characteristic impedance of 50Ω. The line spacing is 50μm and the signal line width is 78μm, as displayed in Figure 3.12(a). Figure 3.12(b) displays the currents distribution trough TL.
Figure 3.12(c) shows the electric field distribution in the port simulated in HFSS. The $S_{11}$ and $S_{21}$ simulations of the coplanar transmission line using HFSS with good result, as is seen in Figure 3.12(d).

Figure 3.12  (a) Diagram of a coplanar waveguide, (b) HFSS simulations of current density, (c) Port definition and electric field and (d) $S_{11}$ and $S_{21}$ simulations.
3.3.2 MTM-MEMS Antenna

The MTM-MEMS antenna is formed with a CRLH-MTM structure with two double MEMS capacitors and four inductors connected to ground, as shown in Figure 3.13. The MEMS capacitor consists of two parallel plates. Additionally, a CPW RF choke is implemented as a feed line to control the MEMS capacitors.

The MTM-MEMS antenna, with an integrated DC bias line, has dimensions of 7 x 11 mm (0.1353\(\lambda\) x 0.2126\(\lambda\)). The basic cell, formed by two double MEMS capacitors and four inductors, has dimensions of 1.397 x 2.002 mm (0.027\(\lambda\) x 0.0039\(\lambda\)), as shown in Figure 3.12, where \(\lambda\) is the guided wavelength.

3.3.3 T Bias Line

In addition, a CPW RF choke was designed to isolate the DC signal from the RF signal. However, it also works to control the MEMS capacitors. The CPW RF choke is designed using a type T feed line. A bias T is commonly used for feeding DC into
active components in such way that the RF behavior is not affected by the DC connection. In other words, it is a bandstop filter that should produce an RF open circuit at the feed point to the rest of the circuit [25]. The design is at a central frequency of 5.8 GHz and has a length of 2.58 mm. It is loaded with a capacitance of 0.36 pF by an interdigital capacitor, as shown in Figure 3.14(a). It is implemented on chip in the same fabrication processes that the MTM-MEMS antenna, and a bridge assures that all the ground planes have the same electric potential. The CPW transmission line is of the meander type, with a length of 90 electric degrees, which makes it possible to achieve a high impedance bias line (> 1,500Ω at 5.3 to 5.8GHz), as shown in Figure 3.14(b); without impacting on the microwave performance of the device, as displayed Figure 3.14(c). The line spacing is 50 μm, and the signal line width is 13 μm.
3.4 Conclusions

In summary, a detailed description of the MTM-MEMS antenna was given. The design method for the CRLH-TL structure, which consisted of a mixed approach using circuit models and full-wave simulations, was presented. Also, MEMS’s techniques to improve the performance of the variable capacitors have been used, such as dimples and holes that support functional stability, operation and a proper release of the structure. Moreover, 3D full-wave simulations and MEMS simulations in Coventorware was shown. Finally, a CPW RF choke was designed to control the MEMS capacitors.
Chapter 4   Experimental Procedures

The work presented in this chapter aims to integrate and to establish a fabrication process for the RF-MTM-MEMS devices. The fabrication process is based on surface micromachining technology, which besides begin a novel fabrication process, it is evolving ad-hoc for reconfigurable MTM-MEMS devices. Coventorware simulations are presented to illustrate the process steps.

4.1  MEMS Technology

The application of Microelectromechanical Systems (MEMS) technology to radio-frequency (RF)/microwave systems is on the verge of revolutionizing wireless communications. Indeed, RF-MEMS enables the implementation of a tunable element in a microwave circuit, typically using a variable capacitor or an inductor, where structures are actuated upon using electrostatic, thermal, magnetic or piezoelectric schemes. Electrostatic actuation is preferred due to its low power consumption and high speed.
The suspended element is usually in the form of a fixed-fixed (two anchor) or a cantilever beam supported on pedestals or anchors [26], [27], [28] and [29]. The tunability, low power consumption (μW), linearity combined with small size, and the ability to coexist with CMOS circuitry has made MEMS an attractive technology to fabricate several reconfigurable RF/microwave devices; one of the most common RF-MEMS devices is a variable capacitor, or a varactor, which can be configured to operate as RF switches, relays, phase shifters, filters, impedance tuners, and resonators among others [30]. From being a purely research concept a few years ago, RF MEMS technology has grown out of research labs into companies that commercially produce devices for the mass market today.

RF-MEMS fabrication technology builds upon integrated circuit (IC) fabrication processes. However, there are a variety of techniques developed specifically for MEMS, such as: Surface Micromachining, Bulk Micromachining, LIGA, Deep RIE Micromachining, Laser Micromachining, and Focused Ion Beam Micromachining, among others.

Basically, the most common technologies for silicon micromachining are surface and bulk; in this work we focus on surface micromachining technology. A typical surface micromachining technique builds devices up from the wafer layer by layer, that is, the process is a repetitive sequence of film deposition (thin or thick) on a wafer, followed by film photo-patterning, and then etching the patterns into the films. In order to create moving, functioning machines, these layers are alternating thin films of a structural material (typically, silicon or metals) and a sacrificial material (typically, silicon dioxide or photoresist). The structural material will form the mechanical elements, and the sacrificial material creates the gaps and spaces between the mechanical elements. The last step is called the “release”, since it aims at removing the sacrificial material and therefore, leaves the structural elements free to move and function, as shown in Figure 4.1.
4.2 Fabrication Process

The fabrication process was realized in the Nanotechnology Research and Education Center (NREC) at the University of South Florida (USF), USA. The Cleanroom Laboratory has 1700 square foot of certified class 1000 space. The NREC facility supports projects based in Nano, CMOS and MEMS technologies.

The MTM-MEMS antenna described in this work was designed and manufactured using the surface micromachining technique, and it is integrated in a CMOS chip. The process under consideration is composed of five materials and four levels of masks on a high resistivity silicon wafer.
4.2.1 Selection of Materials

For the MTM-MEMS devices fabrication process, there are three important aspects that have been considered. The substrate is the first one: it is a high resistivity (> 4000 \( \Omega \)-cm) silicon wafer, rather than a float zone silicon wafer, so that it resembles an insulator as much as possible, and thus allowing for low-loss RF-MEMS devices. The second aspect is related to the selection of materials for high frequency applications, that is, RF response performance, which is evaluated through electromagnetic properties (permittivity \( \varepsilon \) and permeability \( \mu \)), skin depth and dispersion parameter (return loss-S\(_{11}\)). The critical issues underlining high-frequency performance are explained in detail in Appendix A. Basically, they have to deal with dielectric response of the material, that is, their ability to absorb and to store energy, and how much an electromagnetic wave will penetrate into the material [31]. The properties of materials, however, vary with temperature and frequency. In addition, the dielectric properties of the material are also affected by many factors such as purity, chemical state and manufacturing process. Therefore, it is crucial to compile a comprehensive database of the dielectric properties of different materials at different frequencies and temperatures, to improve the current understanding of the device performance for microwave applications. To determine which insulator is better for the fabrication process, the dielectric constant was considered, as displayed in Table 4.1.

Table 4.1 Summary of the insulator materials for the fabrication process [32], [33], [34], [35] and [36].

<table>
<thead>
<tr>
<th>Proposed Material</th>
<th>Preferred Material</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCB, CYCLOTENE 4024-40</td>
<td>SU8-2002 Negative Tone Photoresist</td>
<td>( \varepsilon = 3.2 ) to 4.1 Dimple</td>
</tr>
<tr>
<td>Films Dielectric ( \varepsilon = 2.4 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymide, HD 4100</td>
<td>AZ-P4620 Positive Tone Photoresist</td>
<td>Sacrificial Layer</td>
</tr>
<tr>
<td>Films Dielectric ( \varepsilon = 2.7 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In summary, SU8-2002 and AZ-P4620 were chosen since they are highly compatible with silicon processes, and are the most common in RF-MEMS fabrication processes for the reason that they can be obtained in a variety of thicknesses and they are considerably less expensive than other materials.

On the other hand, the skin depth or penetration depth has been determined for different metals (see Appendix A). As Figure 4.2 shows, titanium presents a larger skin depth with frequency than the other materials (gold, aluminum and copper). For example, the skin depth of gold at 5.8 GHz is 1.032 μm, for aluminum is of 1.071 μm and for titanium is 4.89 μm. Hence, if the skin depth is known, it is possible to determine the thickness of the metals which will be used in the fabrication process in order to minimize losses. On the other hand, a combination of metals is used in this work to achieve optimal device performance. Thus, knowing the skin-depth for each metal, the total thickness can be calculated.

\[ \delta = \sqrt{\frac{2}{\omega \mu \sigma}} \]

Figure 4.2 Skin Depths of Gold, Titanium, Aluminum and Copper. *
To verify the performance and losses for different metals (Ti, Au, Ti/Au and Ti/Al) in the RF response, transmission lines were simulated using HFSS at a design frequency of 5.8 GHz, as illustrated in Figure 4.3. As it can be observed, the return loss in the combination of metals Ti + Au is much lower than others, which means, reflected power reflected is minimal, and impedances are well matched. For instance, to a return loss of -30 dB correspond a 0.1% of reflected power and $Z_M = 46.9 \, \Omega$, and a return loss of -50 dB correspond to a percentage of reflected power of 0% and $Z_M = 49.7 \, \Omega$, as is displayed figure 4.3(a). The $S_{21}$ insertion loss response can be seen the signal quality transmitted through the transmission line and picked up at the receiver will be affected by the impedance discontinuities and by the series resistance losses and the losses from dissipation factor of the dielectric materials. So, due to fundamental properties of materials, higher frequencies will generally be attenuated more than low frequencies. The insertion loss is a direct measure of the ratio of the transmitted amplitude of each frequency component to the incident amplitude at the front of the transmission line. Hence, the better response is give by TL with Au. However, Ti + Al were selected by to be a cheaper material and to have a good response.
The third aspect to consider is MEMS structure performance, which is assessed by the combination of the metals (Ti/Au and Ti/Al) are used as structural materials, as is displayed in Table 4.2.

Table 4.2 Summary of electrical and mechanical properties of the different metals used in the fabrication processes [37].

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity $\rho$ [$\mu\Omega$-m]</th>
<th>Young’s Modulus [GPa]</th>
<th>Melting point [°C]</th>
<th>Poisson ratio</th>
<th>Tensile Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>Au</td>
<td>0.02214</td>
<td>79-109</td>
<td>1064</td>
<td>0.42-0.44</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
<td>0.42</td>
<td>116-120</td>
<td>1668</td>
<td>0.32</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>0.0282</td>
<td>70-79</td>
<td>660.4</td>
<td>0.35</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>0.01678</td>
<td>110-128</td>
<td>1084</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Therefore, a combination of titanium and aluminum was chosen as an option as a structural material for the RF-MEMS devices. Since titanium is a hard material, giving to the structure a more robust mechanical stability, and the malleability and low price of aluminum make this a combination ideal to obtain an efficient RF response.

### 4.2.2 Fabrication Process Simulations in Coventorware

The following simulations are focused on the fabrication process steps, shown in Figure 4.4 (a), which were performed in Coventorware, and are displayed in Figures 4.4(b) and 4.4(c).

### 4.2.3 Fabrication Process Flow

The sequence of the steps followed to fabricate the MTM-MEMS tunable antenna on a high resistivity wafer are illustrated in Figure 4.5.

<table>
<thead>
<tr>
<th>Number</th>
<th>Step Name</th>
<th>Layer Name</th>
<th>Material Name</th>
<th>Thickness</th>
<th>Mask Name</th>
<th>Photoresist</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Substrate</td>
<td>Substrate</td>
<td>SILICON</td>
<td>400</td>
<td>SubstrateMask.</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Thermal Oxidation</td>
<td>SiO2</td>
<td>THERM_OXIDE</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Metal_Ti_1</td>
<td>Metal_Ti</td>
<td>TITANIUM</td>
<td>1</td>
<td>Mask_1</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>Metal_Al_2</td>
<td>Metal_Al</td>
<td>ALUMINUM</td>
<td>3</td>
<td>Mask_2</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Straight Cut</td>
<td></td>
<td></td>
<td>Mask_3</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Dimple</td>
<td></td>
<td>SU8</td>
<td>1</td>
<td>Mask_4</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>Straight Cut</td>
<td></td>
<td></td>
<td>AZP4620</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Sacrificial</td>
<td></td>
<td>AZP4620</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Straight Cut</td>
<td></td>
<td></td>
<td>Mask_3</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Metal_Ti_3</td>
<td>Metal_Ti</td>
<td>TITANIUM</td>
<td>1</td>
<td>Mask_4</td>
<td>+</td>
</tr>
<tr>
<td>10</td>
<td>Metal_Al_4</td>
<td>Metal_Al</td>
<td>ALUMINUM</td>
<td>3</td>
<td>Mask_5</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Release Wet Etch</td>
<td></td>
<td>AZP4620</td>
<td></td>
<td>Mask_6</td>
<td></td>
</tr>
</tbody>
</table>

(a)
Figure 4.4  (a) Fabrication Process list in Coventorware, (b) MTM-MEMS Antenna in Coventorware simulation and (c) MTM-MEMS basic cell for the antenna [38].
The fabrication process consists of five materials and four levels of masks on a high-resistivity silicon wafer (N type, <100> orientation, 4000-8000 Ω-cm resistivity and 490-530 μm thickness). Initially, silicon dioxide is grown on the silicon wafer as an electrical and thermal insulator, as displayed in Figure 4.5(a). Titanium (Ti) and aluminum (Al) are then deposited as structural materials by sputtering, with one suspended level for the mechanical structures. Each metal layer consists of a thickness of 0.5 μm of titanium and 1.5 μm of aluminum, to avoid losses due to skin depth and to give the structure a more robust mechanical stability, as shown in Figures 4.5(b), 4.5(c) and 4.5(d). (Note: Before titanium and aluminum are deposited, it is necessary to do a thermal process at 120 °C for 20 min and then another thermal process after metal deposition at 250°C for 20 min to remove moisture and to promote adhesion of the materials.) Subsequently, SU8-2002 is deposited on the first metal level as a dielectric, and the dimples are formed. The purpose of these is to avoid the collapse of the structure, and to prevent a DC voltage short, therefore ensuring the correct operating performance of the device, as shown in Figure 4.5(e). A sacrificial layer of 5 μm thick with AZ-4620 (positive photoresist, PR+) is deposited using a spinner and patterned by UV lithography, as shown in Figure 4.5(f). The patterned sacrificial layer is thermally cured at a temperature of 90 °C in a nitrogen environment for 20 min. Then, a second metal layer is deposited by sputtering in 0.5 μm steps, until a 2 μm thick metal layer is achieved; this is to avoid burning of the photoresist and breaking of the metal. In this step, the mobile electrodes and bridge structures are formed, as displayed in Figure 4.5(g). Finally, the structures are released using Microposit-1165 remover for 15 min, after two 5 min baths with methanol. A thermal process is then performed in a conventional oven at 120 °C for 15 min, and a plasma process with oxygen during 10 min to eliminate photoresist residues that could cause sticking between the electrodes, as illustrated in Figure 4.5(h). Following these steps, most of the MEMS structures were successfully released; an additional critical-point drying procedure was not necessary, which makes the process simple and efficient. More details of the fabrication process can be found in Appendix B.
Figure 4.5 Fabrication Process. (a) Standard wafer cleaning followed by the thermal growth of SiO2, (b) 0.5μm thick Titanium deposited by sputtering, (c) 2μm thick Aluminum deposited by sputtering, (d) Ground plane patterned with Ti and Al by lithography, (e) Dimple formed by SU8-2002 patterning, (f) AZ-4260 sacrificial layer forming, (g) Definition of anchor by patterning, (h) Ti-Al deposited by sputtering and (i) MEMS release process.
The following pictures present a top-view of the MTM-MEMS antenna after some steps of the fabrication process.

![Top-view images of MTM-MEMS antenna](image)

**Figure 4.6**  Pictures taken with a Ken-A-Vision Optical Microscope. (a) First metal level (Ti/Al), (b) Definition of pedestals, (c) Definition of contacts, (d) Patterning of the second metal layer and of the bridges, (e) Application AZ-4260 as sacrificial layer (f) Patterning of second metal layer, (g) Chemical release (there is still AZ-4620) and (h) Release after plasma.
Chapter 4  Experimental Procedures

The following SEM Photographs show a basic cell of the MTM-MEMS antenna and MEMS Capacitor (Hitachi, Field Emission Scanning Electron Microscope S8000 and SU-70).

Figure 4.7  SEM photographs of the different structures.  (a) MTM-MEM Antenna basic cell, (b) MEMS Capacitor and (c) MEMS Capacitor details such as anchor and pedestal.
In summary, there is very good agreement between the Coventorware simulations illustrated in Figure 4.4 (b) and the results of the fabrication process, as shown in Figure 4.6 (e).

4.3 Challenges in Fabrication Procedures

The main challenges in the fabrication process were the development of the second level of metallization that defines a suspended level of the mechanical structure, and the most critical challenge is the release process. The final steps were determined after a series of experiments.

The first experiment analyzed different thickness of titanium and aluminum. The deposit of metals was realized by means of two different techniques: E-beam and sputtering. The deposit of the metals by sputtering presented good results, that is, they manifest the same grain structure, orientation and a good adhesion between the interface of titanium and aluminum. Another condition in the deposits of metals was a low applied current density; in the case of titanium of 1A and for aluminum 1.3A.

In the second experiment, a comparative study on temperature and bake time effects on AZ-4260 resist was performed. To maximize process reliability, the AZ-4260 photoresist was treated with both a conventional oven and a hot plate. When the resist is treated with a conventional oven the conditions are 90°C during 20 min with nitrogen N$_2$; when it is by hot plate the optimal conditions are 90°C for 10 min. Note: the maximum exposure time for resist in hot plate should be 10 minutes. Hence, for high temperatures close to 150 °C and during a long time exposure bake the photoresist is burned, as shown in Figure 4.8(a).

On the other hand, the thickness of the second metal layer was analyzed. It was concluded that a thick layer was needed to insure mechanical stability and reduce losses at high-frequencies. In this work, the optimal thickness range was determined to be between 2.5 to 4 microns.
Figure 4.8 (a) Second deposits of metal layers by sputtering and (b) Temperature test.

A second experiment was conducted to determine the stress that the structures suffer when the deposit of both titanium and aluminum is performed at the same deposition rate, as displayed in Figure 4.9.

Figure 4.9  (a) Stress and rupture in the deposit of metal layers by sputtering and stress effect on the titanium and aluminum films and (b) Rupture of the metals films.
Hence, a solution for the stress effects on the metal films was carried out step by step in the deposits, that is, the titanium deposition was performed at a deposition rate of 500 Å/sec for 10 min in each step; this procedure was repeated until the desired thickness was reached. For the aluminum layer, the rate of deposition in each step was of 500 Å/sec in 10 min steps, following [39], which describes a method to obtain a thick metal layer using multiple deposition chambers. Although it is not the exact same procedure used here, it is based on the same concept; that is, forming a thick metal layer by multiple deposition steps.

On the other hand, the greatest challenge was to find the appropriate methodology for the release of the MEMS structures without using Critical Point Drying (CPD) [40]. The first release experiment was done with acetone, methanol and then drying in a conventional oven. The results obtained presented deformation, stiction and collapse of the structure, and also left photoresist (AZ-4620) residue, as shown in Figure 4.10.

![Figure 4.10](image)

**Figure 4.10** Effects of release with acetone.

To characterize this part of the process an interferometer (Veeco) was used, since laser interferometry is a high-sensitivity non-contact measurement, necessary due to device fragility and small size. An example of the release of the MTM-MEMS structure using acetone is shown in Figure 4.11. Figure 4.11(a) indicates the interferometry
technique by white and gray stripes; acetone residue can be identified. A profile in both
the X and Y axes is shown, as well as a 3D interactive display as illustrated in Figure
4.11(b) and 4.11(c).

Figure 4.11  Characterization by interferometry. (a) Interferometry applied to the structure, (b) 3D
interactive display and (c) X and Y Profiles where the markers are localized.
Figure 4.12 shows the MTM-MEMS antenna with thin films close to 1.5 μm of titanium and aluminum using a new release technique. In this picture is presented the deformations in the electrodes of the MEMS capacitor when metal thicknesses are thin, that is, the structure performance does not have a robust mechanical stability.

Thus, a new technique for the release of the MEMS structure was determined, based on the previous experiments. This was done with the combination of chemical and dry etching processes [41], [42], and [43].

This new technique consists of three steps: First, a chemical treatment using C₂H₅NO [44] for 15 min and methanol for 5 min for two times. Second, a thermal process at 120°C in a conventional oven in a nitrogen (N₂) environment for 15 min to dry the structures. Finally, a dry etching process under the following conditions: oxygen (O₂), 500 mTorr and 200 Watt during 10 min to eliminate photoresist residues that could cause stiction between the electrodes. The great advantage is avoiding the use of a Critical Point Drying (CPD) process, which has several limitations, such as small sample size and the use of CO₂. This procedure is highly reliable and inexpensive, simple and
easily done. Figure 4.13 shows the characterization of the devices after the release process by interferometry. We can see an interferogram of the antenna where the fringes represents a superior level that the reference level.

![Interferogram of the antenna](image)

**Figure 4.13** Characterization MTM-MEMS antenna by interferometry.

### 4.4 Conclusions

A fabrication process for MTM-MEMS antennas was determined and carried out, with very positive results. This process is fully compatible with the materials used for CMOS integrated circuit fabrication processes and circuits themselves. The metal deposition process was developed by sputtering thorough multiple deposits, obtaining very satisfactory results. This novel fabrication process is one of the outstanding contributions of this research work.
Chapter 5  Measurements, Results and Analysis

This chapter presents the RF measurements and 3D analysis of the MEMS dynamics and topography. The high-frequency measurements were performed using a PNA, and a mechanical analysis was carried out for the MEMS capacitor. These results are then compared with the simulations described earlier in the text.

5.1  Description of the Layout of the Chip

The proposed layout consists of three parts. The first part includes the RF structures, such as the CPW transmission line in open, short, through, transitions, RF choke, and the inductors and capacitors. The second part consist of the MEMS structures, such as vernier gauges and gradient stress, and finally the third part is the total device under test, which is the MTM-MEMS antenna, the MEMS capacitor and the MTM-MEMS antenna array. The following picture shows a sketch of the layout.
Figure 5.1  Sketch of the Layout.

Figure 5.2  Details of the structures of interest. (a) MEMS Capacitor, (b) Inductor, (c) MTM-MEMS Resonator, (d) Bias Line and (e) Gradient stress and Vernier gauges.
5.2 RF Measurements

The RF-measurements were performed on-wafer using an Agilent E8361A Precision Network Analyzer and a Karl Suss probe station, shown in figures 5.3(a) and (b). Prior to S-Parameter measurements, a SOLT (Short-Open-Load-Thru) calibration was performed using an Impedance Standard Substrate (ISS) in the 0.01-20 GHz frequency range, in order to establish the reference plane at the probe tips, as displayed in Figures 5.3 (c), (d), (e) and (f).

Figure 5.3   (a) Vector Network Analyzer, VNA (b) Probe Station (c) Impedance Standard Substrate, ISS (d) Probes Tips (e) Probes Tips on wafer at load pattern and (f) Patterns, load and thru.
This section is divided into two parts: simulations results and measurements results covering all aspects of the performance of the MTM-MEMS antenna. Figure 5.4(a) shows the design of a transmission line as a transition between common connectors (SMA) and the device, which allows to determine the radiation pattern of the antenna. The design is at a frequency of 5.8 GHz and length 12,650 mm, the line spacing is 350 μm and the signal line width is 1,160 μm. Figure 5.4(b) indicates simulation results of the dispersion parameters $S_{11}$ and $S_{21}$ and 5.4(c) shows the Smith Chart demonstrating an impedance match at 50 ohms.

![Figure 5.4](image)

Figure 5.4  (a) Transition Transmission Line, (b) $S_{11}$ and $S_{21}$ simulations in HFSS of the transition and (c) Smith Chart of $S_{11}$ and $S_{21}$ simulations in HFSS of the transition transmission line.
Figure 5.5 shows simulation results of the $S_{11}$ dispersion parameters versus frequency for the MTM-MEMS antenna, when the gap between the electrodes is varied from 1 to 30 μm. Initially, the MEMS capacitor electrodes of the antenna were designed with a gap of 1 to 5 μm corresponding to a frequency of 5.3 to 5.8 GHz; however during the fabrication process the electrodes presented a larger gap, of up to approximately 30 μm.

Figure 5.5  Return loss response of the MTM-MEMS antenna when is varied the gap between electrodes, $m_1 = 5.3$ GHz and a gap of 4 μm, $m_2 = 5.8$ GHz and a gap of 5μm, $m_3 = 7.1$ GHz with a gap of 10 4 μm and $m_4 = 8.4$ GHz with a gap of 30 μm.

Figure 5.6 shows simulation results of return loss ($S_{11}$) of the antenna when the mobile-plate has a displacement of 1 micron, that is, the antenna is tuned in the frequency range 5.3 to 5.8 GHz. The return loss of the antenna is better than 10 dB across 5.75-5.85 GHz, which translates to a 10 dB bandwidth of 2%. The VSWR obtained from HFSS simulations of $S_{11}$ is better than 2 throughout the frequency band of 5.76-5.84 GHz, as displayed in Figure 5.7.
Figure 5.6  Simulated Return Loss of the antenna.

Figure 5.7  Simulated VSWR $S_{11}$ of the antenna.
Figure 5.8 presents 3D simulation of the radiation pattern (Gain Theta, Gain Phi and Gain Total) in HFSS and Figure 5.9 shows the far field simulated characteristics, co-polarized in the E phi-plane (x-z plane, Phi=0°) and the E theta-plane (y-z plane, Phi=90°), with a gap of 5 μm between electrodes.

![3D simulation of radiation pattern](image1)

![Far field simulated characteristics](image2)

Figure 5.8  Radiation Pattern of the MTM-MEMS Antenna, with a gap of 5 μm between of the plates.

![Radiation Pattern of the MTM-MEMS Antenna](image3)

Figure 5.9  Radiation Pattern of the MTM-MEMS Antenna, (a) E-plane co-polarized and (b) H-plane co-polarized.
Figure 5.10 presents 3D simulation of the radiation pattern in HFSS, when the antenna have a gap of 30 μm between electrodes, and Figure 5.11 shows the far field simulated characteristics in the E phi-plane (x-z plane, Phi=0°) and the E theta-plane (y-z plane, Phi =90°).

Figure 5.10  Radiation pattern of the MTM-MEMS antenna, with a gap of 30 μm between the plates.

Figure 5.11  Radiation Pattern of the MTM-MEMS antenna, (a) E-plane co-polarized and (b) H-plane co-polarized.
Chapter 5  Measurements, Results and Analysis

The antenna parameters obtained from full-wave HFSS electromagnetic simulations are listed in Table 5.1. The parameters were calculated based on an isotropic radiator emitting 1 Watt of incident power to the antenna under test.

Table 5.1 Antenna parameters from electromagnetic simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident Power</td>
<td>1 W</td>
</tr>
<tr>
<td>Accepted Power</td>
<td>0.44 W</td>
</tr>
<tr>
<td>Radiated Power</td>
<td>0.01 W</td>
</tr>
<tr>
<td>Radiation Efficiency</td>
<td>3 %</td>
</tr>
<tr>
<td>Gain</td>
<td>-22.4 dBi</td>
</tr>
<tr>
<td>Directive</td>
<td>26.8 dBi</td>
</tr>
</tbody>
</table>

The characteristics of the metamaterial structure can be judged using a dispersion curve of the MTM-MEMS antenna. The dispersion curve is obtained from a zero-resonator structure using the unwrapped phase of the $S_{21}$ dispersion parameter. This is obtained from HFSv10 simulations [45].

Figure 5.12(a) illustrates a basic cell of the MTM-MEMS resonator, and Figure 5.12(b) plots the dispersion curve of the MTM-MEMS resonator. In this dispersion graph, we can see a transition frequency when Beta= 0. In this case, there is a transition frequency at 8.4 GHz corresponding to a gap= 30 $\mu$m between the electrodes. It shows the typical characteristics of a structured metamaterial; the negative sign of the slope demonstrates the existence of the negative phase velocity [5].
Chapter 5  Measurements, Results and Analysis

Figure 5.12  (a) MTM-MEMS resonator and (b) Dispersion diagram of the MTM-MEMS resonator.

Figure 5.13(a) and (b) show the measurements of the bias line of the MEMS capacitor. The bias line is a high impedance transmission line which does not impact the microwave performance of the antenna. The results show high decoupling since the measurements were with an impedance of 50 Ω. However, when the port impedance is changed by the designed impedance, these are matched. In other words, the return loss is low, therefore there are fewer losses, can be seen in Figure 5.14(a) and (b).
Figure 5.13  (a) Measured and Simulated $S_{11}$ and $S_{21}$ parameters for the high impedance bias transmission line and (b) Smith Chart for the high impedance transmission line, $f_1 < f_2$. 
A comparison of the measured and simulated return loss and Smith chart of the bias transmission line is shown in Figure 5.15 (a) and (b). The slight difference between the measured and simulated values can be attributed to the fabrication imperfections in the lithography process; that is, the change in the signal width of 13 μm and line spacing of 50 μm, or material properties variation such as metal loss, among others, due to fabrication conditions.
Figure 5.15 (a) Measured and Simulated Return Loss $S_{11}$ of the bias transmission line and (b) Smith Chart, $f_1 < f_2$. Measured and simulated of the bias transmission line.

Figure 5.16(a) presents the $S_{11}$ response of the MEMS capacitor. This result is a point of reference for the performance of the MTM-MEMS antenna. However, its behavior is not precisely that of a switch; therefore, it is necessary to consider a model of the MEMS
capacitor that takes into account all the parasitic components. Figure 5.16(b) shows the phase of the $S_{11}$ dispersion parameter, whose ripple is indicative of possible resonant frequencies.

Figure 5.16 (a) Measured $S_{11}$ Return Loss for the MEMS capacitor and (b) Measured $S_{11}$ phase for the MEMS capacitor.
An equivalent circuit model for the MEMS capacitor, which satisfactorily models its behavior, is illustrated in Figure 5.17.

![Figure 5.17 Equivalent circuit model of the MEMS capacitor.](image)

Here $R_1$ and $R_2$ are parasitic resistances, and the inductances associated with the top and bottom electrodes are labeled $L_1$ and $L_2$. $C_2$ and $C_3$ are the parasitic capacitances between the open end of the top electrode and the dimples on the bottom electrodes. $C_1$ is the parasitic shunt capacitance at the two ends of the MEMS capacitor.

One of the figures of merit for the MEMS capacitor is its cutoff frequency, as indicated in [46] and [47]:

$$f_c = \frac{1}{2\pi R_{UP} C_{Capacitor}} \quad (5.1)$$

Where $R_{UP}$ is effective resistance or the parasitic resistance of the MEMS capacitor, which is of the order of 10 to 100 $\Omega$. A summary of the capacitance variation with displacement is shown in Figure 3.9 (Chapter 3).

The antenna presents a resonant frequency of 8.65 GHz at -13.8 dB. This was compared with an HFSS simulation with the same gap between electrodes to a resonant frequency of 8.4 GHz at -8.16 dB, as shown in Figure 18 (a).

Figure 5.18(b) shows the phase measurements of the $S_{11}$ dispersion parameters; as can be observed, the zero phase point indicates a transition frequency, and two such points appear in Figure 5.13, corresponding to transition frequencies at 8.4 GHz and 8.65 GHz, from simulation and measurements, respectively.
Figure 5.18  (a) Return Loss, with a gap of 30 μm, \( m_1 = 8.4 \, \text{GHz} \) and \( m_2 = 8.65 \, \text{GHz} \) and (b) Phase of \( S_{11} \).
Figure 5.19(a) shows the results for an antenna array, which can have a multiband performance, or increased gain. Likewise, Figure 5.19(b) displays phase of $S_{11}$, determined from the transitions frequencies.

Figure 5.19  (a) Return Loss $S_{11}$, $m_1 = 4.43$ GHz, $m_2 = 8.5$ GHz and $m_3 = 16.26$ GHz and (b) Phase $S_{11}$. 
A comparison of the measured and simulated return loss ($S_{11}$) of the antenna and feed line is shown in Figure 5.20. The slight difference between the measured and simulated values can be attributed to fabrication imperfections and variation of material properties, such as silicon dielectric constant, metal loss, etc. The return loss for the antenna is better than 10 dB across 8.52-8.76 GHz, which translates to a 10 dB bandwidth of 3%. The VSWR obtained from the measured $S_{11}$ is better than 1.5 throughout the frequency band of 8.52-8.76 GHz. The return loss obtained in this work compares well with two published results for a small resonant antenna and Zeroth-Order resonator antenna employing CRLH-TL for RF Module Integration in the 5.3 to 8.6 GHz frequency band, and after a treatment for improved efficiency, respectively [48] and [49]. In addition, the MTM-MEMS antenna presented in this work has a 26x smaller footprint than similar antennas fabricated with microstrip technology.

The efficiency and gain of the antennas fabricated on thin silicon wafers, however, are expected to be higher than those of the proposed design. This can be achieved by reducing substrate losses and surface waves in a high resistivity silicon substrate. Therefore, a trade-off has to be made between substrate height and cell number, ease of fabrication and efficiency/gain.

![Simulated and Measured Return Loss](image)

**Figure 5.20** Measured and Simulated Return Loss for the antenna.
5.3 Mechanical Measurements

A dynamic modal testing was performed on the MEMS capacitor to determine the principal mechanical properties of the structure, such as natural frequency, damping and mode shapes. This analysis is presented based on the observed physical structural changes. Therefore, precise knowledge of the static (shape, deformations, and stresses) and dynamic (resonance frequencies, amplitude and phase of vibration) properties is necessary. Reliability or fatigue test or other long term examinations also become important thinking of commercial applications and economic reasons. Due to fragility of MEMS parts and their small sizes, non-contact and high sensitive measurements are required. Interferometry is of the one most popular testing method for micro and nano elements [50] and [51]. However, a method to measure surface dynamic strain and stress fields by using a contactless 3D scanning laser Doppler vibrometer has been recently developed [52] and [53]. In this work, the MTM-MEMS device measurements were performed on-wafer using an MSA-400 Micro System Analyzer at the UNAMems Center, Facultad de Ingeniería, UNAM [54], which uses light for non-contact measurements of the three dimensional shape and motion of the microstructures (MEMS); laser-Doppler vibrometry for fast, broadband, out of plane motion; and white light interferometry for high resolution topography. The apparatus is shown in Figure 5.21.
Measurements, Results and Analysis

Regarding the deformation patterns at the natural frequencies, they take on a variety of different shapes depending on which frequency is used for the excitation force. At each natural frequency a deformation pattern occurs in the structure, as is displayed in Figure 5.22. The Figure shows the deformation patterns that will result when the excitation coincides with one of the natural frequencies of the system. At the first natural frequency, there is a first bending deformation pattern in the plate (mode 1). At the second natural frequency, there is a first twisting deformation pattern (mode 2). At the
third and fourth natural frequencies, the second bending and second twisting deformation patterns are seen (mode 3 and 4, respectively). Such natural frequencies and mode shapes occur in all structures to some extent [52] and [53].

![Image](image1.png)

(a) Deformation patterns at different modes and (b) Composed time and frequency response from a simple modal model.

Basically, structural characteristics such as mass and stiffness determine where these natural frequencies and mode shapes occur. For the MEMS design it is necessary to identify these frequencies and know how they might affect the response of the structure when a force excites it. A physical model for the structure could also be approximated using an analytic lumped-mass model or a finite element model. This model is generally evaluated by some set of equations, where there is an interrelationship, or coupling, between the different masses or degrees of freedom (DOF). Typically, a large number of equations must be solved; matrices are often used to organize them.

The matrix representation of all the equations of motion describing how the system behaves is [52]:

\[
M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t)
\]  

(5.2)

Where \( M, C \) and \( K \) are the mass, damping and stiffness matrices respectively; \( \ddot{x}, \dot{x} \) and \( x \) the corresponding acceleration, velocity and displacement, and \( F \) is the force applied to
the system. There are different types of the excitation signals or forces applied, such as: sinusoidal vibration, periodic chirp, and pseudo random motion, among others.

The following figures show the measurement results for the MEMS structures; the MEMS Capacitor and the MTM-MEMS antenna. Figure 5.23(a) displays the measurement area is determined by a grid in where each point is evaluated for their velocity (see color bar). At the first frequency, there is a first deformation pattern in the plate, labeled as “mode 1”. This appears at a natural frequency of 10 KHz in the band 1, as is illustrated in Figure 5.23(b).

![Definition of a measurement grid, Capacitor with R = 6 Ω, excitation type sine AC 2V and DC 1V and 10 KHz and Velocity with respect to frequency for the MEMS capacitor.](image)

Figure 5.23
Figure 5.24 depicts the deformation patterns that will result when the excitation (sinusoidal signal) coincides with one of the natural frequencies, in this case, there is a natural frequency to 20 KHz in the band 2.

Figure 5.24 Animation of the MEMS capacitor with R = 7 Ω, when the excitation is a sinusoidal signal of AC 2V and DC 1V and 20 KHz.

Figure 5.25(a) depicts the deformation patterns that will result when the excitation is type chird and it coincides to a natural frequency of 11.25 KHZ in the band 1. Figure 5.25(b) shows measurements result in each position (x, y and z) that is evaluated from interferometer measurement.
Figure 5.25  Measurement results of the MEMS capacitor. (a) Picture shows the MEMS capacitor with $R = 8 \, \Omega$, when the excitation is type chirp AC 2V and DC 1V and 11.25 KHz and (b) Velocity with respect to frequency for the MEMS capacitor.

Figure 5.26(a) depicts the deformation patterns that will result when the excitation is type chirp and it coincides to a natural frequency of 5.438 KHz in the band 1. Figure 5.26(b) shows measurements result in each position ($x$, $y$ and $z$) that is evaluated from interferometer measurement.
Figure 5.26 Measurement results of the MEMS capacitor. (a) Capacitor with $R = 7 \, \Omega$, excitation type chirp AC 2V and DC 2V and 5.438 KHz and (b) Velocity with respect to frequency for the MEMS capacitor.

Figure 5.27(a) depicts the deformation patterns of the antenna that will result when the excitation is type chirp and it coincides to a natural frequency of 34.31 KHz in the band 1. Figure 5.27(b) shows measurements result in each position ($x$, $y$ and $z$) that is evaluated from interferometer measurement.
5.4 Discussion

This chapter has presented the antenna response in two main aspects: RF and mechanical performance, integrating a study of the antenna considering the MEMS capacitor model and a modal mechanical analysis based on the physical structural changes. These results have been satisfactorily compared to Comsol Multiphysics and Coventorware simulations.

The results show that MTM-MEMS technologies allow to simultaneously add variability, miniaturization (small size much less than $\lambda/4$), broader bandwidth, low losses and design flexibility. These set of measurements, however, represent a subset of all possible measurements, which will be undertaken in the future.
5.5 Conclusions

In this work, the design, fabrication and measurements of an MTM-MEMS antenna as a basic cell have been described. The MEMS variable capacitor is a very important part of the antenna; it is formed by two parallel plates, and the anchor, the most critical part of the MEMS capacitor design. With an appropriate anchor design, a wider range in variable capacitance can be achieved, as well as a high tuning capability of the operating frequency of the antenna, as displayed in the previous simulations.

In this case, the anchor was designed with a size of 22% with respect to plate size, which allowed for less stress, a lower surface tension, and a larger gap between the plates without any deformation, breaking, adhesion or collapse of the structure. The successful release of the structures was performed with a novel procedure, herein described, which avoids problems of stiction, sticking, deformation and collapse of the structure. The measurements of the MTM-MEMS antenna at 8.65 GHz have been presented here; since the gap was larger than expected, the antenna can be tuned with a wider frequency range without adding more cells. In this case, the resonant frequency at 8.65 GHz correspond to a gap of 30 μm. Future works are centered in a methodology to control the response of MTM-MEMS antennas more efficiently.
Chapter 6   Conclusions and Contributions

The work presented in this dissertation had two goals in mind: innovating RF-MTM-MEMS circuits with an original design method and a novel fabrication process, and developing ad-hoc RF-MEMS circuits using surface micromachining technology, which is fully compatible with integrated circuit fabrication processes, and which achieves high performance, low cost and compact size.

The design of the devices was based on Metamaterials Technology using CRLH-TL theoretical equations and full wave electromagnetic simulations, which were used to determine the physical dimensions and RF characteristics. A substantial effort was made to develop process flows and fabrication methods to achieve MTM-MEMS devices on silicon wafers using MEMS fabrication techniques.

The merits and demerits of each design were analyzed in terms of microwave performance, fabrication complexity and adaptability to integration of MTM-MEMS devices in RF wireless communication systems.
In this work, the concept of a MEMS variable capacitor is novel due to the versatility of the developed capacitor in its use as a metamaterial structure and as a radiator. It has been shown that MEMS devices open up new venues for highly integrated RF circuits that can offer reconfigurability, miniaturization, high performance and reliability at any frequency (from very low to high frequencies).

Mechanically, the designed antenna offers a performance with less stress, a lower surface tension, and a larger gap between the plates without any deformation, breaking, adhesion or collapse of the structure. Therefore, MTM-MEMS antenna can be tuned for a larger frequency coverage range from 5.3 to 8.65 GHz corresponding to a gap from 2 to 30 μm. Hence, while the gap is increased, the tune range is larger.

6.1 Contributions

1) A methodology for the design of the reconfigurable MTM-MEMS devices was proposed.

2) These devices achieved miniaturization, them being 26 times smaller than conventional devices, while at the same time presenting high performance, reconfigurability and low losses.

3) The fabrication process was proposed considering materials for high frequency circuits, highly compatible with CMOS technology and with a high degree of material integration. The proposed process uses novel techniques to obtain large metal thickness, and the combination of titanium and aluminum provide a robust support and mechanical stability for the structure.
4) Another important contribution is the combination of materials; in this case, the use of metals and resins to create MEMS devices reduces production costs and opens new ways to manufacture reconfigurable MTM-MEMS devices on different substrates.

5) The release technique presented here, developed as part of this research work, is in the process of being patented.

6) The six publications derived from this work are listed in the next section.

6.2 Limitations and Recommendations for Future Work

MTM-MEMS devices hold immense potential in the development of a multitude of highly-integrated microwave and millimeter-wave circuits. A few of the recommendations to improve and enhance this research are:

a. Future works centered in a methodology to control the performance of MTM-MEMS antennas more efficiently.

b. Undertake an analysis focused on critical aspects in the design of MTM-MEMS devices, specifically, the bridges that connect all ground planes.

c. Refine the mechanical model for the MTM-MEMS structure.

d. Improve MEMS capacitor performance by reducing the residual stress in the anchor of the structure.

e. Optimize gain and efficiency to increase the number of cells.
d. Develop a low-cost, efficient packaging technique to insure device performance.
Publications


Appendix A: Magnetic Properties

Permitivity $\varepsilon'$, also known as the dielectric constant, describes the response of a dielectric material to an electric field and is determined by the ability of a material to be polarized in response to the applied electric field. The absolute permittivity is the product of the permittivity of free space ($\varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$) and the relative permittivity, $\varepsilon'_r$.

$$ \varepsilon' = \varepsilon_0 \varepsilon'_r $$  \hspace{1cm} (A.1)

The complex permittivity, $\varepsilon^*$, is introduced to describe the response of a dielectric exposed to time varying fields and to account for losses. $\varepsilon^*$ can be expressed by:

$$ \varepsilon^* = \varepsilon' - j\varepsilon'' $$  \hspace{1cm} (A.2)

Where $\varepsilon''$ refers to the dielectric loss factor.

The complex permittivity is a measure of ability of a dielectric to absorb and store electrical potential energy, with the permittivity $\varepsilon'$, representing the penetration of microwaves into the material and loss the loss factor $\varepsilon''$, representing the ability of the material to store energy. The loss tangent, $\tan \delta$, represents the efficiency of the material to convert absorbed energy into heat and is also commonly used to describe the dielectric response.

$$ \tan \delta = \frac{\varepsilon''}{\varepsilon'} $$  \hspace{1cm} (A.3)

The angle $\delta$ is the phase difference between the oscillating electric field and the polarization of the material.
Dielectric properties vary with temperature and frequency. In addition, the dielectric properties of the material are also affected by many factors such as the purity, chemical state and manufacturing process. Therefore, it is crucial to compile a comprehensive database of the dielectric properties of different materials at different frequencies and temperatures to improve the current understanding and to increase the judicious use of microwaves for processing of materials [37].

Permeability, \( \mu' \), describes the response of a material to magnetic field. The magnetic permeability is the product of the permeability of free space (\( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \)) and the relative permeability \( \mu_r \).

\[
\mu' = \mu_0 \mu_r \quad \text{(A.4)}
\]

Analogous to the complex permittivity, it accounts for the losses of a material due to an alternating magnetic field, the complex permeability \( \mu^* \), can be expressed by

\[
\mu^* = \mu' - j \mu''
\]

where \( \mu'' \) represents the magnetic loss factor due to relaxation and resonance processes under the influence of an alternating magnetic field.

Permeability controls the penetration depth: the higher the permeability, the less an electromagnetic wave will penetrate the material [31].

Penetration depth or skin depth is a measure of the depth an electromagnetic wave penetrates a material [4]. The skin depth, usually written \( \delta \), is the distance over which a 1/e decay of the \( E \) (Electric), \( H \) (Magnetic) fields and current occurs. When conductivity is high, as for example in metals, the skin depth is given to a very good approximation by [31]:

\[
\delta = \sqrt{\frac{2}{\omega \mu \sigma}}
\]

\[
\text{(A.6)}
\]
where $\sigma$ is the conductivity of the material, $\mu$ is permeability and $\omega$ is the angular frequency. For a perfect conductor, resistivity is zero, therefore the penetration depth=0. Notice that skin depth is inversely proportional to the square root of the frequency. The implication is that at high frequencies, current is only being carried in a thin layer at the surface of conductors. Since skin depth is the effective depth over which current is being carried, the resistance of the conductor increases as the square root of frequency.
## Appendix B: Fabrication Process

<table>
<thead>
<tr>
<th>Process Flow</th>
<th>Process Name</th>
<th>ID</th>
<th>Process Steps</th>
<th>Technical Description Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scribe Wafers</td>
<td>1</td>
<td>Three inch wafer: Lot # A1, A2 and A3 (Device Wafers) &amp; SC1 (Control Wafers)</td>
<td>Wafer Type: N-type; Orientation:&lt;100&gt; r &gt; 4000 - 8000 Ohm.cm, thickness &gt;490-530 mm</td>
</tr>
<tr>
<td></td>
<td>Metrology</td>
<td>2</td>
<td>Four Point Probe Measurement</td>
<td>Calculate resistivity; verify with manufacturer (set voltage limit and current)</td>
</tr>
<tr>
<td>Step 1</td>
<td>RCA Clean (Pre-furnace Cleaning)</td>
<td>3</td>
<td>Dip in HF (50:1) for 20 seconds</td>
<td>Removes native oxide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rinse with DI water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dip in SC1 (15:2:1) for 10 minutes @ 60ºC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rinse with DI water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dip in HF (50:1) for 20 seconds</td>
<td>Removes chemical/sacrificial oxide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rinse with DI water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dip in SC2 (10:2:1) for 10 minutes @ 60ºC</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Rinse with DI water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dip in HF (50:1) for 20 seconds</td>
<td>Removes chemical/sacrificial oxide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rinse with DI water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry with Nitrogen Gun</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wet Oxidation</td>
<td>4</td>
<td>Oxidation furnace FNB3 - Pyrogenic Steam</td>
<td>3000Å @1050ºC, Time = 45 min</td>
</tr>
<tr>
<td>Step 2</td>
<td>Metrology</td>
<td>5</td>
<td>Rudolph Ellipsometer Measurement</td>
<td>Measure oxide thickness of each control wafer top, center bottom record</td>
</tr>
<tr>
<td>Step 3</td>
<td>Deposit Metal Ti</td>
<td>6</td>
<td>Sputtering</td>
<td>thickness 1 micra</td>
</tr>
<tr>
<td>Step 4</td>
<td>Deposit Metal Al</td>
<td>7</td>
<td>Sputtering</td>
<td>thickness 3 microns</td>
</tr>
</tbody>
</table>
### Appendix B: Fabrication Process

#### Step 5: Lithography Mask 1
<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| 8 | Spin HMDS for 2000 rpm for 40 seconds  
Spin 1813 Photoresist for 2000 rpm for 40 seconds  
Soft bake 125 °C @ 1 min  
Expose for 5 seconds Hard contact  
Develop for 1 min 10 seconds with MF 319 developer  
Rinse with DI water for 1 minute  
Dry with Nitrogen Gas  
Inspect resist development with microscope  
Hard bake for 110 °C @ 20 min |
| 9 | Inspect resist development with microscope  
take two pictures SC1 wafer |

#### Step 6: Al Etch
<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| 10 | Wet Etch: Al Etch  
40°C @ 5 min |

#### Step 7: Ti Etch
<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| 11 | Wet Etch  
Ammonium Hydroxide + Hydrogen Peroxide  
NH₄OH + H₂O₂ (2:1) 30 °C @ 3 min |

#### Step 8: Strip Resist
<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| 12 | Solvent Clean  
Acetone, methanol, rinse, and dry |

#### Step 9: SU8-2002 Dimples
<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| 13 | Alphastep profile over the discussed structure  
to determine Ti + Al thickness |
| 14 | Dimples  
thickness 1 mm |

#### Step 8: Lithography Mask 2
<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| 15 | Pre-bake 125°C @ 3 min  
Spin SU8 for 6000 rpm for 50 seconds  
Soft bake 125 °C @ 3 min  
Expose for 10 seconds Hard contact  
Post bake 125 °C @ 3 min  
Develop for 1 min with SU8 developer  
Rinse with DI isopropyl alcohol for 1 minute  
Dry with Nitrogen Gas  
Inspect resist development with microscope  
Hard bake for 125°C @ 3min |
<p>| 16 | |</p>
<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Deposit AZ-P4620</td>
<td>Sacrifice Layer thickness 5 mm</td>
</tr>
<tr>
<td>11</td>
<td>Lithography Mask 3</td>
<td>Spin AZ-4620 for 5500 rpm for 50 seconds&lt;br&gt;Soft bake for 90°C @ 20 min&lt;br&gt;Expose for 63 seconds Hard contact&lt;br&gt;Develop for 60 seconds by 3 baths&lt;br&gt;Rinse with DI water for 1 minute&lt;br&gt;Dry with Nitrogen Gas&lt;br&gt;Inspect resist development with microscope&lt;br&gt;Setp_1 10s @ 500 rpm acc 004&lt;br&gt;Setp_2 50s @ 3000 rpm acc 020&lt;br&gt;Oven&lt;br&gt;281 mW</td>
</tr>
<tr>
<td>12</td>
<td>Deposit Metal Ti</td>
<td>Sputtering thickness 1 micra</td>
</tr>
<tr>
<td>13</td>
<td>Deposit Metal Al</td>
<td>Sputtering thickness 3 micra</td>
</tr>
<tr>
<td>14</td>
<td>Lithography Mask 4</td>
<td>Spin HMDS for 3000 rpm for 40 seconds&lt;br&gt;Spin 1813 Photoresist for 3000 rpm for 40 seconds&lt;br&gt;Soft bake 125 °C @ 1 min&lt;br&gt;Expose for 5 seconds Hard contact&lt;br&gt;Develop for 1 min 10 seconds with MF 319 developer&lt;br&gt;Rinse with DI water for 1 minute&lt;br&gt;Dry with Nitrogen Gas&lt;br&gt;Inspect resist development with microscope&lt;br&gt;Setp_1 10s @ 700 rpm acc 004&lt;br&gt;Setp_2 40s @ 2000 rpm acc 020&lt;br&gt;Hot plate&lt;br&gt;25 mW&lt;br&gt;Oven</td>
</tr>
<tr>
<td>15</td>
<td>Metrology</td>
<td>Inspect resist development with microscope take pictures</td>
</tr>
<tr>
<td>Step</td>
<td>Process</td>
<td>Sequence</td>
</tr>
<tr>
<td>--------</td>
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</tr>
<tr>
<td>Step 15</td>
<td>Al Etch</td>
<td>24</td>
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<tr>
<td></td>
<td>Ti Etch</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Metrology</td>
<td>26</td>
</tr>
<tr>
<td>Step 16</td>
<td>Anneal/Sinter</td>
<td>27</td>
</tr>
</tbody>
</table>
| Step 17 | Lithography Mask 4 | 28 | Realese  
Spin HMDS for 3000 rpm for 40 seconds  
Spin 1813 Photoresist for 3000 rpm for 40 seconds  
Soft bake 125 °C @ 1 min  
Expose for 5 seconds Hard contact  
Develop for 1 min 10 seconds with MF 319 developer  
Rinse with DI water for 1 minute  
Dry with Nitrogen Gas  
Inspect resist development with microscope  
Hard bake for 110 °C @ 20 min |
|        | Metrology | 29       | Inspect resist development with microscope take pictures |
| Step 18 | Release   | 30       | Chemical Process, Conventional Oven and Plasma Process |
References


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