PERFORMANCE OPTIMIZATION OF TUNABLE RF MEMS BASED DEVICES

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by

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Submitted
in fulfillment of the requirements of the degree of Doctor of Philosophy
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DEDICATION

To my family

Certificate

This is to certify that the thesis entitled, ”**Performance Optimization of Tunable RF MEMS Based Devices**”, being the submitted by **Shri. Vishal Kumar** for the award of the degree of Doctor of Philosophy (Ph. D.) to the Indian Institute of Technology, Delhi, is a record of original bonafide research work carried out by him under our guidance and supervision.

In our opinion, the thesis has reached the standard of fulfilling the requirements of all the regulations related to the degree. The results contained in this thesis have not been submitted in part or full, to any other university or institute for the award of any degree or diploma.

We certify that he has pursued the prescribed course of research.

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EPIGRAPH

If there is a will, there is a way.

- Shakespere

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ABSTRACT

Comprehensive studies on Radio Frequency Micro Electro Mechanical Systems (RF MEMS) based devices followed by implementation of novel design and fabrication process to optimize the performances of these devices are presented in this thesis. The work aimed at development of RF MEMS shunt switches, switch based MEMS phase shifter, tunable capacitor and bulk-micromachined inductors to be implemented in the futuristic next generation systems for airborne applications.

To start with Tri-layer (nitride-metal-nitride) membrane rather than all metal membrane have been investigated to enhance the membrane properties and to realize the stress free, thermally stable, and stictionless structure. The process flow was optimized as per the established MEMS process of the Indian foundry named Semiconductor Technology & Applied Research Centre, STAR-C (formerly known as Society for Integrated Circuit and Applied Research, SITAR), Bangalore. All these structures are fabricated on high resistivity Silicon substrate to ensure low RF loss as well as low parasitic capacitance.

Chapter 2 presents an electrostatic RF MEMS shunt switch using the novel tri-layer membrane which results low actuation voltage less than 15V, high isolation better than 35 dB and has stictionless operation. Inductance tuning is implemented by creating the narrow trench in the CPW ground to lower the resonant frequency and enhance the isolation.

Chapter 3 presents the MEMS shunt switch based low actuation voltage, wideband Distributed MEMS Transmission Line (DMTL) phase shifter which exhibit a highly linear phase shift through the entire band. The phase shifter uses the same switch developed during the research. This 1-bit phase shifter can be cascaded with the other bits and can be used in phased array based systems.

Keeping the requirements of tunable devices in futuristic wireless communication architecture in view, two basic components such as tunable capacitor and inductors are developed with enhanced linearity and improved Q factor respectively as mentioned in chapter 4 and chapter 5. The same tri-layer membranes were used to realize capacitor plate and the inductor coil. The thesis concludes by suggesting the room for improvement of these devices as well as the future task directions in this field.

सार

रेडियो फ्रीक्वेंसी माइक्रो इलेक्ट्रो मैकेनिकल सिस्टम्स (आरएफ एमईएमएस) आधारित उपकरणों पर व्यापक अध्ययन, इन उपकरणों के प्रदर्शन को अनुकूलित करने के लिए नोवेल डिजाइन और निर्माण प्रक्रिया के कार्यान्वयन के बाद इस थीसिस में प्रस्तुत किया गया है। आरएफ एमईएमएस शंट स्विच, स्विच आधारित एमईएमएस फेज शिफ्टर, ट्यून करने योग्य कैपेसिटर और बल्क-माइक्रोमशीन इंडक्टर्स के विकास के उद्देश्य से किए गए कार्य को हवाई अनुप्रयोगों के लिए भविष्य की अगली पीढ़ी की प्रणालियों में लागू किया जाएगा।

सभी धातु झिल्ली के बजाय त्रि-परत (नाइट्राइड-मेटल-नाइट्राइड) झिल्ली के साथ शुरू करने के लिए झिल्ली गुणों को बढ़ाने और तनाव मुक्त, तापीय रूप से स्थिर और कठोर संरचना का एहसास करने के लिए जांच की गई है। सेमीकंडक्टर टेक्नोलॉजी एंड एप्लाइड रिसर्च सेंटर, STAR-C (पूर्व में सोसाइटी फॉर इंटीग्रेटेड सर्किट एंड एप्लाइड रिसर्च, SITAR), बैंगलोर के नाम से भारतीय फाउंड्री की स्थापित एमईएमएस प्रक्रिया के अनुसार प्रक्रिया प्रवाह को अनुकूलित किया गया था। इन सभी संरचनाओं को कम आरएफ नुकसान के साथ-साथ कम परजीवी कैपेसिटर सुनिश्चित करने के लिए उच्च प्रतिरोधकता वाले सिलिकॉन सब्सट्रेट पर गढ़ा गया है।

अध्याय 2 नई त्रि-परत झिल्ली का उपयोग करके एक इलेक्ट्रोस्टैटिक आरएफ एमईएमएस शंट स्विच प्रस्तुत करता है, जिसके परिणामस्वरूप 15V से कम एक्चुएशन वोल्टेज, 35 डीबी से बेहतर उच्च आइसोलेशन और स्टिक्शनलेस ऑपरेशन होता है। गुंजयमान आवृत्ति को कम करने और अलगाव को बढ़ाने के लिए CPW ग्राउंड में संकीर्ण खाई बनाकर इंडक्शन ट्यूनिंग को लागू किया जाता है।

अध्याय 3 एमईएमएस शंट स्विच आधारित कम एक्चुएशन वोल्टेज, वाइडबैंड वितरित एमईएमएस ट्रांसमिशन लाइन (डीएमटीएल) चरण शिफ्टर प्रस्तुत करता है जो पूरे बैंड के माध्यम से एक अत्यधिक रैखिक चरण बदलाव प्रदर्शित करता है। चरण शिफ्टर अनुसंधान के दौरान विकसित उसी स्विच का उपयोग करता है। यह 1-बिट चरण शिफ्टर अन्य बिट्स के साथ कैस्केड किया जा सकता है और चरणबद्ध सरणी आधारित सिस्टम में उपयोग किया जा सकता है।

फ्यूचरिस्टिक वायरलेस कम्युनिकेशन आर्किटेक्चर में ट्यून करने योग्य उपकरणों की आवश्यकताओं को ध्यान में रखते हुए, ट्यून करने योग्य कैपेसिटर और इंडक्टर्स जैसे दो बुनियादी घटकों को क्रमश: बढ़ी हुई रैखिकता और बेहतर क्यू फैक्टर के साथ विकसित किया गया है जैसा कि अध्याय 4 और अध्याय 5 में उल्लेख किया गया है। यह वही त्रि-परत झिल्ली है जिसका उपयोग कैपेसिटर प्लेट और इंडक्टर्स के विकास के लिए किया गया। इस क्षेत्र में इन उपकरणों के सुधार के साथ-साथ भविष्य की कार्य दिशाओं के लिए सुझाव देकर थीसिस समाप्त होती है।

TABLE OF CONTENTS

Chapter1: Introduction

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

AlN : Aluminum Nitride

Al : Aluminum

Al_2O_3 : Alumina

Au : Gold

$BaSrTiO_3$: Barium StronciumTitanate

BEOL : Back End of Line

BiCMOS : Bipolar CMOS

CeNSE : Centre for Nano-Science and Engineering

CMOS : Complementry metal oxide semiconductor)

CNT : Carbon Nano Tube

COMP : Compressive Molding Planarization

CPW : Co-planar waveguide

DMTL : Distributed MEMS Transmission Line

DRIE : Deep reactive-ion etching

DPFM : Double Polysiliconfour metal

EIRP : Effective Isotropic Radiated Power

ESR : Equivalent Series Resistance

ECDM : Electrochemical discharge machining

EMC : Electro Magnetic Compatibility

EMI : Electromagnetic Interference

FBAR : Film Bulk Acoustic Resonator

FEM : Finite element method

FETs : Field effect transistors

FOGs : Fiber-optic gyros

FOM : Figure of Merit

FMR : Ferromagnetic-resonant

GaAs : Gallium Arsenide

GAETEC : Gallium Arsenide Enabled Technology Centre

GHz : Giga Hertz

GPS : Global Positioning System

GSM : Global system for mobile communications

HDICPCVD : High Density Inductively coupled plasma chemical vapor deposition

HEMT : High Electron Mobility Transistor

pHEMT : Pseudomorphic High Electron Mobility Transistor

HIS : High impedance surface

HMICs : Hybrid Monolithic Integrated Circuits

HP : Hewlett Packard (HP).

HRS : High Resistivity Substrate

IC : Integrated circuit

ICP : Inductively coupled plasma

IIP3 : Third-order intercept point

I.L. : Insertion loss

IOT : Internet of Things

IPD : Integrated Passive Devices

LCP : Liquid Crystal Polymer

LIGA : Lithography (Lithographie), Electroforming (Galvanoformung), and Plasticmoulding (Abformung)

LTCC : Low Temperature Co-Fired Ceramic

LF : Linearity factor

LNAs : Low Noise Amplifiers

LPCVD : Low Pressure Chemical Vapor Deposition

MST : Micro systems technology

MOEMS : Micro Electro optical systems

µTAS : Micro total analysis systems

MAM : metal-air-metal

MESA : Micro-Elevator by Self Assembly

MESFET : Metal Semi-conductor Field Effect Transistor

MEMS : Micro Electro Mechanical Systems

MESFETs : Metal–semiconductor field effect transistors

MHz : Mega Hertz

MICs : Monolithic Intrgrated Circuits

MIM : Metal-Insulator-Metal

MMICs : Monolithic microwave integrated circuits

µNMR :Micro-nuclear magnetic resonance
MNPM : Magnetic-nano-particles-medium
MTR : Maximum tuning range
MUMPs : Multi User MEMS Polysilicon process
NiFe : Nikel-Iron
NLC : Nematic Liquid Crystal
Ni-Fe : Nickel-Ferrite
nH : Nano-Henery
OPS : Oxidized Porous Silicon
PA : Power Amplifier

PAA : Porous Anodic Alumina
PCB : Printed Circuit Board
PMMA : Poly Methyl Metha Acrylate
PolyMUMPS : Poly Multi User MUMPS
PoP : Package on Package
pH : Pico-Henery
PGS : Patterned Ground Shields
PDMA : Plastic Deformation Magnetic Assembly
PDA’s : Personal data assistants
PECVD : Plasma Enhanced Chemical Vapor Deposition
pHEMT : Pseudomorphic High Electron Mobility Transistor
PZT : Lead zirconium tetitanate

QSC	: Quadruple Series Capacitor
RF	: Radio Frequency
RF MEMS	: RF Micro Electrical Mechanical systems
RFICs	: RF integrated circuits
RFIDs	: Radio Frequency Identification Tags
RIE	: Reactive Ion Etching
R.L.	: Return Loss
RSC	: Rockwell Scientific Centre
SAW	: Surface Acoustic Wave
SCAP	: Silicon capacitive pressure sensor
SCREAM	: single crystal reactive etching and metallization
Si	: Silicon
SiP	: System in Package
SiO_2	: Silicon di-Oxide
SITAR	: Society for Integrated Circuit and Applied Research
SOC	: System on Chip
SOI	: Silicon –On-Insulator
SOS	: Silicon-on-Sapphire
SPST	: Single-Pole Single-Throw
SPDT	: Single Pole Double Throw
SPNT	: Single Pole N throw
SRF	: Self-resonant frequency
SSLDE	: Silicon Sacrificial Layer Dry Etching

STAR-C : Semiconductor Technology and Research Centre

STO : Strontium Titatnate Oxide

TEM : Transverse-Electric-Magnetic

TiO_2 : Titanium Oxide

TIJ : thermal inkjet technology

TRM : Transmit Receive Module

TSV : Through Silicon Vias

TTD : True-time delay

UAVs : Unmanned Aerial Vehicles

UMTS : Universal mobile telecommunications system

VCOs : Voltage controlled oscillators

VSWR : Voltage Standing Wave Ratio

WLAN : Wireless Local Area Network

WLCSP : Wafer Level Chip Scale Package

YIG : Yitrium-iron-garnet

LIST OF SYMBOLS

A : Area of the capacitor plate

Au : Gold

b : Damping Co-efficient

$\propto$: Alpha-Line loss in Np/m

C_{up} : Up-state Capacitance

C_{down} : Down state capacitance

C : Capacitance

C_b : Capacitance associated with the MEMS Bridge

C_{pp} : Parallel plate capacitance

C_f : Fringing field capacitance

C_l : Loaded Line Capacitance

C_{on} : On-state capacitance

C_{off} : Off-state capacitance

C_{ratio} : Capacitance Ratio

C_t : Unit Length Capacitance

Δ : Delta

δ	: Skin depth
dB	: Decibel
E	: Young’s Modulus
ε_0	: Permittivity of the air
ε_{eff}	: Effective Dielectric constant
ε_r	: Relative permittivity of the medium
fF	: Femto-farad
f_0	: Resonant Frequency
f_{cutoff}	: Cut-off Frequency
F_c	: Vander-wall force
F_e	: Electrostatic Pull-down force
G	: Torsional modulus
I	: Moment of Inertia
J	: Torsional constant
k	: Spring Constant
K_z	: Total spring constant
K’	: Spring constant due to stiffness of the bridge
K”	: Spring constant due to biaxial residual stress within the bridge
K (k’)	: Complete elliptic integral of the first kind
K_s	: Stress stiffening spring constant
L	: Inductance
L_t	: Unit Length Inductance
Ms	: Saturation Magnetization

MV/cm	: Mega-volts per centimeter
μ_0	: Permeability of the medium in air
μ	: Permeability
μs	: Micro-second
Np	: Neper- Ratio of gain or Loss of electronic signals
ω	: Omega- Angular Frequency
pF	: Pico-Farad
P_{loss}	: Power loss in the bridge
R	: Resistance
Rs	: Series Resistance
t_d	: Dielectric thickness
g_0	: Initial Gap Height
μs	: Micro-second
π	: Pi
P	: Load distributed across the entire beam
P_{loss}	: Power loss in the bridge
q(x,z)	: Distributed load due to the electrostatic actuating force and the mechanical contact force
Q	: Quality factor
R_{cpw}	: Resistance of CPW line
ρ	: Resistivity
ρ_{si}	: Resistivity of the substrate
Δ	: Delta- difference between two entities

σ : Sigma-Conductivity of the medium

σ_0 : Bi-axial residual stress

s : Periodic spacing between two adjacent MEMS bridges

S_{11} : Reflection Coefficient

S_{21} : Transmission Coefficient

SF_6 : Sulpher Hexa Fluoride

SiO_2 : Silicon di-Oxide

Si_3N_4 : Silicon Nitride

t : Thickness of the beam

t_d : Thickness of the Dielectric layer

t_s : Switching Time

$V_{pull-in}$: Pull-in voltage

V_s : Applied Voltage

V_t : Phase velocity

V_{th} : Threshold voltage

υ : Poission's Ratio

ω_B : Bragg Frequency

w : Width of the beam

W : Width of the actuation electrode

w_b : Width of the bridge

X_e : Weighted volumetric average

ξ : Force per unit length

Z_0 : Characteristic Impedance

Zb : Impedance of the beam

Z_l : Characteristic impedance of loaded line

Z_{lu} : Characteristic impedance of loaded line in UP state

Z_{ld} : Characteristic impedance of loaded line in DOWN state