Reliable and high speed RF MEMS switches with wafer-scale encapsulation

Ke, Feixiang

2009

Ke, F. (2009). Reliable and high speed RF MEMS switches with wafer-scale encapsulation.
Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/47243>

<https://doi.org/10.32657/10356/47243>

Nanyang Technological University

Downloaded on 26 Apr 2023 19:05:21 SGT

**RELIABLE AND HIGH SPEED RF MEMS SWITCHES
WITH WAFER-SCALE ENCAPSULATION**

KE FEIXIANG

School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2009

Acknowledgement

The completion of this thesis could not have been made possible without the insightful and valuable guidance, extraordinary efforts and kind supports of many people during all these years, all of whom deserve recognition for their invaluable help. An incomplete list is as follows.

Foremost amongst these goes to my supervisor, Prof. Miao Jianmin, who provided inspiration and unstinting support throughout this project. I was really enlightened by his expertise, knowledge, and experience. I highly appreciate his advice, comments, and patience, without which, my research effort could never come to fruition.

I sincerely acknowledge Dr. Chew Siou Teck, Dr. Tan Guan Leng, and Dr. Vincent Leng at DSO National Laboratories, for the research opportunity in MEMS field, and their suggestions and encouragement. My special thanks go to my colleagues, Dr. Li King Ho, Dr. Lee Kok Yan and Dr. Ang Kian Sen, for the discussions and help to overcome various technical issues. I would also like to thank DSO National Laboratories for the support of the research work.

I would like to express my appreciation to Prof. Joachim Oberhammer at KTH - Royal Institute of Technology, Stockholm, Sweden, who was collaborating with this project, for his invaluable comments and sharing his experience and knowledge in MEMS area.

I would like to extend my thanks to Research staffs at MicroMachines Centre (MMC), Dr. Chen Longqin, Dr. Wang Zhihong, Dr. Chen Xiao Feng, Dr. Zhu Hong, and Dr. Ciprian, for very useful advices and suggestions.

My many thanks go to all the research scholars as well at MMC. I benefited greatly from discussions and work with them, Sun Jianbo, Chen Bangtao, Tan Chee Wee, Wu Jie, Pradeep Dixit, Xu Ting, Nay Lin, Wu Mingjie, Yuan Yuanhui, Chin Chi Chong, and many more, for friendship, and honestly, for the struggles we went through together in the course of the study.

I am also thankful to the help and support from the laboratory staff of MMC, Mr. Hoong Sin Poh, Mr. Tang Kok Soo, Mr. Nordin Bin Abdul Kassim, Mr. Wong Kim Chong, Mr. Lau Joo Kiang, Mr. Pek Soo Siong, Mr. Ho Kar Kiat, and Mr. Win Maung Muang.

Last, but never the least, I would express my deepest gratitude to my family for their unfaltering love, encouragement, and support.

Tables of Contents

Acknowledgment ----- i

Tables of Contents ----- iii

List of Figures ----- vii

Summary----- xii

Chapter 1 Introduction..... 1

1.1 Background 2

1.2 Objectives 3

1.3 Major Contributions..... 4

1.4 Thesis Outline 6

Chapter 2 Literature Review 8

2.1 MEMS Technology..... 8

2.2 RF MEMS Switches 10

2.2.1 Fundamental of Switching Concept 11

2.2.2 Basic Configuration of RF MEMS Switches 13

2.2.3 Types of RF MEMS Switches..... 14

2.2.4 Actuation Scheme of RF MEMS Switches 20

2.3 Review of RF MEMS Switch Developed 26

Tables of Contents

2.3.1	Series MEMS Switch Developed	27
2.3.2	Shunt MEMS Switch Developed	34
Chapter 3	Design Considerations in RF MEMS Switches	40
3.1	Mechanical Structure of MEMS Switches with Wafer-level Encapsulation	40
3.2	Switch Contact for High Reliability	44
3.2.1	Multi-metal Contact with Hard Metal Coating	45
3.2.2	DC Contact Resistance	48
3.2.3	Effects of Surface Coating Thickness on Contact Resistance	50
3.3	Stress Reduction by Corrugation Introduction in Diaphragm	53
3.3.1	Mechanical Deflection Sensitivity	54
3.3.2	Stress Reduction Ratio	59
3.3.3	Actuation of Stress-reduced Corrugated Diaphragm	61
3.4	RF Design	65
3.4.1	Coplanar Wave Guide	65
3.4.2	Insertion and Isolation Loss	68
3.4.3	Simulation of Device Performance	73
3.5	Summary	77
Chapter 4	MEMS Switches based on Ruthenium/Gold Contact	
	Metallization for High Reliability	78
4.1	Switch Concept Overview	79
4.2	Fabrication Process Flow of Multi-wafer Stacking	81
4.3	Exploration of Critical Process	84
4.3.1	Generation of Corrugation Microstructure	84
4.3.2	Deposition of Low Stress Diaphragm Films	86
4.3.3	Wafer Bonding Technology with Intermediate Layer	88

Tables of Contents

4.4	Fabrication Issues and Suggestions	89
4.5	Performance of Switch Actuation	90
4.5.1	Diaphragm Deflection	90
4.5.2	Pull-in Voltage	92
4.6	Ruthenium-based Contact Properties.....	94
4.6.1	DC Contact Resistance.....	95
4.6.2	Reliability of Switch Contact	98
4.6.3	Current Handling Capability	102
4.7	RF Performance of Switches	102
4.8	Summary	105

**Chapter 5 MEMS Switches Based on Perforated Substrate for Switching
Speed Enhancement..... 107**

5.1	Switch Design Aspects	108
5.1.1	Proposal of High Speed Switch Realization	108
5.1.2	Modeling of Damping Reduction by Perforation Introduction.....	110
5.1.3	Modeling of Switching Times.....	117
5.2	Fabrication Process Flow	122
5.3	Characterization	126
5.3.1	Switching Time Measurements.....	127
5.3.2	RF Measurements.....	129
5.4	Summary	131

Chapter 6 Conclusions and Recommendations..... 132

6.1	Conclusions.....	132
6.2	Recommendations for Future Research	136

Tables of Contents

Appendix A Pressure Deflection Curve of Corrugated Diaphragm 139

Appendix B Stress Reduction Ratio by Corrugation Technique..... 142

Appendix C Calculation of Damping Coefficient..... 145

Appendix D Calculation of Switching Times..... 151

List of Publications 155

List of References..... 156

List of Figures

Figure 1 SPST switch circuits with ideal switch or non-ideal switching device represented by impedance Z_d . The ideal switch operates between perfect open and perfect short while non-ideal switch works between high impedance and low impedance. (a) Series switch connection, and (b) shunt switch connection 12

Figure 2 MEMS series switch and its equivalent circuits. (a) Schematic view of a MEMS switch with bridge microstructure. (b) Cross section views and equivalent circuits of switch-up state and switch-down state..... 17

Figure 3 MEMS shunt switch and its equivalent circuits. (a) Schematic view of a MEMS shunt switch with bridge microstructure, and (b) cross section views and equivalent circuits of switch in two states..... 19

Figure 4 Illustration of magnetic micro-actuator 23

Figure 5 Illustration of parallel plate of electrodes used for typical MEMS devices 24

Figure 6 SEM photo of the Rockwell Scientific MEMS series switch with PECVD silicon oxide membrane, two pull-in electrodes and gold-to gold contact [...]... 28

Figure 7 SEM photos of inline DC-contact MEMS switch developed by the Northeastern University and Analog Devices [24]. (a) Close-up view of switch contact. (b) Overall view of the switch 30

Figure 8 The compact in-line switch based on curled cantilever arm developed by Lincoln Laboratories [25]. (a) SEM photography of the switch at up-position. (b) Cross-sectional view of DC-contact and capacitive switches 31

Figure 9 Toggle-switch using a push-pull concept [26]. (a) Schematic view of the switch. (b) SEM photo of the fabricated switch 32

Figure 10 Series switch based on S-shaped membrane actuator. The switch was fabricated with two separated wafers bonded together through a polymer seal-ring [30]..... 33

List of Figures

Figure 11 Raytheon MEMS capacitive shunt switches [33].....	35
Figure 12 A capacitive MEMS switch developed by The National Taiwan University [34]. (a) The side-view of the switch at “curve-up” position. (b) The top view of the switch at the “down” state.....	36
Figure 13 Capacitive MEMS switches developed by University of Michigan [35-37]: (a) The K-band capacitive MEMS switch with low spring-constant membrane; (b) The inline capacitive shunt switch; and (c) The DC-contact shunt switch	37
Figure 14 Proposed wafer-level encapsulated MEMS switch based on multilayer contact metallization with corrugated diaphragm. (a) Encapsulation with stacked-wafer. (b) Corrugated diaphragm with multilayer contact is part of the encapsulated micro-chamber. (c) Three-dimensional drawing of the switch.....	42
Figure 15 Proposed approach to reduce the damping of the squeeze-film by perforating the base substrate and adding a back-plate with a cavity.....	43
Figure 16 Novel Ru/Au contact metallization scheme as compared to conventional Au and Ru contacts	47
Figure 17 Analysis of contact resistance over the contact force, for contact bumps coated with coating films. (a) Comparison of contact resistances calculated by Equation (11) and Equation (13). (b) Total contact resistances of coated contact-bumps, with the coating film thickness as parameter. (c) Relative total contact resistance change of Ru-coated contacts as compared to gold coated contacts.....	51
Figure 18 Geometrical illustration of the corrugations with dimensions: (a) physical dimensions (b) model of corrugated diaphragm for the numerical simulations and analytical calculations.	55
Figure 19 Mechanical deflection sensitivity of diaphragm vs. corrugation depth for a corrugation number of 2.....	58
Figure 20 (a) Residual stress reduction factor (η) as function of the corrugation depth, for DRIetched and KOH etched corrugations (with corrugation number N_c of 2). The measured η (to be given in Chapter 4) are also illustrated for both corrugated diaphragm with 6 μ m deep corrugations, and flat diaphragm (corrugation depth = 0 μ m. (b) Relationship of stress reduction ratio with corrugation number and corrugation depth which is generated by DRIE.....	60

List of Figures

Figure 21 Illustration of the diaphragm lumped 1D model.	62
Figure 22 Calculated actuation voltage vs. residual stress of a RF switch with a flat diaphragm.....	64
Figure 23 Representation of Coplanar Waveguide.....	66
Figure 24 Simplified Models of DC contact series MEMS switch with equivalent circuits. (a) MEMS switch in the on-state, and (b) MEMS switch in the off-state.	71
Figure 25 Isolation of a Series MEMS Switch with up-capacitance of 2-5fF, calculated by Equation (42).....	72
Figure 26 Simulation results of the isolation at off-state. (a) Effect of suspension height, with a relay metal of 250 μ m x 210 μ m and 150 μ m of transmission line gap. (b) Effect of relay metal area, with 6 μ m of suspension height, 150 μ m of transmission line gap.....	74
Figure 27 Simulated insertion loss of the proposed MEMS switch at on-state. An ideal switch without seal ring is also included for comparison.	75
Figure 28 A MEMS switch with four-side-clamped diaphragm was also simulated by ANSYS, to verify the silicon cap effect on the insertion loss	77
Figure 29 Cross-sectional drawing of the corrugated-diaphragm based RF MEMS switch in the on and off state.	79
Figure 30 Schematic drawing of the two switch parts, before assembling by wafer bonding.....	80
Figure 31 Fabrication process flow: (a) bottom glass wafer process; (b) top silicon wafer process; (c) wafer bonding and post-processing.	82
Figure 32 SEM photo of a RF MEMS switch with a circular corrugated diaphragm (900 μ m in radius). The overall size of the switch device is 3 mm x 2.8 mm x 0.95 mm.	84
Figure 33 SEM Photo of a corrugation with controlled etching profile generated by DRIE process.....	85
Figure 34 The relationship of measured residual stress of gold film and chamber pressure, with 300 W of DC power during the sputtering process.....	87
Figure 35 (a) Measured static center deflection of diaphragm as a function of the corrugation number under zero actuation voltage using the diaphragm edge as the reference. (b) Deformation of a diaphragm with four corrugations obtained	

List of Figures

by optical profiler. The device is unassembled without any actuation voltage.
..... 91

Figure 36 Measured pull-in voltages of MEMS switches in comparison with calculated ones using Equation (27)..... 93

Figure 37 Contact resistance over switching cycles: (a) the first 30 cycles of Au/Ru-Ru/Au contact at different voltage levels, (b) the initial 30 cycles of Au-Au contact at different voltage levels, (c) contact resistance change behavior over cycle number with signal current of 5 mA; the resistances and failure points plotted are average values of the two types of devices tested at 5 mA. SEM photos of rhenium and gold contacts, before & after the cycling tests are also shown. 97

Figure 38 X-ray photoelectron spectroscopy (XPS) of the Ru and Au contact surfaces, indicating the presence of absorbed carbon and oxygen on the contact surfaces.
..... 98

Figure 39 Schematic diagram of testing set-up configuration for the switching-cycle measurement 99

Figure 40 Contact reliability for the Au-Au and Au/Ru-Ru/Au contacts, investigated for different signal currents. Measurement conditions: cycle frequency of 1 kHz, duty cycle of 20%, rectangular and monopolar waveform of 40V peak amplitude..... 100

Figure 41 RF performance of an encapsulated switch including a 3 mm long coplanar waveguide transmission line: (a) Simulated and measured S_{21} and S_{11} in the off-state, (b) Simulated and measured S_{21} and S_{11} in the on-state. The electrode spacing refers to the gap left open in the membrane metallization layer. (c) Share percentage of transmitted, reflected and total lost power. 104

Figure 42 Schematic drawing of three parts of the demonstrator, which will be bonded together by wafer bonding using CYTOP polymer. 110

Figure 43 Schematic drawings of a MEMS microphone and the proposed MEMS switch. (a) Cross sectional view, and (b) top view of the two devices..... 112

Figure 44 Simulation results of damping coefficient of diaphragm with different base substrates and air gaps..... 114

List of Figures

Figure 45	Illustration of the demonstrator with corrugated diaphragm and perforated base substrate. (a) Top view of base substrate with damping holes, (b) cross sectional view of the demonstrator involving three parts bonded together, and (c) lumped one dimensional model of the diaphragm.....	119
Figure 46	Calculated pull-in time and release time for the corrugated diaphragm with different air gaps.	120
Figure 47	Fabrication process flow of the MEMS switch with perforated base substrate, (a) back-support process, (b) base substrate process, (c) top cap process, and (d) wafer bonding and assembly process.....	123
Figure 48	SEM Photo of the perforated base substrate, with holes of 50 μm in radius.	124
Figure 49	SEM Photo of a RF MEMS shunt switch with perforated base-substrate and a circular corrugated diaphragm (1750 μm in radius) before the sputtering process of top electrode. The overall size is 5 mm $\times$ 5 mm $\times$ 1 mm.	125
Figure 50	Measurement setup for switching times and illustration of pull-in time and release time.....	126
Figure 51	Measured switching times of MEMS switches in comparison with calculated values using Equation (50) and Equation (55).	128
Figure 52	Measurement results of Isolation and insertion loss for prototype switch, 8 μm suspension height is used for isolation simulation using HFSS.....	130

Summary

The tremendously fast expansion of wireless and satellite communication systems in the information age is without parallel in history, leading to increase in the demand for miniaturized communication systems with smaller sizes, lighter weights, better functionalities and higher reliabilities. RF MEMS are widely recognized as enabling technologies for the miniaturization due to their promising characteristics of broadband operation, low power consumption and insertion loss, high isolation, and excellent signal linearity. In the past decade, RF MEMS switches are receiving much more attention for communication systems including tuneable matching networks, phase shifters, resonators, and reconfigurable filters. Nevertheless, challenges remain for the RF switches, restricting their applications in many systems. Reliability, packaging, switching speed, and power handling are among the common challenges shared by MEMS switches.

This thesis presents a novel wafer-level encapsulated RF MEMS switch based on a multi-metal contact containing ruthenium and a corrugated $\text{SiO}_2/\text{Si}_3\text{N}_4$ diaphragm. A concept of stacked wafers is proposed to achieve near-hermetic and encapsulated switches, where wafers are processed separately and are subsequently bonded by wafer bonding. A novel multi-layer metal-contact concept, comprising a Cr/Ru/Au/Ru structure, is introduced to improve the contact reliability by having a hard-metal surface of ruthenium without substantial compromise in the contact resistances. The novel contact metallization scheme is proven to be an effective method to increase the contact durability. At a measurement

Summary

current of 1.6 mA, the Ru/Au contacts have an average life-time of about 100 million cycles, whereas the Au/Au contacts reach 24 million cycles only. For larger signal currents, the Ru/Au metal contacts are more robust over the Au/Au contacts by a factor of 10. The total contact resistance of Ru/Au metal contact is 730 m Ω , only 2.5 times as compared to 300 m Ω of soft gold contacts, matching well the theoretical prediction. Furthermore, the corrugations are designed to substantially reduce the influence of the fabrication-induced stress in the membrane, resulting in a highly insensitive design to process parameter variations. The application of corrugations is proven to be an easier way to reduce the residual stress as compared to the approach by process control. The measured pull-in voltage of the MEMS switch is significantly reduced from 105 V for a flat diaphragm (900 μm in radius) to 51 V and 42 V for two-corrugation and four-corrugation diaphragms, respectively, which agree well with the calculation results. For the fabricated DC contact series switches, the measured RF isolation is better than -30 dB up to 4 GHz and still -21 dB at 15 GHz, whereas the insertion loss of the fully packaged switch is about -0.7 dB up to 4 GHz, and -2.8 dB at 15 GHz.

In addition, A DC contact RF MEMS shunt switch, a demonstrator for proof-of-concept, has been designed and fabricated. In contrary to perforating in a moving structure adopted by typical MEMS switch design, the demonstrator employs, for the first time, perforation in the base substrate instead of the diaphragm to reduce the squeeze-film damping, achieving a significant reduction of switching times. The measured pull-in time is greatly reduced from 5.4 ms to 0.435 ms, 12 times in reduction, with the implementation of holes in the base substrate.

Chapter 1 Introduction

The miniaturization of electronic systems towards to a small volume, lightweight, low power consumption, yet more flexibility and better functionality, demands for technologies that can drastically reduce size, weight, manufacturing costs, and improve performance and operation lifetime. Micro-electro-mechanical systems (MEMS) are widely believed to be that technologies which have emerged and grown explosively in the past decades. MEMS are enabling technologies that fabricates the miniaturized mechanical structures and components and integrates them with others driving circuits. The MEMS applications have extended to the area of radio frequency (RF) and microwave systems, enabling wide operational bandwidth, elimination of off-chip passive components, integration with existing integrated circuit (IC) or monolithic microwave integrated circuit (MMIC) with almost ideal micromechanical components such as switches, inductors, resonators, etc., which are produced by micromachining processes.

Novel RF MEMS switches, aiming for high reliability and speed, are developed and presented in this thesis, with the general research background and objectives are dealt with in this chapter. The main contributions from the research and the organization of the thesis are summarized and outlined in the opening chapter as well.

1.1 Background

MEMS switches have been receiving increasing attention in recent years, especially because of their suitability for RF applications in telecommunication, remote sensing, and radar [1], [2], etc. The advantages of MEMS switches over their mechanical and solid state counterparts, the latter including FETs or PIN diode based semiconductor switches, are low insertion loss, low power consumption, high isolation, high linearity, and especially the fact that metal-contact MEMS switches show these high performance criteria over a very large bandwidth from DC up to tens of GHz. Furthermore, due to their fabrication based on highly-developed semiconductor clean-room facilities and logistics, a high level of miniaturization, high volume with potentially low cost fabrication, and a high level of integration with other integrated circuit elements is possible [3, 4]. RF MEMS switch opened up great possibilities for the development of many novel revolutionary RF circuits such as tunable matching networks [5, 6], phase shifters [7, 8], resonators [9, 10], reconfigurable filters and amplifiers [11, 12], and antenna [13].

However, there are also challenges with regard to the performances of MEMS switch. Reliability, packaging, switching speed, and power handling are among the common issues shared by MEMS switches and need to be addressed. Firstly, the reliability of MEMS switch is a major concern for the long term applications, which is affected by many factors including the switch design, encapsulation or packaging of the device, contact material, mechanical properties of microstructures, etc. Secondly, it is necessary to package or encapsulate MEMS switches in a hermetic or near-hermetic environment

filling with inertial gas to enhance the reliability. Exposure to air can cause adverse effects and degrade device performance. Thirdly, switching speed is one limitation of the MEMS switches due to the mechanical movements of moving microstructures. Most of MEMS switches developed so far are only able to operate with switching times from a few tens microseconds to a few hundreds microseconds, while certain communication and radar system require much faster switches. Furthermore, power handling capability is another limitation. Typical RF MEMS switches developed to date are low in power handling (10-100 mW max) [3], which severely restricts the application of RF MEMS switches in many RF circuit or system.

Looking for the solutions to these challenges initiated this project reported in this thesis, focusing on the RF MEMS switches based on wafer-scale encapsulation with corrugated diaphragm, special contact metals containing ruthenium and perforated base substrate to target a significant improvement of device performance.

1.2 Objectives

This project therefore seeks for the development of the reliable and high speed MEMS switch by directing the research efforts towards the novel switch designs which can be realized by micromachining, which aims to achieve the objectives mainly summarized as follows:

- To develop MEMS technologies for reliable and high speed MEMS switch based on a mechanical reliable microstructure, a reliable and robust metal contact, in connection with advanced encapsulation techniques by micromachining.

- To investigate on the reliability of multi-metal contact with hard metal coating, addressing the contact reliability and electric current handling capability.
- To conduct detailed design, analysis, optimization and simulation with regards to the artificially designed corrugated diaphragm for stress reduction, and meticulous designed perforated base substrate for the reduction of squeeze-film damping and thus the switching times.
- To fabricate the MEMS devices with optimized fabrication processes, and characterization of the prototypes with respect to the mechanical and electrical performances.

1.3 Major Contributions

The major contributions have been accomplished as described in the following four aspects:

- A novel wafer-level encapsulated RF MEMS switch based on a corrugated diaphragm and a multilayer metal stack with a ruthenium coating has been developed, aiming for high reliability. A concept of stacked wafers is proposed to achieve near-hermetic and encapsulated switches on wafer level, where wafers are processed separately and are subsequently bonded by polymer wafer bonding. A unique contact metallization of Cr/Ru/Au/Ru is employed in the MEMS switch design to address the contact reliability and current handling capability. The fabricated switches demonstrate an average life time of 7.1 million cycles at a measurement current of 5 mA, which is over ten times as compared to the average life time of 0.66 million cycles by soft gold contacts, much better than the target of 1

million cycles. The total contact resistance of Ru/Au metal contact is 730 m Ω , only 2.5 times as compared to 300 m Ω of soft gold contact, achieving the target of less than 1000 m Ω . Corrugation technique is introduced in the diaphragm which offers an efficacious method to alleviate the high residual stress in the diaphragm and thus reduce the necessary actuation voltage. The measured pull-in voltage of the MEMS switch is significantly reduced from 105 V for a flat diaphragm (900 μ m in radius) to 51 V and 42 V for two-corrugation and four-corrugation diaphragms respectively, which meets the actuation voltage target of 40-60 V. The measured RF isolation for the fabricated DC contact series switches is better than -30 dB up to 4 GHz and still -21 dB at 15 GHz, achieving the target of 20-25dB of isolation at the frequency range from DC to 12 GHz.

- A DC contact RF MEMS shunt switch, a demonstrator for proof-of-concept, has been designed and fabricated. In contrary to perforating in a moving structure adopted by typical MEMS switch design, the demonstrator employs perforation in the base substrate instead of the diaphragm to reduce the squeeze-film damping, achieving a reduction of switching times over ten times.
- Theoretical analysis is carried out to reveal the contact resistance of the novel multi-metal contact at different contact pressures, and the effect of the surface coating thickness on the total contact resistance. Careful design considerations are taken for the proposed MEMS switches, including the artificial corrugation design in diaphragm for stress reduction, and meticulous perforation design in base substrate to reduce squeeze-film damping and thus the switching times.

- Important processes have been explored or optimized, including the generation of slightly positively tapered corrugation by DRIE, deposition of low stress diaphragm films, and flexible wafer bonding with low process temperature which are critical for achieving the specific designed MEMS switches.

1.4 Thesis Outline

This thesis comprises six chapters, where Chapter 3-5 cover the main contributions made by this study. The thesis begins with the introductory chapter, Chapter 1, with a brief introduction of the research background and objectives of the project followed by the summary of the major contributions of the research and the explanation of organization of the thesis.

In Chapter 2, MEMS technology, the fundamentals and basis of RF MMS switches are introduced. Various RF MEMS switches developed previously by industries and universities are reviewed, before our proposals of wafer-level encapsulated RF MEMS switches are presented.

The design considerations in RF MEMS switches are addressed in Chapter 3. The detailed designs are given on the novel multi-metal contact with hard metal coating, the stress-tolerant design by the introduction of corrugation in diaphragm, and RF design. Simulations/calculations are also illustrated on contact resistance, stress reduction ratio and RF performance.

Chapter 4 presents a wafer-level encapsulated RF MEMS switch based on a corrugated diaphragm and multi-metal contact with ruthenium coating. The fabrication processes of the MEMS switch, and the exploration of essential processes are discussed. The mechanical and electrical performances of the fabricated switches are highlighted which include actuation voltages, contact resistance, isolation and insertion losses, etc. The investigation on the contact reliability of the unique ruthenium/gold metallization is also shown in this chapter.

Chapter 5 presents our research work on a RF MEMS shunt switch, a demonstrator for proof-of-concept, using perforation technique in the base substrate to reduce squeeze-film damping. The calculations and simulations of damping coefficients and switching times for the proposed switch with different air gaps and base substrates are provided. The characterization and measurement results on the switching times and RF performance are also stressed in this chapter.

Finally, Chapter 6 concludes the thesis with summary of the research work and achievements which have been accomplished, and recommendations of research topics for future research effort.

Chapter 2 Literature Review

This chapter on the literature review and proposals delivers into three sections. A brief introduction on MEMS technology is given in Section 2.1 followed by the fundamentals and basis of RF MMS switches given in Section 2.2. A review of various RF MEMS switches developed is carried out in Section 2.3.

2.1 MEMS Technology

Micro-electro-mechanical systems (MEMS) are systems with a collection of micro-sensors and actuators based on a range of technologies, which can react to environmental change under microelectronics control and provide excellent system performances. The integration among the micromechanical elements, both sensors and actuators, and the driving or sensing microelectronics is typically through either appropriate packaging or implementation on the same silicon wafer. While the microelectronics are fabricated using integrated circuit (IC) process sequences such as CMOS or bipolar processes, the micromechanical components are fabricated by micromachining processes which selectively etch away parts of silicon wafer or add new structure layers to form the mechanical and electromechanical devices. The advantage of using the micromachining

Chapter 2 Literature Review

processes, which resemble IC process, is not only the implementation of the microstructures, but also the low costs for the fabrication on batch-basis in large volume, and also offers benefits with small size, lower power consumption, higher precision and higher integration level with other electrical elements in semiconductor chips.

MEMS fabrication involves various technologies which can be classified as follows:

- IC fabrication, which includes the conventional techniques of film deposition/growth, doping, lithography, etching, and back-end process and packaging, is used extensively in the MEMS.
- Bulk micromachining is an extension of IC fabrication technology to build mechanical elements which involves extensive real estate consumption. The creation of 3D structure by bulk micromachining normally starts with a silicon wafer, and uses wet-etching or dry-etching technique to remove unwanted parts and left with desired mechanical devices.
- Surface micromachining fabricates devices from a wafer layer-by-layer as compared to the bulk micromachining that creates devices by etching into a wafer. Using the substrate wafer as mechanical support, multiple layers are deposited, patterned and etched to create the moveable and functional microstructures. In this technique, the structural materials form the mechanical elements, and sacrificial materials create the gaps and spaces between the mechanical elements.
- LIGA process is a technology to manufacture 3D microstructures or devices with small sizes and high-aspect-ratios using x-ray lithography. In contrary to the bulk or

surface micromachining, LIGA uses a selective deposition process, such as plating process, to deposit the material at predetermined locations.

MEMS technology can be utilized to produce high quality switches, inductors, varactors, resonators, filters and phase shifters. These micromachined devices integrating with electrical signals up to radio frequency (RF) range are often termed as RF MEMS. Combining the mechanical structures with microelectronics, RF systems or wireless systems can be implemented with various RF MEMS components including oscillators, VCOs (voltage controlled oscillators), mixers, shifters, and filters. The integration of MEMS into high frequency circuits leads to systems with superior performance levels. Compared to traditional RF components, RF MEMS offer significant benefits, including wider bandwidth, lower power consumption and insertion loss, better linearity, lower cost and smaller form factor. With the advent of the RF MEMS technology, the miniaturization of RF circuits with high system integration and low fabrication costs comes to reality for many applications such as wireless communications, radar, satellites, instrumentation and test equipment.

2.2 RF MEMS Switches

A MEMS switch is a miniaturized version of the venerable toggle switch, which uses mechanical moment of a cantilever, an air bridge, or a membrane to achieve a short circuit or an open circuit in a transmission line. A RF MEMS switch refers to the specific micromechanical switch that operates at the frequency of 0.1 to 100GHz. It is connected

to a transmission line with a series or shunt connection, for the purpose to open the line or shunt it to ground upon the actuation of the switch. The condition of switch contact can be either resistive (metal-to-metal) or capacitive (metal-insulator-metal). RF MEMS switches offers benefits including low insertion loss and power consumption, high isolation and integration level with other microelectronic circuits, small size and light weight, excellent linearity, etc. The principles, basis and technologies developed with regards to RF MEMS switches are reviewed in the following sections.

2.2.1 Fundamental of Switching Concept

Series and shunt connections are the two ways to apply SPST (single-pole single-throw) switches¹ in a RF circuit as illustrated in Figure 1, where V_o is the input voltage, Z_0 is the characteristic impedance/resistance of transmission line, Z_L is the load and I_L is the output current flowing through the load. In series connection, the output voltage V_L is zero and $I_L Z_L$ respectively corresponding to the switch-up and switch-down of an ideal SPST switch. When the ideal SPST switches up, the circuit is at off-state and the output voltage is zero. When the ideal SPST switches down, the circuit is at on-state and the output voltage is $I_L Z_L$. While in shunt connection, the output voltage V_L is $I_L Z_L$ and zero respectively corresponding to the switch-up and switch-down of SPST switch. The ideal switch operates between a perfect open circuit and a perfect short circuit.

PIN (p⁺-type intrinsic n⁺-type) diode and FET (field effect transistors) are the two most commonly used switches in RF and microwave regime. However these microelectronic devices are not ideal switches although they have voltage-current relationships that

¹ Single-pole single-throw (SPST) MEMS switches connect or break a single conductor in a single branch circuit.

approximate the ideal switch. The non-idea switch, symbolically represented by a two-terminal impedance Z_d as shown in Figure 1, works between a low impedance state and a high impedance state. The use of Z_d , which is a function of a control bias applied to it, as a switch is based on the impedance difference between low impedance and high impedance. The device is regarded as “electrically short” at low impedance state; and “electrically open” at high impedance state.

Figure 1 SPST switch circuits with ideal switch or non-ideal switching device represented by impedance Z_d . The ideal switch operates between perfect open and perfect short while non-ideal switch works between high impedance and low impedance. (a) Series switch connection, and (b) shunt switch connection

2.2.2 Basic Configuration of RF MEMS Switches

A RF MEMS switch is basically a micro-device fabricated by micromachining, allowing the transmission of a RF signal through a transmission line in the on-state and blocking the electrical signal in the off-state. RF MEMS switches offer a superior performance than their solid state counterparts including PIN diode switches or FET switches as mentioned above. A comparison among RF MEMS switches, PIN diode switches and FET switches are tabulated in Table 1 [14, 15].

Parameter	PIN	FET	RF MEMS
Actuation voltage (V)	±3-5	3-5	20-80
Actuation current (mA)	3-20	0	0
Power consumption (mW)	5-100	0.05-0.1	0.05-0.1
Switch time	1-100ns	1-100ns	1-300µs
Series capacitance at up-position (fF)	40-80	70-140	1-6
On-state series resistance (Ω)	2-4	4-6	0.5-2
Cut-off frequency (THz)	1-4	0.5-2	20-80
Isolation in off-state	Medium	Low	High
Insertion loss at on-state (dB)	0.7-2	>2	0.1-0.2
Power handling (W)	<10	<10	<1
Third-order intercept point (dBm)	+27-45	+27-45	+66-80

Table 1 Comparison of switch performances based on PIN Diode, FET and RF MEMS [14, 15]

A RF MEMS switch typically is driven by an actuation voltage of 20-80 V and consumes near zero actuation current, leading to a very low power dissipation of 0.05-0.1 mW.

Typically a RF MEMS switch has much smaller series capacitance of 1-6 fF and series contact resistance of 0.5-2 Ω , due to its microstructure fabricated with air gap and a low resistive switch-contact respectively, resulting in excellent cut-off frequency, a higher isolation and lower insertion loss. In addition, MEMS switch displays excellent linearity as compared to the other twos. In principle, a RF MEMS switch comprises two distinct parts: an electrical portion and a mechanical or actuation portion. The electrical portion provides transmission line system for RF signal while the mechanical portion activates moveable microstructure. Any RF switch is the combination of the two portions with necessary supplementary, such as electrodes, power supply.

The movable microstructure is inserted into the electrical portion in either series connection or shunt connection, with metal-to-metal contact or metal-inductor-metal contact. The transmission line is implemented in microstrip configuration or coplanar waveguide (CPW) configuration. For a series connection, a line-gap is designed in the transmission line in order for a high isolation in the off-state. The microstructure of the mechanical portion can move laterally, vertically, or torsionally, depends on the design, which is driven by the actuation using electrostatic, magnetostatic, piezoelectric, or thermal scheme, as described detailed in Section 2.2.4.

2.2.3 Types of RF MEMS Switches

RF MEMS switches can be classified into several categories based on circuit connection, switch contact, moving structure, actuation scheme, as summarized in Table 2. From the

circuit configuration point of view, the majority of RF MEMS switches developed so far fall into the two common switch types described as follows.

	Based on circuit configuration
Series connection	Either metal-to-metal or metal-inductor-metal used
Shunt connection	Either metal-to-metal or metal-inductor-metal used
	Based on switch contact
Metal-to-metal	Switching signal from DC to a few tens of GHz
Metal-inductor-metal	Typically working at frequencies > 6 GHz
	Based on moving structure
Cantilever	Small size; sensitivity to thermal stress, vibration and shocks
Bridge	Microstructure with two ends clamped, small size possible
Membrane	Large size of membrane and electrode, low actuation voltage possible
	Based on actuation scheme
Electrostatic	Low power, simplicity and possible small electrode size, fast speed, low costs to implement.
Thermal	Low cost, VLSI compatible, high power, low working frequency
Piezoelectric	High force and low power, polarization needed, relatively small displacement
Electromagnetic	Low voltage, large force and deflection, limited magnetic materials

	Based on movement
Lateral	Area-consuming, poor yield and reliability for contact
Vertical	Most common design
Torsional	Push-pull concept with low actuation voltage possible, large contact distance

Table 2 Categories of RF MEMS switches on circuit connection, switch contact, moving structure, actuation scheme

Series MEMS Switch

A series MEMS switch is shown in Figure 2 (a). A MEMS air-bridge is suspended above the coplanar waveguide (CPW). The bridge is isolated to grounds of CPW by insulation layers. A contact metal is attached beneath the bridge for contact usage. The center signal trace is discontinuous with a gap between the two transmission lines. It should be noted that electrostatic actuation scheme is adopted here. When a DC voltage is applied across the electrodes (the top electrodes and ground planes as shown in Figure 2a), charges are induced on the electrode-metal which tends to attract the electrodes. Above certain threshold voltage, the attraction force is sufficient to overcome mechanical stresses in the bridge, and the suspended air-bridge collapses down towards the bottom electrodes (ground planes) and contacts the center conductor, connecting the two separated transmission lines and leading to the “on” state, refer to “Switch-down” in Figure 2 (b). When the DC potential is removed / released, the bride returns back to the original position by its restoring force, achieving “off state”, refer to “Switch-up” as illustrated in Figure 2 (b).

Figure 2 MEMS series switch and its equivalent circuits. (a) Schematic view of a MEMS switch with bridge microstructure. (b) Cross section views and equivalent circuits of switch-up state and switch-down state

The series switch is placed in series between the transmission lines, which basically, essentially switches between two impedance states. The equivalent circuit for series MEMS switch is also shown in Figure 2, where R_{off} is the off resistance while R_{on} is the on resistance. R_{off} is very large before the switch is actuated, making an open circuit in the transmission lines. When the switch is actuated by applying a bias voltage above threshold across the electrodes, the switch is closed due to a very small resistance of R_{on} , throwing a series resistor between the transmissions lines. As a result, RF signal

propagates freely through the transmission lines. MEMS series switches have extremely large isolation in the off-state and almost zero insertion loss in the on-state. Most of MEMS series switches are based on DC contact (metal-to-metal contact), and can find widely applications for frequency range from DC to 40GHz.

Shunt MEMS Switch

A MEMS shunt capacitive switch is shown in Figure 3. It is similar to the MEMS series switch described above, except that a dielectric layer is deposited over a continuous transmission line and the air-bridge is made of metal, serving as an electrode as well. The shunt switch is placed in shunt between the transmission line and ground. Basically the shunt switch switches between two capacitance states, as illustrated by the equivalent circuits in Figure 3 (b), where C_{on} is the on capacitance when the air-bridge is at up position while C_{off} is the off capacitance when the bridge is at down position.

Before the switch is actuated, the air-bridge is suspended above the CPW and the switch is in the on-state. The ON-capacitance (C_{on}) is very small, allowing RF signal to propagate freely through the transmission line, refer to “Switch-up” in Figure 3 (b). It should be mentioned that electrostatic actuation scheme is also used by the switch. When a DC voltage is applied between the bridge and the center line, the induced electrostatic force exerts to the bridge. Above certain threshold voltage, the bridge snaps down due to the electrostatic attraction force, throwing a shunt capacitor across the transmission line and leading to the “closed” or off-state as shown as “Switch-down” in Figure 3 (b). The

OFF-capacitance” (C_{off}) is much larger compared to C_{on} , which is an effective short circuit to ground at RF frequencies. MEMS shunt switch has almost zero insertion loss in the on-state (switch-up position) and extremely high isolation in the off-state (switch-down position). Generally MEMS shunt capacitive switches are more suitable for higher frequencies (5-100 GHz).

Figure 3 MEMS shunt switch and its equivalent circuits. (a) Schematic view of a MEMS shunt switch with bridge microstructure, and (b) cross section views and equivalent circuits of switch in two states

2.2.4 Actuation Scheme of RF MEMS Switches

Many actuation schemes have been proposed for MEMS switch applications, including thermal, electromagnetic, magnetostatic, piezoelectric, and electrostatic actuation. The main concerns with regards to the actuation are the attainable force and displacement, power consumption, reliability and ease of fabrication. Electrostatic, thermal and magnetostatic switches have been demonstrated a high reliability and wafer-scale manufacturing techniques.

Thermal Actuation

Thermal actuation is widely used for actuating the micro-structures such as cantilever, bridge, and membrane, or even heating fluid/gas in MEMS devices. The actuation relies upon stress generated by thermal mismatch and utilizes the property of thermal expansion to produce motion. When a current is applied across the actuator, it heats up the materials, causing thermal expansions. The strain (ε) developed from low temperature (T_0) to elevated temperature (T_1) due to the thermal mismatch is expressed by,

$$\varepsilon = (\alpha_A - \alpha_B)(T_0 - T_1) = (\alpha_A - \alpha_B)\Delta T \quad (1)$$

where α_A and α_B are coefficients of thermal expansion of material A and B respectively. Typically there is no deflection in the actuator at T_0 . However the thermal strain deforms or deflects the actuator at an elevated temperature of T_1 , if the heated actuator is not constrained and has certain degrees of freedom to expand.

Thermal actuation can be used for MEMS switch, where thermal expansion takes place when a current flowing through resistors embedded in the mechanically moving microstructure. The actuation scheme is able to provide the necessary force and displacement with appropriate designs. The thermal actuation has advantages of cheap implementation, VLSI compatible, and well established technology. However, this actuation scheme is not a favorite one for our design. Besides the possible high power consumption, the main concern of thermal actuation is the relatively low working frequency since the actuation speed is related to the speed at which the actuation part can be heated and then dissipated its heat to return back to its original position.

Piezoelectric Actuation

Piezoelectric actuation depends on piezoelectric crystals, which generate deformation of crystal in response to an applied voltage, and vice versa, produce electrical charge separation in response to an applied mechanical stress.

Piezoelectric actuation is also one of the most widely used actuation mechanisms in MEMS. It has advantages of high mechanical force and low power consumption. However the piezoelectric actuation needs correct microstructure, composition, crystallographic texture, and polarization or poling for maximum material performance and response. The actuation must work under Curie temperature (T_c) to avoid a minimal piezoelectric effect due to that the dipole directions are randomized out. In addition, the displacements are relative small unless an actuator with large physical size or stacked actuator is put into use. The former choice defeats the goal of miniaturization of MEMS

device while the later choice can be difficult to implement in MEMS. As such, piezoelectric actuation is not an ideal actuation scheme mainly due to its limitation in displacement without using an actuator with large size or stacked structure.

Electromagnetic Actuation

Electromagnetic actuation is one of the most familiar actuator mechanism used in macroscopic scale devices, and is common in micromachined devices as well. The conventional magnetic actuator usually utilizes current-carrying coils to generate magnetic flux which is captured and guided to a movable plate, inducing the magnetic force in a magnetic material to actuate the movable plate, refer to Figure 4. The magnetic force (F_{mag}) generated in the air gap can be expressed according to Maxwell's equations [16],

$$F_{mag} = \frac{1}{2\mu_0 A_{gap}} \left(\frac{ni}{\phi_{m,core} + \phi_{m,gap}} \right)^2 \quad (2)$$

where μ_0 is the magnetic permeability of free space, A_{gap} is cross-section area, n is the number of coil turns carrying a current of i , ϕ_m is the magnetic reluctance which is given by

$$\phi_m = \phi_{m,gap} + \phi_{m,core} = \frac{l_{gap}}{\mu_{gap} A_{gap}} + \frac{l_{core}}{\mu_{core} A_{core}} \quad (3)$$

where l is the length. It is obvious that high coil-current (i) and low magnetic reluctance (ϕ_m) promote a large magnetic actuation force in the actuator. In order to minimize magnetic reluctance, it requires a high magnetic permeability material in the actuator

design. Otherwise, the actuator is inefficient to provide necessary gap force and consumes large coil power. The reason is that the reluctance (ϕ_m) will be dominated by the magnetic material ($\phi_{m, core}$) rather than the air gap ($\phi_{m, gap}$) if the actuator is fabricated using low magnetic permeability material, resulting in a very small closing force at the air gap since magnetic energy stored inside the air gap becomes negligible in this case.

Figure 4 Illustration of magnetic micro-actuator

The advantages of electromagnetic actuation are relatively low actuation voltage and the ability to produce large force which allows for large deflection. Whereas, a common problem with magnetic actuator is that the coils are typically two-dimensional and limited in three-dimensional due to the difficulty of fabrication. The choice of magnetic materials is limited as well, which are not always optimum and thus are prone to rather high power consumption and heat dissipation.

Magnetostrictive Actuation

Magnetostrictive actuation relies on magnetization of a ferromagnetic material. The magnetization is accompanied by changes in dimensions of the ferromagnetic material,

which is in a direction parallel to the magnetic field and is independent of the direction of that field. This actuation has advantages of high mechanical force and remote actuation. It can also achieve high frequency contact actuation. However this actuation scheme has the common issues shared by electromagnetic actuation, including the necessary of correct crystallographic texture (electrodes) and pooling for maximum response; limited application temperature due to the curie temperature; and hysteretic characteristics.

Electrostatic Actuation

Electromagnetic actuation is the most commonly used actuation scheme for MEMS device. The electrodes of typical MEMS device can be treated as two parallel plates as shown Figure 5 , where a moveable electrode is used to actuate the microstructure such as a cantilever, bridge or membrane and it is limited to small motion as compared to the sizes of the electrodes.

Figure 5 Illustration of parallel plate of electrodes used for typical MEMS devices

Chapter 2 Literature Review

The capacitance between the parallel plates can be expressed as $C = \varepsilon_0 A / (g_0 - z)$. Here ε_0 is the vacuum permittivity, A is the area of the electrode, and g_0 is the initial gap between the two electrodes without applying an actuation voltage. When an electric field is excited between two parallel plates by applying voltage (V) across them, an induced attractive electrostatic force (F_e) will act on both plates to pull the moveable electrode towards the fixed electrode, increasing the capacitance between the electrodes and thus increasing the stored energy W as well. The work done (dW) in the moving electrode by the electrostatic force (F_e) driven by the voltage is expressed as

$$dW = \frac{V^2}{2} dC = F_{el} dz \quad (4)$$

where dC and dz are the changes in capacitance and distance, respectively. Therefore the electrostatic force is given by

$$F_{el} = \frac{1}{2} \frac{dC}{dz} V^2 = \frac{1}{2} \frac{\varepsilon_0 A V^2}{(g_0 - z)^2} \quad (5)$$

It is clear that F_e is linearly proportional to the plate area but inversely dependent on the separation square between the two plates. This implies that the electrostatic force increases significantly as the plates with large area get closer to each other.

On the other hand, when the electrostatic force F_{el} exerts on the moveable electrode, a mechanical force F_{me} is induced on the electrode as well to balance the F_{el} . Here the mechanical force is expressed by $F_{me} = kz$, where k is the spring constant of the moveable electrode. Considering a balance between the electrical and mechanical force

$$F_{el} = F_{me} \quad (6)$$

$$\frac{\epsilon_0 A V^2}{2(g_0 - z)^2} + kz = 0 \quad (7)$$

Therefore,

$$V(z) = \sqrt{\frac{2(g_0 - z)^2 zk}{\epsilon_0 A}} \quad (8)$$

When z is $g_0/3$, the function reaches the maximum, the voltage at this point is called pull-in voltage

$$V_{pi} = \sqrt{\frac{8k}{27\epsilon_0 A} g_0^3} \quad (9)$$

Although electrostatic actuation requires, in many cases, a relative high actuation voltage of 30-80V this actuation scheme remains the most prevalent technique in use today due to its virtually near zero power consumption, general simplicity, possible small electrode size, and relative low costs to implement. To date, only electrostatic actuated switches have demonstrated operations for a frequency band of DC-100 GHz with high reliability of 100 million to 10 billion cycles [14].

2.3 Review of RF MEMS Switch Developed

The first MEMS switch was presented by Petersen in 1979 [17] which used a thin moveable cantilever beam for the switching of low frequency electrical signals by electrostatic actuation. After that, research in MEMS switches continued and expanded in microwave area as well. In 1990-1991, Hughes Research Laboratories in Malibu, USA,

developed the first RF MEMS switch which exhibited very low insertion loss of -0.4 dB and high isolation of -35 dB across a frequency band of 2-45 GHz [18]. The RF performance of the MEMS switch was better than those of PIN diodes or FETs, despite its poor yield and reliability. Since then, many MEMS switches been developed by industry, university and government laboratories, and also demonstrated superior performances at microwave frequencies. Over the past decade, a variety MEMS switches have been publication with renovated concepts and interesting design features. Some masterpieces among them will be reviewed, in the following sections, on the design features, fabrication process, characteristics and performance.

2.3.1 Series MEMS Switch Developed

In 1995, Rockwell Science Center demonstrated a metal-to-metal contact MEMS switch employing a $2\text{ }\mu\text{m}$ thick PECVD silicon oxide cantilever arm which was electrostatic actuated and fabricated on a semi-insulating GaAs substrate using polyimide as the sacrificial material [19]. With $3\text{ }\mu\text{m}$ suspension height of the cantilever at up-position, the switch had a good isolation of -50 dB at 4 GHz. By adopting a $1\text{ }\mu\text{m}$ thick gold contact with a contact area of $400\text{ }\mu\text{m}^2$, the switch achieved an insertion loss of -0.1 dB at 4 GHz with a pull-in voltage of 28V. In addition, the low process temperature of less than 250°C enabled the monolithic integration of the switch with other RF integrated circuits. The switch underwent two different design iterations afterward, and in 2001, a “clam-shell” design as shown in Figure 6 was published [20], which consisted of two pull-in electrodes on each side on the contact area. The switch membrane was composed of a 2

μm PECVD silicon oxide and suspended with a height of $2.5\ \mu\text{m}$ above the substrate, being connected to the substrate on four anchors through a folded spring structure. Furthermore, damping holes with size of $6\ \mu\text{m} \times 6\ \mu\text{m}$ were etched in the membrane for the purpose of reducing the squeeze-film damping. The top electrodes, which were generated using a $2.5\ \mu\text{m}$ thick evaporated aluminium layer over the silicon oxide membrane, had a size of $75\ \mu\text{m} \times 75\ \mu\text{m}$, resulting in a pull-in voltage of 50-60 V. A $1\ \mu\text{m}$ thick evaporated gold film was used as contact metal. The contact areas were made of two pairs of contact “points”, with a dimension of $3\ \mu\text{m} \times 3\ \mu\text{m}$ on each contact area. The small contact “points” were adopted to reduce the stiction of gold and increase the contact pressure, leading to about $1\ \Omega$ of effective contact resistance. The MEMS switch developed by the Rockwell Science Center provided excellent RF performance over a broad frequency band with an insertion loss of $-0.1\ \text{dB}$ and an isolation of $-30\ \text{dB}$ at 40 GHz.

Figure 6 SEM photo of the Rockwell Scientific MEMS series switch with PECVD silicon oxide membrane, two pull-in electrodes and gold-to-gold contact [20]

Hughes Research Laboratories developed an electrostatic actuated series MEMS switch in 1998-2000 [21, 22]. The switch utilized a flexible bimorph cantilever, made of 2 μm thick PECVD silicon nitride cantilever and a 2.2-2.5 μm plated gold layer, which was suspended 1.5-2.0 μm above the transmission line implemented onto a GaAs substrate. Gold contact with a size of 20 $\mu\text{m} \times 20 \mu\text{m}$ was arranged on each side of the switch, resulting in a total switch resistance of 1-1.5 Ω . The measured insertion loss was -0.1 to -0.15 dB at 1-40 GHz, and the isolation was -45 dB at 4 GHz, and -25 dB at 40 GHz.

The Northeastern University, Boston, USA, and Analog devices presented in 1996 a four-terminal MEMS series switch fabricated on a silicon substrate, with an electroplated nickel cantilever suspended above gate and drain electrodes. The switch with gold-to-gold contact exhibited an initial contact resistance less than 50 m Ω , and was able to operate more than 10⁹ cycles before failure [23]. Three years later in 1999, they published a modified design using a 75 μm long, 30 μm wide and 7-9 μm thick electroplated gold cantilever suspended with a height of 0.6-1.2 μm over the pull-in electrode, leading to a very stiff structure with the spring constant of more than 100 N/m and a mechanical resonant frequency of 1-2 MHz, refer to Figure 7 [24]. The contact metal used for this design was Pt alloy. Two contacts were utilized, with a size of 5 μm^2 for each contact, for the purpose of small overall contact resistance which was measured to be 1-1.5 Ω , indicating a low insertion loss of -0.15 dB for 0.1-20 GHz band. Although the cantilever tip was only 0.4-0.6 μm away from the transmission line, the switch still achieved a good isolation of -40 dB at 4 GHz and around -27 dB at 20 GHz.

Figure 7 SEM photos of inline DC-contact MEMS switch developed by the Northeastern University and Analog Devices [24]. (a) Close-up view of switch contact. (b) Overall view of the switch

Researchers at Lincoln Laboratories developed in 1999-2000 a compact in-line switch based on a curled cantilever arm with 200-nm SiO₂/500-nm Al/200-nmSiO₂ sandwich structure, resulting in a 10-15 μm of separation distance at up-position, as shown in Figure 8 [25]. Further, the corrugations were introduced in the cantilever to adjust the stiffness of cantilever arm and to avoid curling in its width direction. The pull-in electrode was in RF path, directly beneath the cantilever. Both resistive and capacitive switches were developed. The DC-contact switch used platinum (Pt)-to-platinum contact, refer to Figure 8 (b), achieving the contact resistance of less than 1 Ω and the insertion loss of -0.1 to -0.2 dB up to 40 GHz in the closed position. The capacitive switch, refer to Figure 8 (b), had a capacitance ratio of 150-250 and S₂₁ less than -0.7 dB across the 5-40 GHz band.

Figure 8 The compact in-line switch based on curled cantilever arm developed by Lincoln Laboratories [25]. (a) SEM photography of the switch at up-position. (b) Cross-sectional view of DC-contact and capacitive switches

Also in 2000, The Massachusetts Institute of Technology published a MEMS power switch, applying stacked wafer structure with a clamped circular LPCVD silicon nitride diaphragm as the moving structure, which was actuated by electrostatic actuation (20 V) or by pneumatic actuation (1200 Pa) as a secondary means, or through the combination of the two actuation mechanisms. The prototype switch was able to handle current of 400 mA with a contact resistance as low as 14 m Ω .

DaimlerChrysler Research Center, Germany, developed a toggle switch as shown in Figure 9 which relies on a push-pull mechanism in 2002-2005 [26], [27], [28]. The switch was in series configuration with double anchors and two fixed electrodes: top and bottom electrode. A 0.75-1 μm thick aluminum or gold membrane, placed between two electrodes, was fixed at both ends and could be move to either the top or the bottom

electrode under the actuation. The beauty of the switching membrane with two electrodes is the much reduced possibility of self-closing due to high RF power. The distance between lower and upper electrodes was 6 μm , and the distance between membrane and electrodes was 3 μm . The fabricated switch had 10-16 V of switching voltages and exhibited low insertion loss of -0.4 to -0.85 dB for 30 GHz with good isolation of more -15 to -22 dB up to 30 GHz.

Figure 9 Toggle-switch using a push-pull concept [26]. (a) Schematic view of the switch.
(b) SEM photo of the fabricated switch

In 2004, The Royal Institute of Technology, Stockholm, Sweden, published a series MEMS switch based on S-Shaped film actuator as illustrated in to Figure 10 [29, 30]. The switch design also applied double electrode concept and used a 1 μm thick silicon nitride membrane together with switch contact as the core switch element which rolled between the top and the bottom electrodes in electrostatic touch-mode actuation, refer to

Figure 10 (b). The switch was fabricated by two wafers, with mechanical moving (MEMS) part of the switch on the top glass wafer and RF transmission line and polymer seal-ring on the bottom silicon wafer as shown Figure 10 (a). Gold-to-gold contact was used, achieving a resistance of 275 m Ω of each contact at an estimated contact force of 102 μ N at an actuation voltage of 12 V. The closing voltage of the prototype switch was 15.8 V, which enabled the membrane to return to its off-position, 14.2 μ m of contact distance, with a good isolation of -45 dB up to 2 GHz and -30 dB at 15 GHz.

Figure 10 Series switch based on S-shaped membrane actuator. The switch was fabricated with two separated wafers bonded together through a polymer seal-ring [30].

In 2007, The University of Michigan, Ann Arbor, USA published a RF MEMS switch with a special metal contact design employing ball grid array (BGA) dimples to overcome the issue of contact adhesion and arcing especially for the pure gold-to-gold

contact. The used of ball grid array dimples across the gold-to-gold interface limited the effective contact area to a few tens of nanometers in diameter, demonstrating fast switching speed in microseconds, RF power handling more than 1 W and achieving hot switching in excess of 100 million cycles [31].

2.3.2 Shunt MEMS Switch Developed

In 1996, Texas Instrument developed the first practical MEMS capacitive shunt switch as shown in Figure 11 [32, 33], also known as Raytheon shunt switch. The switch was based on a fixed-fixed 0.3-0.5 μm thick aluminum membrane suspended across polymer posts, residing around 4 μm above the transmission line on the substrate. The switch applied a centre pull-in electrode and used a 100 nm thick silicon nitride layer to isolate metal membrane from the pull-in electrode, achieving an on-off capacitance ratio of 40-110 with a pull-in voltage of 30-60V. A set of 3-6 μm^2 holes was etched in the membrane to get a mechanical Q of 1 to 2. Raytheon switch typically had has a resonant frequency of around 100 kHz and a switching times of about 3-8 μs . In addition, the isolation of the shunt switch is -20 dB at 10 GHz, and an insertion loss of -0.3 to -0.5dB at 10 GHz which is nearly equal to the loss of the transmission line.

Figure 11 Raytheon MEMS capacitive shunt switches [33]

A MEMS capacitive switch, with a microactuator curled due to the residual stress difference in its bimorph structure as shown in Figure 12 [34], was developed and published in 2000 by The National Taiwan University. The micro-actuator structure was composed of several cantilevers connected in series, and was designed to be two-sectional: the straight-beam section was made of 0.5 μm thick aluminium (Al) layer while the curve-section was made of a 0.1 μm thick chromium (Cr) film on top of a the aluminium film. The curvature of the curve-section depends on the film thickness ration of Cr/Al and the location of the Cr film. Under the actuation voltage of 26-30 V which was applied between the cantilevers and the bottom electrode, the cantilevers was snapped down in cascading manner onto the substrate. Furthermore, the switch was fabricated on a GaAs substrate which is capable of monolithic integration with MMIC because of the low temperature process (250 $^{\circ}\text{C}$). The fabricated MEMS switch achieved an insertion loss of -0.2 dB and an isolation loss of -17dB at 10 GHz, respectively.

Figure 12 A capacitive MEMS switch developed by The National Taiwan University [34].
 (a) The side-view of the switch at “curve-up” position. (b) The top view of the switch at the “down” state

In 1998, The University of Michigan, Ann Arbor, USA presented a capacitive switch based on a low spring-constant membrane, refer to Figure 13 (a) [35]. A $2\mu\text{m}$ thick, electroplated gold membrane was attached using a serpentine springs to anchors. The membrane of such design is compliant due to its low spring constant of 1-3 N/m, resulting in relative low pull-in voltage of 8-15 V. A pull-up electrode was also used in this design, which was $2\mu\text{m}$ above the movable membrane, to prevent its undesired movement and to fix the membrane in the up-position when the switch was not being activated. The switch demonstrated an isolation of about -30 dB up to 40 GHz and an insertion loss of -0.2 dB at 20 GHz.

An inline capacitive shunt switch [36], as shown in Figure 13 (b), was also developed in 2001 by The University of Michigan. The switch was similar to the Raytheon switch. A $0.8\text{ }\mu\text{m}$ thick gold bridge, suspended at a height of $1.7\text{--}2.2\text{ }\mu\text{m}$ above a nitride layer at the centre portion of the switch, was anchored to the centre conductor, while the bottom electrode was attached to the grounds of CPW. The necessary pull-in voltage for the bridge was $25\text{--}30\text{ V}$. Although the capacitance ratio was only $30\text{--}40$, excellent isolation was able to be obtained with this design.

Figure 13 Capacitive MEMS switches developed by University of Michigan [35-37]: (a) The K-band capacitive MEMS switch with low spring-constant membrane; (b) The inline capacitive shunt switch; and (c) The DC-contact shunt switch

Also in 2002, The University of Michigan published on DC-contact shunt switch used for $0.1\text{--}20\text{ GHz}$ operation [37]. The metal-to-metal contact MEMS switch was built by removing the dielectric layer, which is used by typical MEMS shunt switch, in the center part of the switch as shown in Figure 13 (c). The switch was composed a $0.8\text{ }\mu\text{m}$ thick

gold bridge fixed at two ends with two pull-in electrodes and a centre DC-contact area. The contact metal was gold-to-gold with a $40\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$ dimple used at each of the contact areas, leading to a contact resistance of $0.6\text{--}1.0\text{ }\Omega$ per dimple. The performance of a dc-contact shunt switch was an isolation of -30 dB at $0.1\text{--}5\text{ GHz}$ and -20 dB at 20 GHz . In 2005, researchers at National Institute of Advanced Industrial Science and Technology, Japan, and at Tokyo University, Japan, published an electrostatic actuated MEMS shunt switch with a $1\text{ }\mu\text{m}$ thick gold bridge suspended over 100-nm PZT/ 2.5-nm HfO_2 multilayer dielectric which was deposited on a bottom gold electrode [38]. The multilayer dielectric, fabricated by the combination of sputtered PZT and sol-gel coated HfO_2 , is distinct from the typical Si_3N_4 due to a high equivalent dielectric constant of $79\text{--}82$ and a low leakage current of $1.58 \times 10^{-6}\text{ A/cm}^2$. The RF performance of a fabricated π -match switch achieved an insertion loss less than -0.5 dB from 50 MHz to 20 GHz , and an high isolation of -30 to -65 dB up to 57 GHz .

In 2006, Ajou University of Korea and Tohoku University of Japan published a RF MEMS shunt switch with corrugated bridge [39] in order to reduce stress of membrane and thus to achieve a low actuation voltage necessary to drive the movable air-bridge structure. The shunt switch consists of an electrostatic actuated thin Ni bridge with a length of $300\text{ }\mu\text{m}$, width of $100\text{ }\mu\text{m}$ and thickness of $0.3\text{--}1.0\text{ }\mu\text{m}$. Corrugations were introduced at both ends the bridge, achieving lower actuation voltage of $20\text{--}80\text{ V}$ for the corrugated bridge of the concave structure as compared to $50\text{--}100\text{ V}$ for the plat bridge of the planar structure.

Chapter 2 Literature Review

Table 3 below shows a comparison of switch performances among the MEMS switches reviewed, in terms of actuation voltage, contact resistance, isolation, insertion loss, and switching time.

Switch	Actuation Voltage (V)	Contact Resist. (Ω)	Insertion & Isolation (dB)	Switch Time (μ s)
Rockwell series [20]	50-60	0.8-2	Iso.: -30(40GHz) Ins.: -0.1(50GHz)	
Hughes series [21,22]	40-60	1-2	Iso.: -44(2-4GHz) Ins.: -0.15(0.1-6GHz)	2-4
Analog Devices series [24]	60-80	1-1.5	Iso.: -27(20GHz) Ins.: -0.15(0.1-20GHz)	2-3
Lincoln Laboratories series [25]	30-80	1-2	Iso.: -22(30GHz) Ins: -0.2(40GHz)	1-20
DaimlerChrysler series [26].	10-16	/	Iso.: -15-22(30GHz) Ins: -0.85(30GHz)	/
KTH series [30]	12-16	0.275	Iso.: -30(15GHz)	/
Raytheon shunt [33]	30-50	0.25-0.35	Iso.: -35(30GHz) Ins: -0.07(10-40GHz)	3-5
National Taiwan Univ. shunt [34]	8-15	/	Iso.: -30(40GHz) Ins: -0.2(20GHz)	/
University of Michigan shunt [36]	35	0.15-0.35	Iso.: -20(40GHz) Ins: -0.2(20GHz)	/
NIAIST shunt [38]	/	/	Iso.: -30(57GHz) Ins: -0.5(20MHz- 20GHz)	/

Table 3 Comparison of performances of MEMS switches reviewed.

Chapter 3 Design Considerations in RF MEMS Switches

In this chapter, the design considerations in RF MEMS switches will be described, which cover the proposed mechanical structure of switches with wafer-level encapsulation shown in Section 3.1, a novel multi-metal contact with hard metal coating to address the contact reliability and current handling capability given in Section 3.2, and the stress-tolerant design by the introduction of corrugation in diaphragm described in Section 3.3. Also, the RF design and the simulation of RF performance for the proposed switch will be discussed in Section 3.4.

3.1 Mechanical Structure of MEMS Switches with Wafer-level Encapsulation

First of all, packaging is an important aspect for MEMS switches with metal-to-metal contacts. Exposure to air is an issue in terms of reliability and lifetime of the devices. Dust entrapment or contamination can cause adverse effects to metal contacts and degrade device performances. Therefore, there is need to address the encapsulation of such type of MEMS switch, especially for the metal contact part. As a solution to the challenge, this thesis proposes a microstructure employing stacked-wafer concept as shown in Figure 14, to achieve the wafer-level encapsulation. The fabrication of MEMS

Chapter 3 Design Considerations in RF MEMS Switches

switches involves two wafers bonded together using polymer seal ring through wafer bonding process, during which a micro-chamber filled with inertial gas was created to accommodate switch contacts, refer to Figure 14 (a). The encapsulation of the switch contact at an early stage in the fabrication, as proposed here, allows for the protection of switch contact against contamination, and also an ease handling for the subsequent process steps. It should be mentioned that the metal-to-metal contact switch is selected in the design since this type of switches can operate well for a large frequency band from DC to many tens of GHz with near-ideal signal switching behavior.

Secondly, the core of the switch is a thin and flexible silicon nitride diaphragm generated from the top silicon wafer, which is also a part of the encapsulated micro-chamber formed between the diaphragm and the base substrate. The diaphragm is an out-of-plane movable microstructure driven by electrostatic force. A completely clamped diaphragm, even if millimeter-sized, is very stiff and would require large actuation voltage. Therefore, in order to reduce the stiffness and the possible high residual stress in the film, the diaphragm of the proposed switch design is endowed with specially designed corrugations, as illustrated in Figure 14 (b), which provides an effective means to reduce the actuation voltage necessary to drive the movable diaphragm. Noted that the electrostatic actuation scheme is selected in the switch design due to its very low power consumption, generally simplicity, ease of implementation, and relatively short response time.

Chapter 3 Design Considerations in RF MEMS Switches

Figure 14 Proposed wafer-level encapsulated MEMS switch based on multilayer contact metallization with corrugated diaphragm. (a) Encapsulation with stacked-wafer. (b) Corrugated diaphragm with multilayer contact is part of the encapsulated micro-chamber. (c) Three-dimensional drawing of the switch

Thirdly, the reliability of metal-to-metal contact MEMS switch is strongly related to the contact materials used which is still an issue of ongoing investigations, because the contact/opening force profile of microactuators is different from macroscopic relays. Soft metals such as gold and gold alloys offer low contact resistance even at low contact

Chapter 3 Design Considerations in RF MEMS Switches

forces but suffer limited life time because of increased contact wear [40]. Furthermore, they need large opening forces to overcome the large adhesion force between closed soft-metal contacts, which is especially difficult to be achieved in conventional switch designs with deflected cantilever/membrane structures characterized by active closing but passive opening [41]. This thesis introduces a new concept of contact-metallization as shown in Figure 2-14 (b), utilizing a 50-nm chromium/50-nm ruthenium/500-nm gold/50-nm ruthenium (Cr/Ru/Au/Ru) multilayer stack which is designed to address contact reliability issues by having a hard contact surface but still keeping the total contact resistance in the same order as gold alloy contacts.

Figure 15 Proposed approach to reduce the damping of the squeeze-film by perforating the base substrate and adding a back-plate with a cavity

Furthermore, switching speed of MEMS switch still remains one of the limitations of MEMS switches due to their mechanical movements of moving parts. A method for increasing switching speed is to perforate the moving part, such as bridge or diaphragm, in order for reducing the damping due to the air flow in a narrow air gap. Contrary to perforating in bridge/diaphragm adopted by typical MEMS switch design [42, 43], the approach proposed in this thesis to reduce the damping of the squeeze-film applies perforation in the base substrate instead of the diaphragm due to the fact that the diaphragm is part of the encapsulated micro-chamber. As shown in Figure 15, the based substrate is perforated and another wafer, the back plate with a cavity generated inside, is added in this switch design.

3.2 Switch Contact for High Reliability

RF MEMS switches can be categorized by contact method and fall into two categories: metal-insulator-metal (the typical capacitive switches) and metal-to-metal (the typical resistive switches). Metal-to-metal switches, normally inserted into an electrical circuit in a series-configuration, utilize physical direct contact of metals and can thus be operated from DC to microwave frequencies. Such metal-contact MEMS switches are typically based on a cantilever, an air-bridge or a membrane movable by a micromachined actuator to establish and to break the metal-metal contact. A drawback with regards to metal-contact switches is that they are susceptible for contact stiction if the restoring forces are low.

Chapter 3 Design Considerations in RF MEMS Switches

Moreover, typical metal-contact switches are suitable for hot-switching² only for low-power signals with currents of up to a few tens of milliamperes, primarily due to contact surface degradation such as arcing, which severely restricts the applications of RF MEMS switches. To address the contact issue in terms of reliability and current handling capability for the proposed MEMS switch, a multilayer stack of contact metals was designed as described in the following sections.

3.2.1 Multi-metal Contact with Hard Metal Coating

The performance of metal-contact MEMS switches relies much on the contact materials used, especially for medium power applications. In connection with the strength of the actuator used, the metal contact material determines the on-state resistance and also current handling capability. Furthermore, the contact material influences the contact reliability because of material-dependent contact degradation through mechanical wear, fretting, creep, arcing, electromigration, localized hardening, etc. [44], [45]. Also, when opening the switch, the material-dependent adhesion forces between the closed contacts determine the risk for permanent contact stiction [46], [47]. Initially, soft gold (Au) [s] and slightly harder gold-nickel (AuNi) alloys [48] were used in RF MEMS switch designs because of their low bulk resistivity, low contact resistance even at small contact forces, and their fabrication compatibility with MEMS fabrication methods. However, soft contact materials also exert large contact adhesion forces which require strong opening forces, and are susceptible to contact wear and contact hardening which affects

² Cold-switching, i.e. removing of the signal current during the switch transition in contrast to hot-switching where the contacts are separated with the applied signal, allows for much higher current handling

Chapter 3 Design Considerations in RF MEMS Switches

the contact performance. Therefore, different harder contact materials known from the macroscopic relay manufacturing and designed for much larger contact and opening forces, have been studied for their suitability as contact material in miniaturized and microswitches: copper/tungsten/gold stack (Cu/W/Au) [49], rhodium (Re) [50], tungsten (W), molybdenum (Mo), palladium (Pd) [51], silver/tungsten/rhodium (Ag/W/Re) [52], palladium multilayer structures (Ag/Pd, Au/Ag/Pd, Au/Pd) [53], and Ag/W/CdO [54].

Ruthenium has so far only been employed in macroscopic relays because it requires a high contact force [55]. This thesis introduces a new concept of contact-metallization, utilizing a chromium/ruthenium/gold/ruthenium (Cr/Ru/Au/Ru) multilayer stack as shown in Figure 14, with a covering ruthenium (Ru) layer. Ruthenium has been getting increased attention over palladium even in macroscopic relay manufacturing, because it offers similar electrical properties and because of the limited availability and drastically increased price of palladium in recent years [56]. Ruthenium, a much harder material as compared to gold alloy metallization systems, offers the advantages of reduced contact wear and reduced stiction, lower erosion per arcing operation and better resistance stability. But ruthenium also needs a much stronger actuator for a stable, low contact resistance. The metallization multilayer stack utilized in the switches presented in this paper consists of 50 nm chromium/50 nm ruthenium/500 nm gold/50 nm ruthenium (bottom-up, i.e. from the diaphragm to the contact surface), and was applied as contact metallization for the switch contacts both on the moving membrane and on the bottom part (CPW).

capability in the on-state and is therefore limited in its applications, even though suitable for many circuit re-configuration tasks.

Chapter 3 Design Considerations in RF MEMS Switches

Figure 16 Novel Ru/Au contact metallization scheme as compared to conventional Au and Ru contacts

By using different materials for the surface film and the contact asperity, the surface properties and the total contact resistance can be controlled with reduced interdependence. Figure 16 shows how the principal concept of the proposed contact metallization scheme: a thin surface coating with a hard and thus reliable ruthenium layer is expected only to slightly increases the total contact resistance, since only the film resistance term but not the constriction term is determined by the higher resistivity of ruthenium as compared to gold. In a word, the characteristics of the multilayer metallization bear a hard contact surface (due to the very thin Ruthenium layer) and a relative small contact resistance (due to the bulk soft gold). It should be noted that the comparison illustrated in Figure 16 is based on the theoretical analysis results of contact resistance as shown in Figure 17, and also the measurement results of contact reliability described in Section 4.6.2.

3.2.2 DC Contact Resistance

The major part of the volume of the proposed metallization stack consists of gold, which gives the contact metal bar on the moving diaphragm a line resistance close to a pure gold contact bar, i.e. much lower as compared to full ruthenium contacts. However, the ruthenium coating results in an increased contact resistance. The total contact resistance R_{CR} is the sum of a constriction resistance term R_c , and a film resistance term R_f [57]:

$$R_{CR} = R_c + R_f = \frac{\rho}{2a} + \frac{\rho_f d}{\pi a^2} \quad (10)$$

with the resistivity ρ of the main body of the asperity (contact-spot), here gold, a the radius of the asperity, ρ_f the resistivity of the film covering the asperity, here ruthenium, and d the thickness of that film, refer to Figure 16.

The constriction resistance term (R_c) is a consequence of a current flow being constricted through the asperity, while the film resistance term (R_f) is due to ruthenium film covered upon the asperity. Typically, multiple asperities are involved in the contact making in microswitches, especially at low signal currents. In that case, for equation (10), an equivalent asperity radius can be defined as $\hat{a} = \sqrt{a_1^2 + a_2^2 + \dots a_n^2}$, with $a_1, a_2, \dots a_n$ the asperity radiuses of the individual contacts [58]. Even for initially multiple contact points, it has been shown that for signal currents of 1 mA and for soft gold contacts, one single contact point begins to dominates over other contact points after a certain number of hot-switching cycles have been carried out [59]. Such re-formation of the contact geometry after a relatively low number of hot-switching cycles, based on plastic deformation of the contact surface caused by the actuator's contact force and the power dissipation in the

Chapter 3 Design Considerations in RF MEMS Switches

contacts due to the voltage drop over the contacts and the ohmic contact resistance, has also been described as “burn-in behavior” by other authors [60]. For such observations, however, it is difficult to distinguish between the effects of surface cleaning and plastic contact deformation, especially if the switches are not hermetically packaged and therefore exposed to environmental influences between the fabrication and the tests, which is the case for almost all reports carried out so far.

The effective contact area A_c of the asperity is given by πa^2 , and the relationship between the effective contact area A_c and the contact force is given via the material hardness H by $F = A_c H$ [61]. Thus, in Equation (10), the (equivalent) asperity radius a , which is unknown and difficult to determine, can be expressed and substituted by $a = \sqrt{\frac{F}{\pi H}}$, resulting in:

$$R_{CR} = R_c + R_f = \sqrt{\frac{\rho^2 \pi H}{4F}} + \frac{\rho_f dH}{F} \quad (11)$$

The constriction resistance term R_c in Equation (11), can also be expressed more accurately by taking the mean free path λ of the electrons into account, as given by Nikolic [62]:

$$\hat{R}_C = \gamma(\lambda/a) R_M + R_S = \frac{1 + 0.83(\lambda/a)}{1 + 1.33(\lambda/a)} \frac{\rho}{2a} + \frac{4\rho\lambda}{3\pi a^2} \quad (12)$$

with ρ the electrical resistivity of the asperity material. The term R_M is called the Maxwell spreading resistance due to lattice scattering, and the term R_S is the Sharvin resistance due to boundary scattering in small constrictions. γ is an interpolation function [59]. The R_S term, in contrast to macroscopic relays, is of relevant dimension. The total contact resistance based on this equation results to:

Chapter 3 Design Considerations in RF MEMS Switches

$$\begin{aligned}\hat{R}_{CR} &= \hat{R}_c + R_f = \gamma(\lambda/a)R_M + R_s + R_f = \frac{1 + 0.83(\lambda/a)}{1 + 1.33(\lambda/a)} \frac{\rho}{2a} + \frac{4\rho\lambda}{3\pi a^2} + R_f \\ &= \frac{1 + 0.83(\sqrt{\frac{\lambda^2 F}{\pi H}})}{1 + 1.33(\sqrt{\frac{\lambda^2 F}{\pi H}})} \frac{\rho}{2\sqrt{\frac{F}{\pi H}}} + \frac{4\rho\lambda}{3\pi} \frac{F}{\pi H} + \frac{\rho_f dH}{F}\end{aligned}\quad (13)$$

3.2.3 Effects of Surface Coating Thickness on Contact Resistance

Theoretical analysis and simulations were carried out for the proposed multilayer contact metallization as compared to pure gold contact and pure ruthenium contact, based on the modes described in the above section, and the computation results are depicted in Figure 17. The material properties used for the simulations are from those listed in Table 4. Figure 17 (a) compares the two calculation methods according to Equation (11) and (13), by plotting the total contact resistance over the contact force. The results of both equations do not differ significantly. Figure 17 (b) plots the total contact resistance depending on the film thickness of the ruthenium coating, as compared to single material gold contacts and as compared to single material ruthenium contacts. The ruthenium coating increases the total contact resistance as compared to gold-coated gold contacts. Figure 17 (c) displays the relative increase, depending on the contact force and on the thickness of the coating.

Chapter 3 Design Considerations in RF MEMS Switches

Figure 17 Analysis of contact resistance over the contact force, for contact bumps coated with coating films. (a) Comparison of contact resistances calculated by Equation (11) and Equation (13). (b) Total contact resistances of coated contact-bumps, with the coating film thickness as parameter. (c) Relative total contact resistance change of Ru-coated contacts as compared to gold coated contacts.

Chapter 3 Design Considerations in RF MEMS Switches

Item / Material	Ag	Au	Mo	Pd	Pt	Re	Ru	W	Cr
Electrical conductivity ($\text{m}\Omega^{-1} \text{ mm}^{-2}$)	63.0	45.7	19.4	9.3	9.5	5.2	14.9	18.0	7.4
Density (g/cm^3)	10.5	19.3	10.2	12.03	21.45	20.90	12.3	19.1	7.19
Melting temperature	960	1063	2620	1555	1774	3170	2450	3400	1857
Boiling temperature	2212	2966	5560	3170	3850	5900	4900	5930	2672
Minimum arc voltage (V)	12.0	12.5	12.0	14.0	14.0	-	-	13.5	-
Minimum arc current (A)	0.4	0.35	0.75	0.80	0.90	-	-	0.8-1.2	-
Price (USD/ounce [49])	4.58	262	5.12	635	603	52.6	141	7.7	-

Table 4 Physical properties of metals suitable for MEMS switch contacts [49].

Figure 17 effectively demonstrate the advantages of the proposed contact coating method: The metallization stack with a 50 nm thick ruthenium coating on top of gold contacts, as utilized for the fabricated switches in this thesis, offers the surface properties of ruthenium contacts, i.e. hardness and durability. The total contact resistance of the novel metallization stack, however, is at least 3 times smaller as compared to pure ruthenium switch contacts, for typical MEMS micro switch contact forces of 200-400 μN . And as compared to the much softer gold contacts with inferior surface durability, the total contact resistance increases only by 1.9-2.5 times for a contact force of 200-400 μN .

It should be noted that the hardness values of ruthenium-film and gold-film for the analysis are obtained by Nanoindentation test, a widely used method to determine the hardness and Young's modulus of thin film [63], using a Nanoindenter XP (MTS System Corp.) with a Berkovich tip and a dynamic contact module (DCM). 500 nm thick thin

Chapter 3 Design Considerations in RF MEMS Switches

films of pure gold and ruthenium were sputtered on glass wafers for the measurement. 10 indentations were conducted on each sample. The measurement results are: Au-film hardness $H_{Au} = 1.6$ GPa; Ru-film hardness $H_{Ru} = 10.1$ GPa. Additionally, electron mean free path of gold and ruthenium used for the analysis are: $\lambda_{Au} = 38$ nm [59] and $\lambda_{Ru} = 10.8$ nm [64], respectively.

3.3 Stress Reduction by Corrugation Introduction in Diaphragm

Most of the RF MEMS switches developed so far use a moveable cantilever, air-bridge or membrane structure to achieve electrical contact and break. A RF MEMS switch based on a periphery-clamped diaphragm structure is proposed in this thesis, in order for the wafer-scale encapsulation. A periphery-clamped diaphragm structure is much less sensitive to thermal stress, vibration and shocks, enabling a better mechanical reliability as compared to the typical single-side clamped cantilever or two-side fixed air-bridge structure [65]. However, one drawback of a periphery-clamped diaphragm having high residual stress in the film may give rise to undesirable effects such as much higher actuation voltage, film buckling, or even membrane cracking.

There are two possible ways to overcome the stress issue. One approach to reduce the initial stress is by the optimization of stress-control processes. Another solution is the utilization of corrugation technique, which was initially used in the silicon microphone

Chapter 3 Design Considerations in RF MEMS Switches

and is an effective way to alleviate the residual stress in diaphragm [66, 67]. The theoretical analysis on the stress-reduced diaphragm with corrugation is described in the following sections, in terms of mechanical deflection sensitivity, stress reduction, and necessary actuation voltage.

3.3.1 Mechanical Deflection Sensitivity

The critical part of the MEMS switch is the diaphragm which is an out-of-plane movable microstructure driven by the electrostatic force. As we know, the periphery-clamped diaphragm has the disadvantage of possible high residual stress in the film, especially for sandwich structure (gold film electrode / SiO_2 film/ Si_3N_4 film/ relay metal) adopted for this design. In addition to the exploration of fabrication processes for low stress membrane film, the corrugation technique is an effective way to alleviate the high residual stress in the diaphragm and to optimize its mechanical deflection sensitivity [68, 69, 70, 71, 72].

Figure 18 Geometrical illustration of the corrugations with dimensions: (a) physical dimensions (b) model of corrugated diaphragm for the numerical simulations and analytical calculations.

The corrugation geometry used for the MEMS switch is shown in Figure 18. The grooves for the corrugations were generated into the silicon wafer either by deep reactive ion etching (DRIE) or by wet etching using potassium hydroxide (KOH). With DRIE method, it is necessary to control of the slope of trench-wall, with a preferable angle of about 95° , to guarantee for good sidewall coverage of the subsequent metal layer deposition. When wet-etching in KOH, the etch profile angle is 54.7° according to the crystal orientation of the (100) silicon substrate. The periodical length of the corrugation is set to be $50\text{ }\mu\text{m}$, the top corrugation width is $30\text{ }\mu\text{m}$, and depth of the corrugation is $6\text{ }\mu\text{m}$, as tabulated in Table 5.

Chapter 3 Design Considerations in RF MEMS Switches

Parameters	Symbol	Values
Diaphragm radius	R	900 μm
Diaphragm thickness	t_d	1.7 μm
Width of top corrugation	b_c	30 μm
Pitch of the corrugations	λ	50 μm
Profile angle of corrugation	β	95 ⁰
Number of corrugation	N_c	0, 2, and 4

Table 5 Parameters used in the proposed corrugated diaphragm, (the bottom width w_c of the corrugations is determined by the corrugation depth h_c and the profile angle β , using $w_c = \lambda - b_c + h_c \cos \beta$).

The centre deflection, z , of the periphery-clamped circular diaphragm due to a uniform pressure (P) on the diaphragm can be expressed by [73]:

$$P = 4 \frac{t_d z}{R^2} \left[\sigma_0 \frac{b_p}{2.83} + \frac{a_p}{4} E \left(\frac{t_d}{R} \right)^2 \right] \quad (14)$$

where the influence of the initial stress, σ_0 , of the diaphragm is taken into account. The corrugated profile factor (q), and q -relative parameters (a_p and b_p) are given by the following equations:

Chapter 3 Design Considerations in RF MEMS Switches

$$q = \sqrt{\frac{S}{\lambda} \left[1 + \frac{3}{2} \left(\frac{h_c}{t_d} \right)^2 \right]} \quad (15)$$

$$a_p = \frac{2(q+1)(q+3)}{3 \left(1 - \frac{\nu^2}{q^2} \right)} \quad (16)$$

$$b_p = 32 \frac{1-\nu^2}{q^2-9} \left[\frac{1}{6} - \frac{3-\nu}{(q-\nu)(q+3)} \right] \quad (17)$$

E , ν , R , t_d , are the Young's modulus, Poisson's ratio, radius, thickness of the diaphragm, respectively. λ , S , h_c are the spatial period, arc length and depth of corrugations, respectively. The derivation of Equation (14) is given in detail in Appendix A.

The electrostatic force F exerted on the corrugated diaphragm can be approximated by,

$$F = PA_{eff} = 4A_{eff} \frac{t_d z}{R^2} \left[\sigma_0 \frac{b_p}{2.83} + \frac{a_p}{4} E \left(\frac{t_d}{R} \right)^2 \right] \quad (18)$$

where A_{eff} is the effective actuation area of the diaphragm. Therefore the mechanical deflection sensitivity (S_m) of a circular corrugated diaphragm can be calculated by the following formula:

$$S_m = \frac{dz}{dF} = \frac{R^2}{4A_{eff} t_d \left[\sigma_0 \frac{b_p}{2.83} + \frac{a_p}{4} E \left(\frac{t_d}{R} \right)^2 \right]} \quad (19)$$

The mechanical deflection of the proposed silicon oxide/nitride ($\text{SiO}_2/\text{Si}_3\text{N}_4$) diaphragm is calculated based on the above equations with the parameters tabulated in Table 5. The calculation results are plotted in Figure 19, showing the influence of the corrugation depth and residual stress. The mechanical deflection sensitivity increases for small corrugation depths due to the reduction of the internal stress. However, too large corrugation depth dramatically decreases the mechanical deflection sensitivity due to the

Chapter 3 Design Considerations in RF MEMS Switches

larger flexural rigidity in the tangential direction for a diaphragm with very deep corrugation, which increases the stiffness of diaphragm. It is clearly seen that optimum corrugation depths exist at different stress levels giving maximum mechanical deflections. For a residual stress of 60 MPa in the proposed SiO₂/Si₃N₄ diaphragm, the optimum corrugation depth is around 6 μm. Obviously, the application of corrugations offers the possibility to control mechanical deflection sensitivity and is often an easier way as compared to the approach of the film deposition process control.

Figure 19 Mechanical deflection sensitivity of diaphragm vs. corrugation depth for a corrugation number of 2.

3.3.2 Stress Reduction Ratio

The application of corrugation offers the possibility to control mechanical deflection sensitivity by means of dimensions of corrugations and the number of corrugations to be used, which is often an easier way compared to the approach by process-control. Furthermore, the corrugation approach increases the design robustness since it is much more tolerant to deviations in the fabrication induced stress levels of the different layers, and thus does not require frequent fine-tuning of the process parameters. The intrinsic tensile stress in a corrugated membrane is significantly released by the corrugations in the structure. Several analytical models for designing corrugated diaphragms with residual stress are available [73], [74], [70]. Fuldner *et al* [75] proposed a new method to derive an analytical model for corrugated diaphragms for silicon microphones. For relatively high stress and shallow corrugations, i.e. corrugations with a depth h_c less than 0.4 times its period ($w_c + b_c$) [76], the increased bending stiffness in the tangential direction can be neglected, and a corrugated diaphragm with initial stress σ_0 performs like a flat diaphragm with a reduced stress σ in equilibrium. Referring to the model shown in Figure 18, the stress reduction ratio (η) by the introduction of corrugated diaphragms can be calculated to

$$\eta = \frac{\sigma_0}{\sigma} = 1 + 6 \sin(\beta) \left(\frac{h_c}{t_d} \right)^2 \frac{N_c w_c}{R - N_c (w_c + b_c)} \quad (20)$$

where R is the radius of the diaphragm, t_d the thickness of the diaphragm, h_c the corrugation depth, N_c the number of corrugations, w_c the width of bottom corrugations, b_c the width of top corrugations, β the profile angle of corrugations, respectively as shown in Figure 18. The derivation of Equation (20) is given in detail in Appendix B.

Figure 20 (a) Residual stress reduction factor (η) as function of the corrugation depth, for DRIEtched and KOH etched corrugations (with corrugation number N_c of 2). The measured η (to be given in Chapter 4) are also illustrated for both corrugated diaphragm with $6\mu\text{m}$ deep corrugations, and flat diaphragm (corrugation depth = $0\mu\text{m}$). (b) Relationship of stress reduction ratio with corrugation number and corrugation depth which is generated by DRIE.

Chapter 3 Design Considerations in RF MEMS Switches

The residual stress reduction for the present switch due to the corrugations is calculated using this analytical model with the parameter set listed in Table 5. Noticed that η equals one for a flat diaphragm and larger than one for a corrugated diaphragm. The calculated stress reduction factors as compared to a flat membrane are shown in Figure 20 (a) for corrugations etched by KOH with a profile angle of 54.7° ($\beta=125.3^\circ$) and for corrugations etched by DRIE with a profile angle of 85° ($\beta=95^\circ$). The stress reduction is significant in both cases and especially effective for the DRIE configuration. Thus, DRIE was chosen as etching technique for the corrugations of the switches presented here. For the case of corrugations generated by DRIE, the relationship of both corrugated depth and number of corrugation with the residual stress reduction is computed for the proposed corrugated diaphragm with the parameters tabulated in Table 5. The calculation results are shown in Figure 20 (b). It is evident that the corrugation depth and corrugation number have high influence on the residual stress of the diaphragm. In general, high residual stress reduction ratios can be achieved by increasing the corrugation depth and corrugation number.

3.3.3 Actuation of Stress-reduced Corrugated Diaphragm

Figure 5 shows a lumped 1D model of a movable diaphragm, which is electrostatically actuated and works against a lumped linear spring with a spring constant of k . This model is a good first-order representation of a wide variety of pull-in devices. Neglecting the air damping effect, the displacement (z) of the inertial mass (the movable diaphragm with a

Chapter 3 Design Considerations in RF MEMS Switches

mass of m) driven by the electrostatic force F_{el} is governed by the following differential equation:

$$m \frac{d^2 z}{dt^2} + kz = F_{el} \quad (21)$$

Figure 21 Illustration of the diaphragm lumped 1D model.

where the electrostatic force (F_{el}) generated by actuation voltage V across the parallel plates of area A as can be obtained using Equation (5),

$$F_{el} = \frac{\epsilon_0 A V^2}{2(g_0 - z)^2} \quad (22)$$

By expanding F_{el} using a Taylor series approximation about a minimum displacement z_0 , and substituting it in Equation (21), the dynamic equation of motion becomes [77]:

Chapter 3 Design Considerations in RF MEMS Switches

$$m \frac{d^2 z}{dt^2} + \left(k - \frac{\varepsilon_0 A V^2}{(g_0 - z_0)^3} \right) z = \frac{1}{2} \frac{\varepsilon_0 A V^2}{(g_0 - z_0)^2} \left[1 - 2 \frac{z_0}{g_0 - z_0} + \dots \right] \quad (23)$$

Furthermore, an effective linearized uniform electrostatic pressure (P_{eff}) on the diaphragm can be obtained by the following equation by linearizing F_{el} at the zero deflection point ($z_0 = 0$) [77]:

$$P_{eff} = \varepsilon_0 V^2 \left(\frac{1}{2g_0^2} + \frac{z}{g_0^3} \right) \quad (24)$$

On the other hand, for a periphery clamped circular diaphragm with initial stress of σ_0 , the relationship between an applied uniformed pressure p and the central deflection z can be expressed by [78]

$$P = \frac{Et}{1-\nu} \left(\frac{7-\nu}{3R^4} \right) z^3 + \frac{4Et^3}{3R^4(1-\nu)} z + \frac{4\sigma_0 t_d}{R^2} z \quad (25)$$

where E is the Young's modulus, ν is the Poisson ratio, R is the radius of the circular diaphragm, and t_d is the thickness of the diaphragm. Substituting Equation (24) in Equation (25) to replace P by P_{eff} , using the pull-in deflection ($z = \frac{g_0}{3}$), and replacing E by $\frac{E}{1-\nu^2}$ (the elective modulus accounting for the fringing field correction [79]), we obtain

$$\varepsilon_0 V^2 \left(\frac{1}{2g_0^2} + \frac{1}{3g_0^2} \right) = \frac{Et}{(1-\nu)(1-\nu^2)} \left(\frac{7-\nu}{3R^4} \right) \left(\frac{g_0}{3} \right)^3 + \frac{4Et^3}{3R^4(1-\nu)(1-\nu^2)} \left(\frac{g_0}{3} \right) + \frac{4\sigma_0 t}{R^2} \left(\frac{g_0}{3} \right) \quad (26)$$

After rearrangement and replacing σ_0 by σ_0/η , we can obtain a general formula to calculate the pull-in voltage for both flat and corrugated diaphragms:

$$V_{pi} = \sqrt{\frac{6g_0^2}{5\epsilon_0} \left[\frac{7-\nu}{81(1-\nu)(1-\nu^2)} \left(\frac{Etg_0^3}{R^4} \right) + \frac{4}{9(1-\nu)(1-\nu^2)} \left(\frac{Et^3g_0}{R^4} \right) + \frac{4}{3} \frac{\sigma_0tg_0}{\eta R^2} \right]} \quad (27)$$

Here, $\eta = 1$ for a flat diaphragm while $\eta > 1$ for a corrugated diaphragm, which is determined by Equation (20).

Figure 22 Calculated actuation voltage vs. residual stress of a RF switch with a flat diaphragm.

Figure 22 plots the pull-in voltage of a flat diaphragm as a function of the initial stress σ_0 , which is calculated by Equation (27). The geometric parameters of the flat diaphragm are the same as those listed in Table 5 . Obviously the actuation voltage for snapping down the diaphragm to make electric contact depends very much on the suspension height g_0

Chapter 3 Design Considerations in RF MEMS Switches

and residual stress σ . A small g_0 and a low σ give a low pull-in voltage. However in reality, a trade-off must be taken into consideration to choose a proper suspension height g_0 . A larger suspension height is good for higher RF isolation although it leads to a higher actuation voltage. In order to achieve the required isolation at the off-state, it is necessary to keep a proper suspension height in the actual switch design. Therefore an effective and essential way to decrease the pull-in voltage, in this case, is to reduce the internal residual stress of diaphragm by the corrugation technique.

3.4 RF Design

Electric portion is one of the distinction parts of the switch, which includes the transmission line for RF signal transmission use. The design considerations on the electric portion are given in this section.

3.4.1 Coplanar Wave Guide

The type of the transmission line of the switch is coplanar wave guide (CPW) that is to be implemented on the top surface of the base substrate. CPW is formed from a signal conductor separated from a pair of ground-planes, all on the same plane, atop a dielectric medium as shown in Figure 23. CPW has advantages over microstrip including the facilitation in shunt as well as series surface mounting of components, elimination of the need for via hole and wraparound, reduced radiation loss and dispersion, planar structures

Chapter 3 Design Considerations in RF MEMS Switches

defined photolithographically with relatively low dependence on substrate thickness, simplicity and lower costs of fabrication, etc.

Figure 23 Representation of Coplanar Waveguide

CPW has its principle grounding in the form of wide strips adjacent to the signal trace, so that its signal characteristics are almost entirely governed by laterally defined dimensions. The characteristics impedance of a CPW line, terminated with a purely resistive load, is given by [80],

$$Z_0 = \frac{30\pi K'(\psi)}{\sqrt{\epsilon_{eff}} K(\psi)} \quad (28)$$

where $K(\psi)$ is the complete elliptic integral of the first kind with modulus ψ and can be expressed by,

$$K(\psi) = \int_0^{2\pi} \frac{d\phi}{\sqrt{1 - \psi^2 \sin^2 \phi}} \quad (29)$$

here,

Chapter 3 Design Considerations in RF MEMS Switches

$$\psi = \frac{w}{w + 2s} \quad (30)$$

$$\psi' = \sqrt{1 - \psi^2} \quad (31)$$

$$K'(\psi) = K(\psi') \quad (32)$$

where w is the width of the center signal conductor and s is the separation gap between the signal line and each of the coplanar ground planes as illustrated in Figure 23. ϵ_{eff} is the effective permittivity of CPW and is defined in the fundamental way as [81],

$$\epsilon_{eff} = \left(\frac{c}{v_p}\right)^2 \quad (33)$$

where c is the free-space light speed and v_p is the phase velocity of the dominant mode in the CPW. The effective permittivity of CPW can also be approximated by [82],

$$\epsilon_{eff} = 0.5(\epsilon_r + 1) \left\{ \tanh\left[1.785 \log\left(\frac{h}{s}\right) + 1.75\right] + \left(\frac{\psi s}{h}\right) [0.04 - 0.7\psi + 0.01(1 - 0.1\epsilon_r)(0.25 + \psi)] \right\} \quad (34)$$

It should be noted that this equation provides accuracy within approximately 1.5% as long as $h/s \geq 1$.

Houdart [83] derived two closed expressions for the characteristics impedance, depending on the range of ψ involved.

$$\frac{K(\psi)}{K'(\psi)} = \frac{1}{\pi} \ln\left(2 \frac{1 + \sqrt{\psi}}{1 - \sqrt{\psi}}\right) \quad \text{for } 0 \leq \psi \leq 0.707 \quad (35)$$

$$\frac{K'(\psi)}{K(\psi)} = \frac{1}{\pi} \ln\left(2 \frac{1 + \sqrt{\psi}}{1 - \sqrt{\psi}}\right) \quad \text{for } 0.707 \geq \psi \geq 1 \quad (36)$$

It is obvious that the characteristics impedance of CPW can be obtained by the Equation (28) to Equation (36), provided that the physical dimensions of the CPW are known.

Chapter 3 Design Considerations in RF MEMS Switches

Furthermore, the thickness of substrate (h) is usually much larger than the separation gap (s) of CPW in the typical MEMS switch designs, resulting in reasonable accuracy for computation of characteristics impedance.

On the other hand, in practice, it is often required to find out the width of w and the spacing s of CPW, being given the characteristics impedance of CPW. Although one can manipulate the above mentioned equations with different values of w and s to achieve the specific characteristics impedance, a fast and effective method to determine physical parameters to get the target is through computer-aided simulation. For the proposed MEMS switch, the physical dimensions of CPW were obtained with the aid of *Si8000m* of Polar Instruments Inc. [84] which applies the similar equations as mentioned above. Given that the line impedance is set to be of 50 ohm, the nominal dimensions of the coplanar waveguide (CPW) are 250 μ m signal line width and 35 μ m gap to the ground lines, which results in a characteristic impedance of 50.2 Ω for a conductor thickness of 1 μ m on a 750 μ m thick *Pyrex 7740* glass substrate with a nominal dielectric constant of 4.6.

3.4.2 Insertion and Isolation Loss

Insertion loss (α_{IL}) is an important parameter used to characterize the electrical performance of microwave switch. It is typically defined as the ratio of the power delivered to the load (P_1) of an idea switch in the “on” state to the actual power delivered by the switch (P_2). Insertion loss (α_{IL}) is generally expressed in decibels (dB) by

Chapter 3 Design Considerations in RF MEMS Switches

$\alpha_{IL} = 10 \log_{10} \left(\frac{P_1}{P_2} \right)$. Insertion loss (α_{IL}) of a MEMS switch is sometimes taken for S_{21} ³,

written as $\alpha_{IL} = 10 \log_{10} \frac{1}{|S_{21}|^2}$. The insertion loss (S_{21}) of a series MEMS switch can be

calculated by $|S_{21}|^2 = 1 - \frac{R_s}{Z_0}$ [85]. Therefore α_{IL} can be written as,

$$\alpha_{IL} = -10 \log_{10} \left(1 - \frac{R_s}{Z_0} \right) \quad (37)$$

where R_s is the series resistance of the switch in the on-state, and Z_0 is the characteristic impedance of transmission line. A Model of a DC contact series MEMS switch with its equivalent circuit in the on-state is drawn in Figure 24 (a). The series resistance (R_s) is composed of DC contact resistance of R_c , a short section of transmission line (R_l), and an equivalent resistance of R_{sl} due to transmission line loss as illustrated in Figure 24 (a),

$$R_s = 2R_c + R_l + 2R_{sl} \quad (38)$$

R_s is typically dominated by DC contact resistance (R_c) for most of the MEMS switch design. It is obvious that the insertion loss of a DC contact series MEMS switch is strongly related to its series resistance (R_s). For a typical MEMS series switch with a total

³ S_{21} is a scattering parameter (S parameter). The S-parameter matrix is commonly used to describe the relationship between the reflected (b_i), incident (a_i) power waves for a two-port network. The S-parameter matrix is given by,

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

Expanding the matrices into equations gives,

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

where S_{11} is the input port voltage reflection coefficient, S_{12} is the reverse voltage gain, S_{21} is the forward voltage gain, and S_{22} is the output port voltage reflection coefficient.

Chapter 3 Design Considerations in RF MEMS Switches

series resistance (R_s) of 1Ω to 3Ω , the insertion loss is estimated to be -0.088dB to -0.27dB by Equation (37).

Isolation (α_{ISO}), another important characterization parameter, is a measure of the off-state performance of a switch. It is defined as the ratio of microwave power delivered to a load (P_I) of an idea switch in the “on” state, to the actual power delivered to the load (P_3) when the switch is in the “off” state. Isolation (α_{ISO}) of a switch is sometimes taken for

S_{21} , expressed in decibels (dB) as $\alpha_{iso} = 10 \log_{10} \frac{1}{|S_{21}|^2}$.

The isolation of a DC contact MEMS switch is strongly dependent on its off-state capacitance C_u . A Model of a DC contact series MEMS switch with its equivalent circuit in the off-state is shown in Figure 24 (b). The off-state capacitance (C_{off}) consists of a parallel-plate capacitance C_{pa} ($C_{pa1} + C_{pa2}$) with an area overlapped by switch contact and transmission lines, a fringing capacitance C_{fr} which is about 30% to 60% of C_{pp} , and a parasitic capacitance of C_p at the line-gap of the centre signal trace, with the overall off-state capacitance expressed by,

$$C_{off} = C_{pa} + C_{fr} + C_p \quad (39)$$

The isolation (S_{21}) of the series switch in the off-state is given by [85]

$$S_{21} = \frac{2j\omega C_{off} Z_0}{1 + 2j\omega C_{off} Z_0} \quad (40)$$

Chapter 3 Design Considerations in RF MEMS Switches

Figure 24 Simplified Models of DC contact series MEMS switch with equivalent circuits. (a) MEMS switch in the on-state, and (b) MEMS switch in the off-state.

The isolation can be approximated as follows, if $S_{21} \ll -10\text{dB}$ and $2\omega C_{off} Z_0 \ll 1$,

$$|S_{21}|^2 \approx 4\omega^2 C_{off}^2 Z_0^2 \quad (41)$$

Therefore the isolation, in decibels, of a DC contact MEMS series switch is written as,

Chapter 3 Design Considerations in RF MEMS Switches

$$\alpha_{ISO} = 10 \log_{10} \frac{1}{|S_{21}|^2} \approx 20 \log_{10} \frac{1}{2\omega C_{off} Z_0} \quad (42)$$

For a typical series switch with an off-state capacitance of 2 to 5 fF, the isolation, calculated by Equation (42), at a frequency band from 1 GHz to 20 GHz is shown in Figure 25. It is obvious that smaller off-state capacitance gives out better isolation as expected. An up-state capacitance of 2 fF results in an isolation of -58 to -29 dB for a frequency band of 1- 20 GHz, which is spectacular performance as compared to any other solid-state device.

Figure 25 Isolation of a Series MEMS Switch with up-capacitance of 2-5fF, calculated by Equation (42)

Chapter 3 Design Considerations in RF MEMS Switches

It should be pointed out that the calculation of the off-state capacitance (C_{off}) is not straightforward since the parasitic capacitance as well as the fringing capacitance must be taken into account in order to precisely predict the electrical performance of a device. In the actual MEMS design, the RF performances, including isolation and insertion loss, are normally computed or simulated with the aid of a simulator as described in the following section.

3.4.3 Simulation of Device Performance

The electric performance of the proposed switch design is evaluated by *HFSS* (High Frequency Structure Simulation) [86] simulator, an industry-standard software for S-parameter, full-wave SPICE extraction, and electromagnetic simulation of components for high-frequency and high-speed applications. *HFSS* is widely used for the design variety components such as on-chip embedded passives, PCB interconnects, RF components, and high-frequency IC packages, etc.

A full geometric model of the MEMS switch can be created by 3D modeler of *HFSS* for the simulation, with the exact physical dimensions and materials of the proposed switch. The RF simulations revealed that the geometric dimensions of switch contact play an important role in the isolation of the switch, including the overlap contact area, suspension height of contact-metal above transmission line, and transmission line gap. The effects of contact area and suspension height are shown in Figure 26 (a) and Figure 26 (b) respectively. It is clearly that a smaller size of contact area leads to higher isolation, and a larger suspension height is advantageous to better isolation as expected.

Figure 26 Simulation results of the isolation at off-state. (a) Effect of suspension height, with a relay metal of 250 μm x 210 μm and 150 μm of transmission line gap. (b) Effect of relay metal area, with 6 μm of suspension height, 150 μm of transmission line gap.

Chapter 3 Design Considerations in RF MEMS Switches

The nominal suspension height of the diaphragm of 6 μm was chosen for the proposed MEMS switch, which fulfils the required minimum isolation of -21 dB up to 10 GHz and -18 dB at 15 GHz, refer to the black colored curve in Figure 26 (a). Note that the isolation is also determined by the overlapping contact area of $250\text{ }\mu\text{m} \times 210\text{ }\mu\text{m}$, refer to the black colored curve in Figure 26 (b). The overlapping contact area of $250\text{ }\mu\text{m} \times 210\text{ }\mu\text{m}$ is unexceptionally large for a MEMS switch, designed with the intention of having a large metal volume for an efficient heat sink for the contact resistance power dissipation to the substrate, potentially increasing the current handling capability.

Figure 27 Simulated insertion loss of the proposed MEMS switch at on-state. An ideal switch without seal ring is also included for comparison.

Chapter 3 Design Considerations in RF MEMS Switches

The insertion losses of the proposed RF MEMS switch was computed and the result is given in Figure 27 (the blue dotted curve with seal ring). The insertion loss (S_{21}) at on-state, which increases as the frequency goes up, is better than -0.1 dB up to 3 GHz and about -0.7 dB at 15 GHz. It should be pointed out that the silicon cap as illustrated in Figure 2-14 is used for the purpose of encapsulation of MEMS switch with periphery clamped diaphragm. However the silicon cap does affect the insertion loss of the switch, especially those portions above the centre signal line. To verify this by simulation, the insertion loss of a MEMS switch with four-side-clamped diaphragm (refer to Figure 28) was also computed and the simulation result is plotted (the black dotted curve) in Figure 27 as well. In this case, the effect from the silicon cap was minimized since there is not any portion above the centre signal line any more. The simulation results show an obvious reduction in insertion loss for the MEMS switch with four-side-clamped diaphragm. This implies that the proposed silicon cap may contribute much to the insertion loss at higher frequency ranges. Comparing two curves in Figure 27, for instance at 15 GHz, it is seen that the insertion loss increases from -0.4 dB to -0.7 dB, where -0.3 dB is contributed by the proposed silicon cap.

Figure 28 A MEMS switch with four-side-clamped diaphragm was also simulated by *ANSYS*, to verify the silicon cap effect on the insertion loss

3.5 Summary

The design considerations in the proposed RF MEMS switches are described in this chapter focusing on the theoretical analysis on the novel multi-metal contact with hard metal coating, the stress-tolerant design by the introduction of corrugation in diaphragm, and the RF design and the simulation of RF performance for the proposed switch.

Chapter 4 MEMS Switches based on Ruthenium/Gold

Contact Metallization for High Reliability

The wafer-level encapsulated RF MEMS switch based on a corrugated diaphragm and multilayer stacked metal contacts with ruthenium coating for high reliability is developed and described in this chapter. The switching concepts of the electrostatic actuated MEMS switch are outlined in Section 4.1. The fabrication processes of the MEMS switch are presented in Section 4.2. While the details of the exploration or optimization of essential processes, which are critical for achieving the specific designed MEMS switches, is provided in Section 4.3. A fabrication issue and the possible solution are discussed in Section 4.4. The mechanical performances of the flat and stress-reduced corrugated diaphragms were measured and the results are highlighted in Section 4.5. In addition, the investigation and results with regards to the unique ruthenium/gold contact design are shown in Section 4.6, and the characterization on the RF performances is given in Section 4.7. Finally, in Section 4.8, a brief summary on the development of the ruthenium/gold contact and corrugated diaphragm based switches is provided.

4.1 Switch Concept Overview

As highlighted in Section 2.4, a wafer-level encapsulated RF MEMS switch based on a corrugated diaphragm and ruthenium metal contacts is proposed. A unique ruthenium/gold contact is designed to improve the switch contact reliability and power handling. Artificially created corrugations in the $\text{SiO}_2/\text{Si}_3\text{N}_4$ diaphragm are utilized to considerably reduce residual stress in the membrane.

Figure 29 Cross-sectional drawing of the corrugated-diaphragm based RF MEMS switch in the on and off state.

Figure 29 shows a cross-sectional drawing of the RF MEMS switch concept. The core of the switch is the thin and flexible 100 nm SiO_2 /1200 nm Si_3N_4 diaphragm suspended on polymer distance keepers above the bottom glass substrate. For the switch in the off-state,

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

this configuration results in a nominal distance of 6 μm between the metal contact bar on the membrane and the coplanar waveguide signal lines on the bottom wafer. The membrane is actuated by the electrostatic forces between the metal electrodes on the membrane and electrodes on the bottom wafer.

Figure 30 Schematic drawing of the two switch parts, before assembling by wafer bonding.

The switch is fabricated in two parts on separate wafers which are finally assembled by bonding with an adhesive polymer ring as shown in Figure 30, resulting in a basic encapsulation of the switches on wafer-scale. Another advantage of this two-wafer fabrication concept is that it enhances the integration capability of the MEMS switch with

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

other RF circuits or substrates [30]. It means that the moving parts (top silicon with membrane) can be integrated with a large variety of bottom substrates containing RF circuits which may not be fabrication compatible to the MEMS moving part.

4.2 Fabrication Process Flow of Multi-wafer Stacking

The fabrication of the diaphragm RF MEMS switch involves surface micromachining as well as bulk micromachining processes, and also full-wafer bonding. The fabrication needs seven photolithography masks and one silicon shadow mask. Two of photolithography masks are used for the processing of the bottom glass wafer; four for the top silicon wafer; and one photolithography mask and a silicon shadow mask for a metal deposition after the wafer bonding. The process flow is outlined in Figure 31.

The process starts on the bottom 750 μm thick Pyrex glass wafer. A coplanar wave guide was formed on the bottom glass wafer by sputtering a 50 nm Cr/50 nm Ru/500 nm Au/50 nm Ru metal layer, which is patterned by a lift-off process using AZ 9260 photoresist as shown in Figure 31 (1). Afterwards, polymer (*CYTOP CTL809M* fluoropolymer) is spin-coated on the glass wafer with a thickness of 2 μm . The polymer is subsequently patterned by reactive ion etching (RIE) using oxygen plasma, refer to Figure 31 (2).

The top silicon wafer is processed separately before bonding with the bottom glass wafer. A 4 μm deep circular recess is firstly generated into the top silicon wafer (200 μm thick) by deep reactive ion etching (DRIE) using a photoresist mask as shown in Figure 31 (3).

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

The 4 μm deep recess together with the polymer bonding layer and the contact metallization layers determines the nominal contact separation in the off-state.

Figure 31 Fabrication process flow: (a) bottom glass wafer process; (b) top silicon wafer process; (c) wafer bonding and post-processing.

The next step is the creation of slightly positively tapered corrugations as illustrated in Figure 31 (4). The structural layers of the diaphragm are then formed by growing a 100 nm thick silicon dioxide layer by dry thermal oxidation, followed by a LPCVD

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

deposition of silicon nitride with a thickness of 1200 nm as illustrated in Figure 31 (5). Next, the $\text{SiO}_2/\text{Si}_3\text{N}_4$ film is patterned afterwards by RIE in a CF_4/O_2 plasma, using a photoresist mask, refer to Figure 31 (6). Finally, the contact metal for the metal contacts is created by sputtering a 50 nm Cr/50 nm Ru/500 nm Au/50 nm Ru multilayer patterned by a lift-off process with AZ9260 photoresist as depicted in Figure 31 (7). The lift-off resist is subsequently dissolved in acetone. Besides cleaning in isopropanol and DI water, no further cleaning step was undertaken.

The two processed wafers, the glass wafer and top silicon wafer, are bonded together by the intermediate layer bonding technique using *CYTOP* as shown in Figure 31 (8). After the wafer bonding, the $\text{SiO}_2/\text{Si}_3\text{N}_4$ film on the backside of the top wafer is removed by RIE in CF_4/O_2 plasma, refer to Figure 31 (9). The back hole on the silicon side of the assembly is subsequently generated by DRIE etching using a 7 μm thick AZ9260 photoresist mask, which is stopped at the $\text{SiO}_2/\text{Si}_3\text{N}_4$ film to release the diaphragm film, as depicted in Figure 31 (10). Finally, a 10 nm Ti/400 nm gold layer is deposited on the back hole through a 200 μm thick silicon shadow mask to produce the top electrode, see Figure 31 (11).

Figure 32 shows a SEM picture of the fabricated RF MEMS switches with corrugated diaphragm. The overall size of the dies is much larger than the packaged switch and has the dimensions of 3 mm $\times$ 2.8 mm $\times$ 0.95 mm.

Chapter 4 *Highly Reliable Switches with Ruthenium-based Contacts*

Figure 32 SEM photo of a RF MEMS switch with a circular corrugated diaphragm (900 μm in radius). The overall size of the switch device is 3 mm $\times$ 2.8 mm $\times$ 0.95 mm.

4.3 Exploration of Critical Process

There are important processes that need to be explored or optimized as described as follows. Among them, the generation of slightly positively tapered corrugation by DRIE, deposition of low stress diaphragm films, and flexible wafer bonding with low process temperature are critical for achieving the specific designed MEMS switches.

4.3.1 Generation of Corrugation Microstructure

The challenge of corrugation generation by DRIE is the control of the profile angle of trench-wall, with a preferable angle of about 85° , for the purpose of better sidewall

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

coverage of gold film at the last process step. The corrugation shape is determined by DRIE etching process. Typical DRIE is anisotropic dry etching process with vertical trench, which is not what we need for the corrugation generation. However the corrugation shape can be tuned by process parameters. For the proposed switch, the corrugation is generated by 8 seconds of etching time and 5 seconds of passivation time, applying 100 W of platen power with our STS tool. The profile angle of corrugation is about 85° as shown in Figure 33.

Figure 33 SEM Photo of a corrugation with controlled etching profile generated by DRIE process

It should be mention that the scallops (nearly sinusoidal ridges), formed on the sidewall surfaces of the corrugation trenches during the DRIE process [87, 88] affect trivially the coverage and uniformity of the deposited $\text{SiO}_2/\text{Si}_3\text{N}_4$ film, since the sidewall surface roughness of the corrugation trench is less than 100 nm.

4.3.2 Deposition of Low Stress Diaphragm Films

The moving microstructure of the switch developed in this thesis is a diaphragm which is composed of 100 nm silicon oxide (SiO_2)/1200 nm silicon nitride (Si_3N_4)/350 nm gold (Au), with 1200 nm thick silicon nitride as the core part. The compressively stressed thermal silicon dioxide is used as a base layer to compensate tensile stresses of silicon nitride subsequently deposited on it. The gold film is for making actuation electrode usage. The residual stress of sandwich-structured diaphragm must be kept as small as possible to avoid possible high actuation voltage, film buckling or film cracking.

Silicon nitride film is commonly obtained by chemical vapor deposition (CVD) from dichlorosilane (DCS, SiCl_2H_2) and ammonia (NH_3) with an excellent uniformity of film thickness and composition [89]. However the silicon nitride film generated by CVD process may suffer high residual stress, typically as high as GPa level, and thus is not well suitable for making microstructure. On the other hand, low pressure chemical vapor deposition (LPCVD) process is a commonly used method to fabricate stress-controlled silicon nitride film on semiconductor substrate [90], which was also explored and utilized to deposit low stress silicon nitride film here, at moderately high temperatures (850°C) and low pressure (250 mtorr), using dichlorosilane (SiCl_2H_2) and ammonia (NH_3). The residual stress of silicon nitride film highly depends on the process conditions, especially on the gas-ratios of DCS (SiCl_2H_2) and ammonia (NH_3). Stress reduction can be accomplished by increasing $\text{SiCl}_2\text{H}_2/\text{NH}_3$ gas-ratio. The 1200nm silicon nitride film deposited by a gas-ratio of 6:1 (DCS: NH_3) at 850°C results in a tensile stress of 40MPa. For comparison, the typical process with a gas-ratio of 3:1 (DCS: NH_3) leads to several

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

hundreds MPa of tensile stresses in the deposited silicon nitride films with the same thickness.

Figure 34 The relationship of measured residual stress of gold film and chamber pressure, with 300 W of DC power during the sputtering process

The gold film deposited on top of the $\text{SiO}_2/\text{Si}_3\text{N}_4$ diaphragm is for making electrode purpose, refer to Figure 29. The residual stress of the gold film due to process must also be kept as small as possible to avoid undesired effects such as the high actuation voltage. A 10 nm Ti/400 nm gold layer is deposited to create the membrane electrode by sputtering process for the proposed MEMS switches. It is observed that the chamber pressure, during the process, has much influence on the residual stress of the gold film and plays an important role in the stress-control for the metal film, refer to Figure 34. A chamber

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

pressure of 8 mtorr results in 15 MPa of tensile stress in the gold film. It should be pointed out that the low chamber pressure of 6mT, will lead to a compressive stress of 24.2 MPa.

4.3.3 Wafer Bonding Technology with Intermediate Layer

The diaphragm configuration of the MEMS switch is accomplished by bonding two wafers together. The commonly used anodic bonding technique, which involves a glass and a silicon wafer [91], is not suitable here, since the base glass wafer has already been covered a metallization layer (CPW) with a thickness of 0.6 μm and does not provide sufficient glass – silicon contact surface. Therefore, we explored intermediate wafer bonding technique using *CYTOP CTL809M* fluoropolymer (from Asahi Glass Co. Ltd [92]) to solve the wafer bonding issue. *CYTOP* is an innovation in the field of fluoropolymers [93]. It has an amorphous (noncrystalline) nature that differs from conventional fluoropolymer, an extremely high optical transparency, and solubilization in specific fluorinated solvent and thus the capability of being spun-on surface with good adhesion. Furthermore, it possesses the same excellent chemical, thermal, electrical and surface properties as conventional fluoropolymers. The intermediate wafer bonding technique by *CYTOP* provides advantages of low process temperature of 160 $^{\circ}\text{C}$, a flexible bonding approach without stringent requirements on surface flatness of processed wafers, and capability of achieving selective bonding area by conventional lithography.

To fabricate the proposed MEMS switches, *CYTOP* polymer is spun on the glass wafer. A 1000 rpm of spin speed and 30s of spin-time result in a coating thickness of 2 μm . The *CYTOP* polymer is pre-cured at 90 $^{\circ}\text{C}$ for 20 minutes followed by 100 $^{\circ}\text{C}$ for 30 minutes,

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

according to a pretreatment recipe developed by our group. The *CYTOP* polymer is then patterned by photolithography using AZ9260 photoresist and subsequently by etching in a reactive ion etching (RIE) chamber by oxygen plasma. The alignment of two wafers during the wafer bonding process is conducted by a commercial wafer bonder *Karl Suss* MA6 mask aligner. The alignment accuracy by the machine is within 5 μm . The fully curing of *CYTOP* polymer is carried out in the wafer bonder, at 160 $^{\circ}\text{C}$ with 2bar of pressure for 60 minutes.

4.4 Fabrication Issues and Suggestions

At the last step of the MEMS switch fabrication as shown in Figure 31 (11), a 200 μm thick silicon shadow mask, created by DRIE, is used to create the pattern of the top electrodes on the diaphragm and to mask out the areas of the exposed bottom wafer. The shadow mask is placed directly onto the wafer stack by manual alignment under a microscope. However, an issue arose from the shadow mask is that the slot in the top-electrode metal layer above the signal line (see Figure 29) generated by sputtering in this step is unsharp and inaccurate. The nominal width of the opening in the shadow-mask is 320 μm , while the actual width of the fabricated opening is about 280 μm . The reason for the decreased opening in the electrode metal layer is that the shadow mask is placed at a vertical distance of 200 μm above the diaphragm during the sputtering, which results in very unsharp edges of the metal pattern and thus increase the insertion loss of the switch as described in Section 4.7.

Chapter 4 *Highly Reliable Switches with Ruthenium-based Contacts*

One solution to overcome the issue is the reduction of the vertical distance of the shadow-mask to the diaphragm, which can be achieved by involving a CMP process step to thin down the top silicon handle wafer before the release of the diaphragm.

4.5 Performance of Switch Actuation

The measured mechanical performances of the flat or stress-reduced corrugated diaphragms are presented in this section, focusing on the membrane deflections and pull-in voltages of various diaphragm designs with different corrugation numbers.

4.5.1 Diaphragm Deflection

An ideal planar diaphragm remains flat without any bending after membrane release. This is because the residual tensile stress is in-plane and uniformly distributed, leading to the in-plane force, which increases the rigidity of the diaphragm but does not generate the bending moment, while the tensile stress is asymmetry for a corrugated diaphragm. The bending moments at the edges of diaphragm, in this case, do not fully counteract the asymmetrical stresses and thus cause deformation. [94].

The diaphragm deformation of the fabricated switch under zero actuation voltage was measured by a *Dektak 3ST* surface profiler. The stylus force of the profiler was set to be 5 μN during the measurement. It should be noted that the stylus force is much less than the

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

actuation force needed to pull down the diaphragm and equivalent to an actuation voltage of 4 V according to Equation (27) while the pull-in force is 541 μN to 3380 μN for an actuation voltage of 42 V to 105 V, respectively.

Figure 35 (a) Measured static center deflection of diaphragm as a function of the corrugation number under zero actuation voltage using the diaphragm edge as the

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

reference. (b) Deformation of a diaphragm with four corrugations obtained by optical profiler. The device is unassembled without any actuation voltage.

The test results are plotted in Figure 35 (a). A static deflection of diaphragm was found in all diaphragms measured, in a bowing-up form. With the number of corrugations increased, the magnitude of the static centre deflection of the diaphragm is also enlarged. It should be noted that the static center deflection was observed even in a diaphragm without any corrugations. The reason is that the diaphragm of the MEMS switch has a relay metal deposited at the centre, which is center-asymmetry and not an ideal flat membrane anymore. The internal tensile stress in the metal and diaphragm becomes non-uniform in the actual case, resulting in the out-of-plane force which generates the bending moment and deflect the center part of the diaphragm. With the increased number of corrugations, the total stress in the diaphragm is reduced, resulting in the higher static diaphragm deflection because the stress between the metal and diaphragm remains the same. Figure 35 (b) shows the deformation of a diaphragm, which is unassembled without any actuation voltage, with four corrugations obtained by optical profiler. It should be pointed out that the static deflection will cause an increase in the pull-in voltage.

4.5.2 Pull-in Voltage

The 100 nm SiO₂/1200 nm Si₃N₄/400 nm Ti/Au film results in an overall residual tensile stress of 56 MPa at wafer level, which is measured by the *Tencor* thin film stress

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

characterization system, determined by the wafer curvature before and after depositing the film.

Number of corrugation	0	2	4
Measured actuation voltage (V)	105	51	42
Calculated actuation voltage (V) by Equation (27)	106	54.7	44.8
Calculated stress reduction ratio (η) by Equation (20)	1	4.7	9.5
Equivalent stress σ_0/η (MPa)	$\sigma_0/1 = 56$ $\sigma_0/4.7 = 11.9$ $\sigma_0/9.5 = 5.9$		
Gap ($g_0 + \delta$, in μm)	$7 + 0.3$	$7 + 0.5$	$7 + 0.8$
Radius/equivalent radius (μm)	$900/792$	$900/792$	$900/792$

Table 6 Measured and calculated pull-in voltage, calculated stress reduction ratio η , and measured diaphragm deformation of the proposed MEMS switches.

Figure 36 Measured pull-in voltages of MEMS switches in comparison with calculated ones using Equation (27).

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

The necessary pull-in voltages were measured for the MEMS switches with the flat and corrugated diaphragms. The measurement results are shown in Figure 36. For comparison, the calculated pull-in voltages by using Equation (27) are also given in Table II, where g_0 is the gap at the edge of diaphragm and δ is the centre deflection. The calculation results agree quite well with the measurement ones with errors of less than 7%. Note that the measured values are a little smaller than calculated ones. The reason is that we took $(\sigma + \sigma_0)$ as the air-gap for calculation which is a little larger than the actual average values of air-gap between the diaphragm and base substrate. The pull-in voltage is greatly reduced from 105 V for flat diaphragm to 51 V and 42 V for the two-corrugation and four-corrugation diaphragms, respectively. Obviously, the reduction in pull-in voltage is significant with the introduction of corrugation, which can effectively reduce the internal stresses of diaphragm. It should be highlighted that the equivalent diaphragm stress is only 11.9 MPa and 5.9 MPa with 2 and 4 corrugations, respectively. It is not an easy way to achieve such low stress levels alone by typical stress-control process for a diaphragm with the multilayer structure (400 nm Ti/Au film electrode/1200 nm Si₃N₄ /100 nm SiO₂/500 nm relay metal) [95].

4.6 Ruthenium-based Contact Properties

The contact properties of the proposed ruthenium-based multilayer contact metallization are measured and discussed in this section, including the DC contact resistances, switch contact reliability and current handling capabilities.

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

4.6.1 DC Contact Resistance

The DC single-contact resistance of the MEMS switches was measured by four-probe measurement during subsequent switching cycles, subtracting the line resistance of the contact bar between the two contact points. A measurement current of 1.6 mA was applied for 10 s during each cycle. Ten devices chosen from two wafers were tested, one wafer with Au-Au metal contacts and another wafer with Au/Ru-Ru/Au metal contacts.

Figure 37 (a) shows the measured contact resistance of a single Au/Ru-Ru/Au contact plotted over the first 30 switch cycles of 5 assembled switches actuated at different actuation voltage levels. Here Au/Ru or Ru/Au refers to the Cr/Ru/Au/Ru multi-layer metallization system. For comparison, the measured data of single Au-Au contacts are shown in Figure 37 (b). As expected, higher actuation voltage creates a larger contact force resulting in lower contact resistance. Especially for Ru, the contact surfaces have to adapt to each other during the first switching cycles, until the contact resistance is stabilized. At low contact forces (actuation voltage of less than 60 V for Au/Ru-Ru/Au contacts and less than 40 V for Au-Au contacts), the resistance of the first cycles is very unstable.

The Au/Ru-Ru/Au contacts require an actuation voltage of 80 V to result in a stable contact resistance of 730 m Ω , whereas an actuation voltage of 40 V is sufficient for a contact resistance of less than 700 m Ω for Au-Au contacts. This indicates that Au/Ru-Ru/Au contacts require a force at least four times larger than for Au-Au contacts. An

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

actuation voltage of 80 V results in a contact resistance of about 300 mΩ for the pure Au-Au contacts. The contact resistance of the novel ruthenium multi-metal contacts is much lower as compared to pure ruthenium contacts in the literature, and our contact resistance measurement confirms the theoretically predicted contact resistance increase for the chosen metal stack very well. For both metallization types, the variation in the contact resistance among different devices is less than 10% after an initial “burn-in” phase of the contacts about 30 switching cycles as illustrated in Figure 37 (a) and (b).

Furthermore, the contact surfaces, prior to measurement cycles, have been inspected by x-ray photoelectron spectroscopy (XPS), shown in Figure 10. Especially the Ru sample shows carbon peaks in the C1s region. These species are the surface contamination from adsorbed gases, which is further explanation of the switches requiring a few cycles with applied signal current to locally clean the asperities from surface contaminants before a stable and lower contact resistance is established.

Figure 37 Contact resistance over switching cycles: (a) the first 30 cycles of Au/Ru-Ru/Au contact at different voltage levels, (b) the initial 30 cycles of Au-Au contact at different voltage levels, (c) contact resistance change behavior over cycle number with signal current of 5 mA; the resistances and failure points plotted are average values of the two types of devices tested at 5 mA. SEM photos of ruthenium and gold contacts, before & after the cycling tests are also shown.

Figure 38 X-ray photoelectron spectroscopy (XPS) of the Ru and Au contact surfaces, indicating the presence of absorbed carbon and oxygen on the contact surfaces.

4.6.2 Reliability of Switch Contact

The reliability of the Au/Ru-Ru/Au switch contacts as compared to the Au-Au contacts was investigated in terms of switch-cycle measurements. A square-shaped waveform of 1 kHz with a duty-cycle of 20% and a unipolar amplitude of 40 V, on top of a DC offset of 40 V for the Au/Ru-Ru/Au switches and 30 V for the Au-Au switches, was applied to the switch actuator and monitored by an oscilloscope together with the current in the switched transmission line, as shown in Figure 39.

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

Figure 39 Schematic diagram of testing set-up configuration for the switching-cycle measurement

The reliability of the two different contact metallizations was investigated at different signal currents and the results are listed in Table III and plotted in Figure 40. Two wafers were tested, one for Au-Au metal contacts and the other for Au/Ru-Ru/Au metal contacts. Two devices were measured for each current level of 1.6 mA, 5 mA and 10 mA, respectively. One device with Au-Au contact metal was also tested at 0.1 mA.

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

Figure 40 Contact reliability for the Au-Au and Au/Ru-Ru/Au contacts, investigated for different signal currents. Measurement conditions: cycle frequency of 1 kHz, duty cycle of 20%, rectangular and monopolar waveform of 40V peak amplitude.

Signal current (mA)		0.1	1.6	5	10
Switch cycles, Au-Au contacts (million)	Series 1, Au	>1000 (test stopped)	28.90	0.85	0.24
	Series 2, Au	not measured	18.0	0.47	0.103
Switch cycles, Au/Ru-Ru/Au contact (million)	Series 1, Ru	not measured	126.0	7.80	3.30
	Series 2, Ru	not measured	87.0	6.51	2.53

Table 7 Contact reliability of Au-Au and Au/Ru-Ru/Au in number of switch cycles, measured for different signal currents.

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

The measurements show that Au-Au contacts work well for signal currents below 1 mA, achieving over 1 billion switching cycles before the tests were stopped). At current levels above 1 mA, however, the switches fail prematurely. The durability of the Au/Ru-Ru/Au contacts is higher by a factor of about 4 times at current level of 1.6 mA and about 10 times at current levels of more than 5 mA, as compared to the Au-Au contacts. All of the Au-Au switches failed due to contact welding, observed by irreversible contact stiction. The observed failure mode of the Au/Ru-Ru/Au switches was either due to contact stiction (for 1.6 mA) or a sudden increased resistance above 100 Ω (for 5 mA and 10 mA). The contact resistances were measured during the life-time tests, without any obvious contact resistance changes (less than 20% of change) before sudden contact stiction or sudden increased resistance occurred, see Figure 9 (c) showing the case of 5 mA. This is not surprising since ruthenium is a material much harder than gold. The gold asperities on the contact surface are much easier deformed and weld easier together due to the much lower hardness of gold as compared to ruthenium. Figure 37 also shows the SEM photos of ruthenium and gold contacts, before & after the cycling tests. The possible reason behind the sudden increased resistance is due to frictional polymerization after a high number of switching cycles [96], [97]. The frictional polymerization is the formation of organic polymer on metal contacts which increases the contact resistance rapidly.

It should be mentioned that RadantMEMS has developed an electrostatically actuated MEMS switch which demonstrates a lifetime of 100 billion cycles [98]. While most MEMS switches published by other research groups present near or less than billion cycles of lifetime.

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

4.6.3 Current Handling Capability

The current handling capacity of the transmission line alone, consisting of the 50 nm Cr/50 nm Ru/500 nm Au/50 nm Ru metallization stack, was investigated in a separated study. A signal line of 3000 μm long, 125 μm wide and 1.2 μm thick, was fabricated on a 750 μm thick glass which has much lower thermal conductivity than silicon. The maximum DC current handling capacity of this line can achieve as high as 6.6 A, which corresponds to a current density of 44 $\text{mA}/\mu\text{m}^2$ by consideration of the cross-section area of the signal line, without significant degradation observed after several tests. The measured electrical resistance of the line was relatively stable within 5% variation of increment even tested for 24 hours at a lower DC current of 0.5 A, corresponding to a current density of 3.3 $\text{mA}/\mu\text{m}^2$.

4.7 RF Performance of Switches

The RF performance of the prototypes was measured by using a *HP 8722D* network analyzer using GSG microwave probe. The measurement results of isolation and insertion loss of the whole chip, i.e. the packaged switch and the 3 mm long coplanar waveguide, are shown in Figure 41, together with the simulation results. The measurement results of the isolation S_{21} for a MEMS switch with 6 μm of nominal suspension height and a 250 $\mu\text{m} \times 210 \mu\text{m}$ large contact areas, match the simulation results very well over a large frequency range. Up to 1 GHz, the measured isolation is better than -45 dB and at 15 GHz, the isolation is still better than -20 dB.

(a)

(b)

Figure 41 RF performance of an encapsulated switch including a 3 mm long coplanar waveguide transmission line: (a) Simulated and measured S_{21} and S_{11} in the off-state, (b) Simulated and measured S_{21} and S_{11} in the on-state. The electrode spacing refers to the gap left open in the membrane metallization layer. (c) Share percentage of transmitted, reflected and total lost power.

The measured insertion loss of the switch is about -0.7 dB up to 4 GHz, and -2.8 dB at 15 GHz. These values, however, are worse than the simulation results using the nominal design values, as shown in Figure 41 (b), and are also much worse than typical MEMS switch insertion losses [99]. This discrepancy was investigated and it was found that the higher insertion loss is mainly caused by the fabrication inaccuracy of the slot in the top-electrode metal layer above the signal line as mentioned above in Section 4.4. The

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

nominal width of the opening in the shadow-mask is 320 μm , 70 μm wider than the centre signal line. However, the actual width of the fabricated opening is about 280 μm which is much narrower than the nominal 320 μm . The too narrow slot generates much reflected power as shown in Figure 41. Simulations by *Ansoft HFSS* Version 9.2 show that the insertion loss and return loss drastically improve when the open slot in the metal electrode layer changes from 280 μm to 320 μm (Figure 41b). However, even for the nominal 320 μm slot in the top metal electrode, the simulated return loss is relatively high as shown in the figure, which is the result of a general mismatch of the transmission line design to the 50 Ω measurement setup. Also, the radiation and material losses of the fabricated switches with their 3 mm long transmission line piece are relatively high. Figure 41(c) shows the share of the transmitted power, reflected power, and total power losses (radiated and dissipated) of the switch plotted in the evaluated spectrum. Approximately 2% of the power losses are contributed by the metal contacts, the remaining part is dielectric, radiation and other ohmic losses.

The RF measurements are very well reproducible, and 5 different devices of the same design, obtained from the same fabricated wafer, were evaluated with very well matching results.

4.8 Summary

A wafer-scale encapsulated RF MEMS series metal-contact switch with a circular corrugated diaphragm are developed and presented in this chapter. The switch employs

Chapter 4 Highly Reliable Switches with Ruthenium-based Contacts

corrugations in the diaphragm to result in a design less sensitive to residual stress in the membrane. Moreover the concept for the contact metallization utilizing a multilayer metal stack with a final ruthenium cladding is used to address the contact reliability and current handling capability. The switch is fabricated in two components on two separate wafers which are subsequently bonded by polymer wafer bonding, resulting in a near-hermetic, encapsulated switch on wafer level.

It was observed that all diaphragms have static bowing-up deflections under zero actuation voltage due to the center-asymmetry structure of the relay metal on the diaphragm. The magnitude of the static centre diaphragm deflection enlarges with the increase in the corrugation number due to the reduced stress in the diaphragm while the stress between the relay metal and diaphragm remains the same. The application of corrugations is proven to be an easier way to reduce the residual stress as compared to the approach by process control. Furthermore, the greater robustness of the ruthenium metal contact coating could successfully be proven by reliability measurements, compared to switches of the same design with pure gold contacts. The RF isolation of the switch corresponds very well to the simulation results, but the insertion loss is worse which was shown to be attributed by an inaccurate shadow-mask sputtering process.

Chapter 5 MEMS Switches Based on Perforated Substrate for Switching Speed Enhancement

A wafer-level encapsulated RF MEMS shunt switch, as a demonstrator for proof-of-concept, with a perforated base substrate is presented in this chapter. The introduction of damping holes is proven to be an effective way to reduce the damping due to air flow and therefore increase the switching speed, by the development of the demonstrator as described in the following sections. In Section 5.1, a brief introduction of the proposal to release the high speed switch is firstly given, followed by the details of modeling of damping reduction by perforation and modeling of switching times for switches with perforated substrates, respectively. The calculations and simulations of damping coefficients and switching times for the proposed switches with different air gaps and base substrates are provided as well. The fabrication of the device, involving three stacked wafers, is discussed in Section 5.2. The characterization of the fabricated switches is highlighted in Section 5.3 which covers the pull-in times and release times of the switches, and RF performance of the devices including isolation and insertion losses for a frequency band from DC to 25 GHz. Lastly, Section 5.4 closes this chapter with summary on the design, fabrication and characterization aspects with respect to high speed switch with the introduction of perforation in the base substrate.

5.1 Switch Design Aspects

Switching speed is one of the few disadvantages of RF MEMS switch compared to its solid-state counterpart such as PIN diodes or FET transistors. A lot of attention has been paid on the switching speed of MEMS switch which still remains one of the limitations of MEMS switches due to their mechanical movements of moving-parts. [100], [101] , [102]. A method for increasing switching speed is to perforate moving part, such as bridge or diaphragm, in order for reducing the damping due to the air flow in a narrow air gap [103], [104]. Unfortunately, this approach is not suitable for the concept of wafer-level encapsulation proposed in Section 2.4. The reason is that the diaphragm itself of the proposed switch is part of encapsulated micro-chamber and can not be perforated.

To resolve this issue, we apply perforating technique to the base-substrate instead of diaphragm to remain the integrity of micro-chamber and reduce the damping at the same time. A demonstrator, a RF MEMS shunt switch, was proposed and developed as described in the following sections. For the first time the perforated base substrate by meticulous design is introduced to tremendously reduce squeeze-film damping and thus significantly increase the switching speed.

5.1.1 Proposal of High Speed Switch Realization

Typical DC contact series switches give high isolation from 0.1-20 GHz, while the

Chapter 5 High Speed MEMS switches with Perforated Substrate

typical capacitive shunt switches with silicon oxide or nitride dielectric film have excellent isolation at 10-120 GHz [14]. One type of shunt switch based on metal-to-metal contact by removing dielectric layer was developed [14], [105], which is an alternative shunt switch and can be used to replace series switch for 0.1-20 GHz operation.

A demonstrator, a RF MEMS shunt switch, was proposed for proof-of-concept which is based on metal-to-metal contact and corrugated diaphragm as shown in Figure 42. It involves three parts which are fabricated separately before being bonded together by wafer-bonding processing. The concept of three-stacked-wafer provides a means to assemble/package the MEMS switch at wafer-level, enabling the encapsulation of the contact metals in a micro-chamber filling with inertial gas.

The proposed switch consists of a circular diaphragm with a contact metal attached beneath it in the centre, two off-centre pull down electrodes, coplanar waveguide (CPW) and acoustic holes in the base substrate, and a cavity on the backplate. The implementation of hole in the base-substrate is to reduce the damping due to the squeeze film in the air gap between the diaphragm and base-substrate. The core of the switch is the thin and flexible silicon nitride diaphragm suspended at a height of 8 μm above the CPW, moving up and down under electrostatic actuation for switching purpose. The corrugation technique was also introduced to the diaphragm to alleviate the possible high residual stress in the diaphragm.

Figure 42 Schematic drawing of three parts of the demonstrator, which will be bonded together by wafer bonding using CYTOP polymer.

5.1.2 Modeling of Damping Reduction by Perforation Introduction

The distinction part of the RF MEMS switch is the moveable diaphragm together with the relay metal that is driven by electrostatic actuation. A moving structure with small size can be profoundly influenced by the gas surrounding them. When the MEMS diaphragm

Chapter 5 High Speed MEMS switches with Perforated Substrate

is actuated by an alternative voltage, it will move down and up to make electric break and open, respectively. During the operation of the switch, the air (or gas) in the gap will be squeezed and pushed from the underneath the substrate. The air molecules undergo several collisions in the gap between the diaphragm and base substrate. The air moving in the narrow air gap results in increased viscous damping [106]. This may lead to serious damping and thus slowing switching speed, and decreasing mechanical sensitivity as well. Therefore, it is necessary to reduce the length of the narrow path by making damping holes in the base-substrate. The proposed MEMS switch employs a base substrate that has been perforated for the purpose to reduce the damping due to air flow.

Zuckerwar undertook analysis of mechanical response for condenser microphone by appropriately modeling the opening in the backplate [107], [108]. Despite the model was created for condenser microphone application, it is still applicable for the proposed switch here. As we know, a diaphragm of a microphone is excited by an incident sound pressure, resulting in the capacitance change between the membrane and backplate and producing output voltage. While a diaphragm of the proposed switch is driven by actuation voltage, leading to the deflection of membrane for switching purpose. Both devices are composed of electrical and mechanical systems. Although the electrical systems of the two devices can be quite different, their mechanical systems are similar. A comparison of the mechanical systems between microphone and the switch is shown in Figure 43. The MES microphone consists of three parts: diaphragm, backplate and backchamber. Similarly, the MEMS switch involves diaphragm, base substrate and backchamber as well. The only difference is that the microphone adopts a slot in the backplate while the switch does not. The two devices, therefore, should bear the similar

Chapter 5 High Speed MEMS switches with Perforated Substrate

damping characteristics due to their similar mechanical systems. As such, the equations derived by Zuckerwar, describing the mechanical response of the microphone, will also be applied below for the proposed switch application.

Figure 43 Schematic drawings of a MEMS microphone and the proposed MEMS switch. (a) Cross sectional view, and (b) top view of the two devices.

The damping coefficient, also termed as air resistance, of a diaphragm is due to the viscous damping losses in the air gap and the damping holes is governed by following equation [107], [108],

Chapter 5 High Speed MEMS switches with Perforated Substrate

$$B_a = \frac{8\pi T \text{Im}(D)}{\omega} \quad (43)$$

where T is the diaphragm tension, ω is the angular velocity, a is the radius of the diaphragm, and D is the air layer damping term (an dimensionless quantity) and is given by,

$$D = \frac{j4\omega\rho_0 J_0(Ka)}{\pi} \sum_{m=0}^{\infty} \left[-j\omega \left(\frac{z_m}{z_0} \right) + \sum_{s=1}^q \left(\frac{f_s}{z_0} \right) S_s \Gamma_m J_0(\xi_m a_s) \right] \\ \times \frac{1}{T_m J_0(\xi_m a)} \left\{ \frac{J_2(Ka) \delta(m)}{4K^2 a^2} + \frac{J_1(Ka) [1 - \delta(m)]}{2Ka (K^2 a^2 - \xi_m^2 a^2)} \right\} \quad (44)$$

where ρ_0 is the static air density (1.205 kg m^{-3}), m is the number of summation terms, z_m is the diaphragm displacement function [108], z_0 is the interim unknown diaphragm displacement in a trial expression [108], q is the number of holes, f_s is the air velocity at the k^{th} opening in the back-support, S_s is the area of the k^{th} opening in the back-support, Γ_m and T_m are numerical constants [108], ξ_m is the symmetric radical component of the scalar wave number, a_s is the location of the k^{th} opening in the back-support, $\delta(m)$ is a conditional function ($\delta(m) = 1$ when $m = 0$; $\delta(m) = 0$ otherwise), $J_0(Ka)$, $J_1(Ka)$ and $J_2(Ka)$ are the zero, first-order and second-order Bessel functions of Ka , respectively. Here K is the wave number of sound in the diaphragm and can be expressed by

$$K = \omega \sqrt{\left(\frac{\sigma_M}{T} \right)} \quad (45)$$

where σ_M is the mass surface density of diaphragm. The derivation of Equations (43) to (45) is given in detail in Appendix C.

Figure 44 Simulation results of damping coefficient of diaphragm with different base substrates and air gaps.

One method of increasing switching speed of the diaphragm is to reduce the damping resistance through the meticulous design of base-substrate (with damping holes) and air gap. When holes are perforated in the substrate, the damping can be reduced significantly as the air has an alternative path to escape through the holes rather than being squeezed out from the edge of the substrate. Obviously from Equation (43) and Equation (45), the damping coefficient is dependent on the location of holes in the base substrate. It should be noted that the diaphragm deflection is non-uniform in the radial direction and location dependent, and the f_s is also dependent on the hole location due to the non-uniform

Chapter 5 High Speed MEMS switches with Perforated Substrate

distributed pressure on the base substrate. Therefore, the physical location of holes in the base-substrate does play an important role on the damping characteristics.

A simulation of damping coefficient of the diaphragm of the proposed MEMS switch was performed, based on the parameters listed in Table 8. For comparison, the damping coefficient of diaphragms with different air gaps (thus different actuation voltages as shown in Table 9) are also computed as shown in Figure 44. It is seen that at switching speeds below a few thousand of cycles/second, there is not much change of damping coefficient with the increase of switching speed. The damping coefficient keeps, roughly, constant at the low switching speed ranging from 50 to around 5000 cycles/second. However, the damping coefficient is dependent strongly on the opening in the base substrate and air gap. The damping coefficient is reduced significantly with the implementation of damping holes in the base substrate. The reduction of the damping coefficient for each air gap is as high as 13 times. This implies with the perforated base-substrate, the air finds an alternative path and takes much less time to escape from the gap. Furthermore, one can imagine that the air takes less time to escape from the air gap if it is enlarged. Therefore, the damping coefficient should be reduced with the increase of air gap. And this is true, which is clearly shown in Figure 44. For example, the damping coefficient of the proposed diaphragm will be reduced from 3.7×10^{10} Ns/m⁵ to 2.4×10^9 Ns/m⁵ when air gap increase from 4 to 10 μm when base substrate is not perforated.

It should be pointed out that damping models of Škvor [109] and Starr [110] are very popular among many authors and widely used for MEMS application, which are based on the concepts of the number of damping holes, plate area and air gap thickness. However,

Chapter 5 High Speed MEMS switches with Perforated Substrate

their models do not take in account of the location of damping holes in the backplate, the thickness of the backplate, and the influence of the backchamber. On the other hand, Zuckerwar's model mentioned above considers all these factors including the location of damping holes, the backplate thickness, and the influence of the backchamber [107]. Zuckerwar's model was verified to give better accuracy for condenser microphone application by C.W. Tan [111], [112], and thus was applied here for the switch application.

Parameters	Symbol	Values
Diaphragm radius	a	1750 μm
Diaphragm thickness	d	1.75 μm
Mass surface density of Diaphragm	σ_m	$3290 \times 1.75 \times 10^{-6} \text{ kg/m}^2$
Diaphragm tension	T	$50 \times 1.75 = 87.5 \text{ N/m}$
Substrate radius	$b = a$	1750 μm
Unpolarized air gap	g_0	8 μm
Back chamber volume	V_{om}	$\pi \times (1750 \mu\text{m})^2 \times 150 \mu\text{m}$
Number of holes per rings	bl	10
Location of radius ring	al	450, 620, 790, 960, 1130, 1300, 1470 μm
Hole radius	rl	50 μm
Hole depth	ll	500 μm
Polarization voltage	V	60 V

Table 8 Parameters of the proposed MEMS switch with corrugated diaphragm and perforated base substrate.

5.1.3 Modeling of Switching Times

One shortcoming of the RF MEMS switch is the relatively large switching times. The inertial due to mechanical movement still limits its switching speed. Figure 45 (c) shows a schematic drawing of one-dimensional model of the diaphragm which is a good first-order representation of a wide variety of pull-in device. The inertial mass (the moveable diaphragm with a mass of m) of one-dimensional macro-model moves along z coordinate. The equation of motion of the diaphragm is

$$F_{spring} + F_{damping} - F_{electra} = m \frac{d^2 z}{dt^2} \quad (46)$$

where F_{spring} is spring force of the diaphragm governed by $F_{spring} = k (g_0 - z)$, k is the equivalent spring constant of the diaphragm with an initial air gap of g_0 . $F_{damping}$ is the gas damping force exerted to the diaphragm due to the squeeze film damping. $F_{electra}$ is the electrostatic force generated by actuation voltage V across the parallel plate of area A . Steenken et. al., derived the following equations to express $F_{damping}$ and F_{el} [103]:

$$F_{damping} = \frac{-B_a (A^2 g_0^3)}{(1 + \gamma \frac{g_0}{z}) z^3} \frac{dz}{dt} \quad (47)$$

$$F_{electra} = -\epsilon_0 A V^2 \left(\frac{1}{2z^2} + \frac{1}{\pi W_s z} \right) \quad (48)$$

where γ is the slip-flow constant ($\gamma = 9\lambda / g$), λ is the mean free path of gas molecules that is about 70 nm under atmospheric pressure at room temperature, W_s is a factor considering fringing effect (the fringing field of the top electrode is approximated by a microstripline with width W_s and gap z). By substituting Equation (47) and Equation (48)

Chapter 5 High Speed MEMS switches with Perforated Substrate

in Equation (46) and rearrangement, we can obtain the following differential equation of motion for the one-dimensional system:

$$m \frac{d^2 z}{dt^2} + \frac{B_a (A^2 g_0^3)}{(1 + \gamma \frac{g_0}{z}) z^3} \frac{dz}{dt} + k(z - g_0) + \varepsilon_0 A V^2 \left(\frac{1}{2z^2} + \frac{1}{\pi W_s z} \right) = 0 \quad (49)$$

The switching time can be obtained from Equation (49) by integration, if inertial effects and fringe fields are neglected. For the pull-in motion ($V > V_{pi}$), from the up-position ($\bar{z}_1$) to the down-position ($\bar{z}_0$), the switching time is [103],

$$t_{pull-in}(\bar{z}) \Big|_{\bar{z}_1}^{\bar{z}_0} = \frac{-8B_a(A^2 g_0^3)}{A\varepsilon_0 V_{pi}^2 f_1(-\gamma) f_2(-\gamma) f_3(2\delta)} \times \left[f_3(2\delta) \ln(\bar{z} + \gamma) - \frac{f_1(-\gamma)}{3} \ln(f_2(\bar{z})) \right. \\ \left. + \frac{f_1(-\gamma) - 3f_3(2\delta)}{6} \ln(f_1(\bar{z})) - \frac{f_2(-\gamma)(f_2(-\delta\gamma) - 3\delta)}{\sqrt{3f_3(\delta)}} \arctan \frac{f_2(\bar{z}) - 3\delta}{\sqrt{3f_3(\delta)}} \right] \Big|_{\bar{z}_1}^{\bar{z}_0} \quad (50)$$

where the normalized position $\bar{z} = z / g_0$, and

$$\delta = \cosh \left[\frac{1}{3} \arccos h \left(\frac{2V_{eff}^2}{V_{pi}^2} - 1 \right) \right] \quad (51)$$

$$f_1(x) = f_2(x)[f_2(x) - 6\delta] + 3f_3(2\delta) \quad (52)$$

$$f_2(x) = 3x + 2\delta - 1 \quad (53)$$

$$f_3(x) = x^2 - 1 \quad (54)$$

For the switching-up motion ($V = 0$), from the down-position ($\bar{z}_0$) to the up-position ($\bar{z}_1$), the switching time is [103],

$$t_{release}(\bar{z}) \Big|_{\bar{z}_0}^{\bar{z}_1} = \frac{-8B_a(A^2 g_0^3)}{27A\varepsilon_0 V_{pi}^2 (1 + \gamma)} \times \left[\frac{1 + \gamma}{\gamma \bar{z}} + \ln \left(\frac{1}{\bar{z}} - 1 \right) - \frac{1}{\gamma^2} \ln \left(1 + \frac{\gamma}{\bar{z}} \right) \right] \Big|_{\bar{z}_0}^{\bar{z}_1} \quad (55)$$

The derivation of Equations (47) – (55) is given in detail in Appendix D.

Chapter 5 High Speed MEMS switches with Perforated Substrate

It is seen that the switching time depends strongly on the damping coefficient B_a , pull-in voltage V_{pi} and ratio of V/V_{pi} (for pull-in motion). The switching time can be reduced by decreasing B_a by perforating base substrate, increasing the pull-in voltage V_{pi} and actuation voltage V , since smaller B_a and larger voltages mean weaker damping force and stronger electrostatic force.

Figure 45 Illustration of the demonstrator with corrugated diaphragm and perforated base substrate. (a) Top view of base substrate with damping holes, (b) cross sectional view of the demonstrator involving three parts bonded together, and (c) lumped one dimensional model of the diaphragm.

Figure 46 Calculated pull-in time and release time for the corrugated diaphragm with different air gaps.

Chapter 5 High Speed MEMS switches with Perforated Substrate

Figure 46 plots the switching times as a function of air gap g_0 calculated by using Equation (50) and Equation (55), with the damping coefficient B_a , pull-in voltage V_{pi} and actuation voltage tabulated in Table 9 and other geometric parameters of the MEMS switch as listed in Table 8. Obviously pull-in and release time can be greatly reduced, about 13 times, with the implementation of damping holes inside the base-substrate due to the much smaller air forces. Notice that the switching times, either pull-in or release time, increase with air gap g_0 reduced. This is because the larger damping coefficients for the smaller air gap g_0 , and lower pull-in voltages are needed in correspondence with the smaller air gaps. It should be pointed out that the proposed switch was made purposely with a large diaphragm of 1750 μm in radius and an air gap of 8 μm , for the purposed to demonstrate the switching speed increase by the perforation in the base substrate.

Air gap	3 μm	4 μm	5 μm	6 μm	7 μm	8 μm	9 μm	10 μm
Damping coefficient with holes B_a (Ns/m, 100Hz)	0.612	0.256	0.130	0.0746	0.0462	0.0312	0.0218	0.0159
Damping coefficient without holes B_a (Ns/m, 100Hz)	8.03	3.40	1.74	1.01	0.635	0.426	0.300	0.219
Pull-in voltage V_{pi} (V)	12.6	19.3	27.1	35.6	44.9	54.9	65.6	77.0
Actuation voltage V (V) (110% of V_{pi})	14	21	30	39	49	60	72	85

Table 9 Damping coefficient B_a , pull-in voltage V_{pi} and Actuation voltage V of the proposed switch for different air gaps

Chapter 5 High Speed MEMS switches with Perforated Substrate

5.2 Fabrication Process Flow

Three silicon wafers are involved in the fabrication of the MEMS switches, which are fabricated separately before being bonded together to achieve a wafer-level encapsulated MEMS switch as illustrated in Figure 42. The fabrication process flow is depicted in Figure 47, utilizing micromachining and wafer bonding processes. The fabrication needs seven photolithography masks and one silicon shadow mask.

The process starts on the bottom-support, fabricated with a 350 μm thick silicon wafer. A polymer (*CYTOP* from Asahi Glass Co. Ltd) is firstly spin-coated with a thickness of 2 μm on the silicon wafer. The polymer is afterward patterned by reactive ion etching (RIE) with oxygen plasma, using photoresist mask as shown in Figure 47 (1). A cavity with a depth of 150 μm is subsequently generated into the silicon wafer by deep reactive ion etching (DRIE), refer to Figure 47 (2).

The base substrate is fabricated using a 500 μm thick silicon wafer with high resistivity ($>5000 \Omega\cdot\text{cm}$). A 1.8 μm thick SiO_2 is deposited on the silicon wafer by dry oxidation. After that a coplanar wave guide (CPW), that is composed of 50 nm Cr/50 nm Ru/500 nm Au/50 nm Ru, is formed on the wafer by sputtering and lift-off process, see Figure 47 (3). Afterwards, *CYTOP* polymer is coated and patterned on the wafer by the same processes mentioned above for bottom-support, refer to Figure 47 (4). To generate through holes into the silicon wafer, AZ9260 photoresist with a thickness of more than 11 μm is spin-coated and patterned first, followed by the removal of SiO_2 by RIE with

Chapter 5 High Speed MEMS switches with Perforated Substrate

Figure 47 Fabrication process flow of the MEMS switch with perforated base substrate, (a) back-support process, (b) base substrate process, (c) top cap process, and (d) wafer bonding and assembly process

Chapter 5 High Speed MEMS switches with Perforated Substrate

CF₄/O₂ plasma (Figure 47 (5)). The formation of through holes is conducted next by etching silicon using DRIE technique, see Figure 47 (6). A SEM Photo of a fabricated perforated base substrate is shown in Figure 48.

The top cap is for the creation of corrugated diaphragm and contact metal purpose. A 6 μm deep circular recess is firstly generated into the top silicon wafer (200 μm thick) by DRIE, as illustrated in Figure 47 (7). The next step is the creation of slightly positively tapered corrugations by an optimized DRIE process as described in Section 4.3, see Figure 47 (8), followed by the deposition of 100nm SiO₂ by dry oxidation and 1200nm Si₃N₄ by LPCVD. The thin film of SiO₂/Si₃N₄ serves as the out-of-plane moving microstructure of the MEMS switch. SiO₂/Si₃N₄ film is afterwards patterned by the photolithography and RIE using CF₄/O₂ plasma, as depicted in Figure 47 (9). The contact metal, a multilayer metallization of 50 nm Cr/50 nm Ru/500 nm Au/50 nm Ru, is deposited onto the SiO₂/Si₃N₄ film by sputtering and lift-off processes refer to Figure 47 (10).

Figure 48 SEM Photo of the perforated base substrate, with holes of 50 μm in radius

Chapter 5 High Speed MEMS switches with Perforated Substrate

The bottom-support, base substrate and top cap are then bonded together at wafer-level by the intermediate layer bonding technique using *CYTOP* polymer, as shown in Figure 47 (11). After the wafer bonding, the $\text{SiO}_2/\text{Si}_3\text{N}_4$ film on the backside of the top wafer is removed by RIE in CF_4/O_2 plasma. The diaphragm release is done by DRIE which stops at the $\text{SiO}_2 / \text{Si}_3\text{N}_4$ film, using a $7\text{ }\mu\text{m}$ thick AZ9260 photoresist mask, as depicted in Figure 47 (12). Finally, a 10 nm Ti/ 400 nm gold layer is sputtered on the wafer stack to create the membrane electrode, refer to Figure 47 (13). A $200\text{ }\mu\text{m}$ thick silicon shadow mask is used in this process. Figure 48 shows a SEM Photo of the fabricated MEMS shunt switch with perforated base-substrate and corrugated diaphragm. The overall size is $5\text{ mm} \times 5\text{ mm} \times 1\text{ mm}$.

Figure 49 SEM Photo of a RF MEMS shunt switch with perforated base-substrate and a circular corrugated diaphragm ($1750\text{ }\mu\text{m}$ in radius) before the sputtering process of top electrode. The overall size is $5\text{ mm} \times 5\text{ mm} \times 1\text{ mm}$.

Chapter 5 High Speed MEMS switches with Perforated Substrate

It should be noted that for comparative measurements, switches with normal base substrates (without perforation) have also been fabricated.

5.3 Characterization

The characterization of the fabricated and wafer-level encapsulated switches in terms of the switching times and RF performance is presented in this section. For comparison, switching times of both switches with or without perforation are measured.

Figure 50 Measurement setup for switching times and illustration of pull-in time and release time

5.3.1 Switching Time Measurements

Switching time is acquired by measuring the time delay between the change of the actuation signal and that of the responding output signal, as shown in Figure 50. Pull-in time is the time the contact metal beneath the diaphragm takes to touch the base substrate, while release time is defined as the time required for the diaphragm (together with contact metal) to move from the down-state to its original suspension height g (or more that 95 % of g).

Both pull-in and release time are measured with the set-up as shown in Figure 50. A square waveform with a duty-cycle of 20 % was applied to the switch actuator and monitored by a digital oscilloscope at the signal-out side. A unipolar amplitude of 30 V, on top of a DC offset of 30 V for the switches with an air gap of $8\mu\text{m}$, refer to Table 9. The frequency of the square waveform is 100 Hz and 50 Hz for the measurement of pull-in and release time, respectively. The measurement results are tabulated in Table 10 and also shown in Figure 51. For comparison, the calculated values by Equation (50) and Equation (55) are also given. The pull-in time is greatly reduced from 5.4 ms to 0.435 ms, 12 times in reduction, with the implementation of holes in the base substrate. Same, the release time is also significantly reduced from 40.6 ms to 3.2 ms, about 13 times in reduction, with the artificially creation of holes in the base-substrate. It is noticed that the calculation results tally quite well with the measurement values, with less than 13 % of error. Furthermore, although the damping coefficients were not measured directly, the measurement results validate the damping model indirectly since the calculated switching

Chapter 5 High Speed MEMS switches with Perforated Substrate

times are based on the damping coefficients obtained from the models mentioned above in Section 5.1.2.

Figure 51 Measured switching times of MEMS switches in comparison with calculated values using Equation (50) and Equation (55).

	Calculated	Measured
Pull-in time with holes (ms)	0.473	0.435
Pull-in time without holes (ms)	6.46	5.4
Release time with holes (ms)	3.59	3.2
Release time without holes (ms)	49.0	40.6

Table 10 Comparison of measured switching times and calculated values using Equation (50) and Equation (55)

Whereas the switching speeds of the current switch design, with a diaphragm of 3500 μm in diameter, are quite slow even with a perforated base substrate, as compared to less than

Chapter 5 High Speed MEMS switches with Perforated Substrate

1 μ s of published data from other research group. The main reason is that a large diaphragm is used. The proposed switch as a demonstrator was developed for proof of concept, focusing on the possible improvement in the performance of MEMS switch by employing closed diaphragm and perforated base-substrate. However, the proposed switch still can find some applications, such as the automated re-configuration of telecommunication networks [113], an application which has attracted increased attention of the RF MEMS community, any MEMS switch with sub-second switching time is fast enough. It should be mentioned that the proposed switch design can be scaled down in size. The switching times will be reduced if the physical dimensions of diaphragm are reduced.

5.3.2 RF Measurements

The fabricated RF MEMES shunt switches were measured for the RF performance using a *HP 8722D* network analyzer, *Cascade* GSG microwave probes. The measurement results of isolation and insertion loss are shown in Figure 52. Simulation results of isolation and insertion loss by *HFSS* (High Frequency Structure Simulation) are also plotted in the figure for comparison. The isolation is below -40 dB up to 14 GHz, and about -35 dB at 25 GHz with an air gap of 8 μ m. The measured insertion loss is about -0.7 dB up to 4 GHz, and -2.1 dB at 25 GHz for the encapsulated shunt switch with a 5 mm long coplanar waveguide (CPW) transmission line.

Chapter 5 High Speed MEMS switches with Perforated Substrate

It should be noted that the measured values of insertion loss are worse than -1.5 dB after 10 GHz. The unideal insertion loss, higher than desired, is caused mainly by inaccuracy of geometric dimensions of CPW deposited on the base substrate. The measured dimensions of the CPW are $250\text{ }\mu\text{m}$ signal line width and $35\text{ }\mu\text{m}$ gap to the ground lines, which results in a characteristic impedance of less than $50\text{ }\Omega$ (about $36\text{ }\Omega$ for frequencies larger than 10 GHz) on the proposed $500\text{ }\mu\text{m}$ thick silicon base-substrate. Simulations by HFSS, as depicted in Figure 52, shows that the insertion losses of the proposed MEMS switch with such transmission line fit the measured values quite well under a wide frequency ranges.

Figure 52 Measurement results of Isolation and insertion loss for prototype switch, $8\text{ }\mu\text{m}$ suspension height is used for isolation simulation using HFSS.

5.4 Summary

In this chapter, the design, fabrication and characterization aspects of a DC contact RF MEMS shunt switch with a perforated base substrate are discussed. An approach for the wafer-level encapsulation is proposed, which applies, for the first time for MEMS switch, the perforating technique in the base substrate to provide an effective way for reducing the damping coefficient and thus increasing the switching speed of the switch. The modeling of damping reduction by perforation and modeling of switching times for switches with perforated substrates are elaborate, respectively, with the calculations/simulations of damping coefficients and switching times for the proposed switches being included as well. In addition, the fabrication of the MEMS is presented which adopts three-wafer fabrication concept and involves both surface micromachining process and bulk micromachining process. The switching times and RF performances of fabricated switches are measured and the results are highlighted.

Chapter 6 Conclusions and Recommendations

Conclusions and recommendations are provided in this last closing chapter. Section 6.1 concludes the research work done and the achievements made during the course of this project. Section 6.2 presents the recommendations of future work beyond the thesis and also outlines the research topic may merit further study in the future.

6.1 Conclusions

This thesis presents novel RF MEMS switches based on a corrugated diaphragm and a multilayer metal stack with a ruthenium coating to achieve a wafer-level encapsulated RF MEMS switch with high reliability. Furthermore, Perforation is also introduced, for the first time, in the base substrate for the purpose of enhancing switching speed of the switches. The objectives set forth in Section 1.2 are met upon completion of this project. Aiming for developing technologies for reliable RF MEMS switches with high speed, the research effort described in this thesis focus mainly on the aspects outlined as follows:

- A concept of stacked wafers is proposed to achieve near-hermetic and encapsulated switches on wafer level, where wafers are processed separately and are subsequently bonded by polymer wafer bonding. The wafer-scale encapsulation provides an effective means to avoid contamination of switch and especially of the metal

Chapter 6 Conclusions and Recommendations

contacts during the post-processing. In addition, the stacked wafer concept in MEMS fabrication also enhances the integration capability of the MEMS switch with other RF circuits or substrates, i.e., the moving microstructure from the top silicon wafer can be integrated with a variety of bottom substrates containing RF circuits which may not be fabrication compatible to the MEMS moving part.

- A unique contact metallization is employed in the MEMS switch design to address the contact reliability and current handling capability, utilizing a multilayer metal stack of Cr/Ru/Au/Ru with a ruthenium layer as the surface coating. The characteristics of the multilayer metallization bear a hard contact surface (due to the very thin Ruthenium layer) and a relative small contact resistance (due to the bulk soft gold). The novel contact metallization scheme is proven to be an effective method to increase the contact durability, by reliability measurements of the fabricated switches. An average life time of 7.1 million cycles at a measurement current of 5 mA, which is over ten times as compared to the average life time of 0.66 million cycles by pure, soft gold contacts, much better than the target of 1 million cycles. The total contact resistance of the multilayer metallization contact is 730 m Ω , only 2.5 times as compared to 300 m Ω of soft gold contact, matching very well the theoretical prediction and also achieving the target of less than 1000 m Ω of contact resistance.
- Corrugation technique is introduced in the diaphragm for the MEMS switches, which offers an efficacious method to alleviate the high residual stress in the diaphragm and to optimize its mechanical deflection by means of proper geometric dimensions and optimized number of corrugations to be used. The application of

Chapter 6 Conclusions and Recommendations

corrugations is proven to be an easier way to reduce the residual stress as compared to the approach by process control. The measured pull-in voltage of the MEMS switch is significantly reduced from 105 V for a flat diaphragm (900 μm in radius) to 51 V and 42 V for two-corrugation and four-corrugation diaphragms respectively, which agree well with the calculation results by derived analytical equations.

- In contrary to perforating in a moving structure such as a bridge or a membrane adopted by typical MEMS switch design, our approach to reduce the squeeze-film damping applies perforation in the base substrate instead of the diaphragm due to the fact that the diaphragm is part of the encapsulated micro-chamber formed between the diaphragm and the base substrate. This concept fulfills the performance enhancement by wafer-scale encapsulation integrated with diaphragm and by perforation to reduce the damping at the same time. The switching times of a demonstrator, a DC contact RF MEMS shunt switch designed for proof-of-concept, are reduced over 10 times with the adoption of perforated base substrate.
- Theoretical analysis is carried out to reveal the contact resistance of the novel metallization stack for different contact pressures, and the effect of the surface coating thickness on the total contact resistance. The theoretical analysis predicts that the proposed contact metallization scheme leads the way to improve the contact reliability by having a hard-metal surface of ruthenium without substantial compromise in the contact and transmission line resistances, which is confirmed by measurement results as well.
- Careful design considerations are taken for the proposed MEMS switches, including the artificial corrugation design in diaphragm for stress reduction, and meticulous

Chapter 6 Conclusions and Recommendations

perforation design in base substrate to reduce squeeze-film damping and thus the switching times. Corrugation model is created to depict stress reduction ratio in terms of corrugation depth and corrugation number. Pull-in voltages necessary to drive the stress-reduced corrugated diaphragms are also addressed and simulated by the derived equations. Modeling of MEMS switch with perforated base substrate is conducted as well, focusing on squeeze-film damping reduction via perforation with effects of different base substrates and air gaps. Furthermore, the switching times of the proposed MEMS switch with perforated base substrate are also calculated which tally quite well with the measurement results.

- The fabrication of the MEMS switches involves both surface and bulk micromachining processes. There are important processes have been explored or optimized. Among them, the generation of slightly positively tapered corrugation by DRIE, deposition of low stress diaphragm films, and flexible wafer bonding with low process temperature are critical for achieving the specific designed MEMS switches.
- Characterization is conducted for the fabricated MEMES switches on both mechanical and electrical performances including the static diaphragm deflection, initial and equivalent stresses in diaphragms, actuation voltage, pull-in time, release time, contact resistance, life times for different currents, isolation and insertion losses, etc. The measurement results, all in all, agree quite well with the predictions by the calculations or simulations.

6.2 Recommendations for Future Research

In the current project, wafer-level encapsulated RF MEMS switches based on stress-reduced corrugated diaphragm and ruthenium/gold hard-surface/low-resistivity contact metallization has been developed, successfully achieving more than one billion switching cycles at signal current less than 1 mA. Nevertheless, the following aspects need to be taken into considerations to design and fabricate the new version of switch in the future:

- Improved top electrode deposition process by using CMP process to reduce the vertical distance from the shadow-mask to the diaphragm, and to make metal patten with sharp edges as described in Section 4.4.
- Modified design of coplanar waveguide on the perforated silicon wafer.
- Minimization of moveable microstructure (diaphragm) size to increase the switching peed, besides the adoption of corrugated base substrate.
- Intermediate wafer bonding using hermetic or quasi-hermetic material to minimize the out-gassing in the micro-chamber accommodating the switch contact parts. Thermal compression wafer bonding or eutectic wafer bonding is a possible solution to provide hermetic packing of the device. In addition, encapsulation based on liquid crystal polymer (LCP) could also be an easy and cost effective way to provide quasi-hermetic encapsulation for the contact metals.

In addition, the research topics or directions identified as follows can be pursed in the future.

- Further investigation of switch contact reliability of the proposed Cr/Ru/Au/Cr

Chapter 6 Conclusions and Recommendations

contact metallization at low current less than 1 mA, as well as high current, e.g. higher than 350 mA. In the current project, the reliability test was stopped when a switch achieved 1 billion switching cycles at signal current less than 1 mA. However, it is worth further investigating and studying contact reliability of Cr/Ru/Au/Ru as compared to gold, beyond 1 billion cycles in a controlled testing environment, although the tests are time consuming. Furthermore, there is need to determine the life time of the proposed contact metallization at high current-level, for example, up to 350 mA, and conduct failure analysis on the failure mode or mechanism for both metal contacts.

- Failure analysis on Ru/Au contact after millions or billions cycles to figure out the failure mechanisms behind the sudden increase of resistance which was observed in the previous experiments.
- Study on the alternative contact materials. Apart from ruthenium, some other hard metals like molybdenum (Mo), tungsten (W) can be candidates of hard materials as surface coating of contact metallization. In addition, dissimilar metal contact such as gold/molybdenum, gold/tungsten, gold/ruthenium, could be the potential solutions to overcome stiction issue as well. Dissimilar metal contact is a concept where two types of metals are utilized for two contact parts, respectively.
- Investigation of RF power handling capability. Theoretical and experimental characterization of the MEMS switch with diaphragm and proposed Ru/Au metallization for high RF power application can be conducted to determine the minimum pull-in RF power which induces self actuation, and also the maximum RF power which the MEMS switch is able to handle, using experiment setup with high RF power source from several Watts up to more than 10 W. Theoretical analysis

Chapter 6 Conclusions and Recommendations

shall also be carried out on electrical current distributions, heat dissipation and contact resistance effects of the MEMS switches of high RF power operations.

- Development of MEMS switch with high switching speed for high RF power applications. With a miniaturized periphery-clammed moveable diaphragm which provides strong restoring force, the MEMS switch design, employing unique Ru/Au metallization and perforated base substrate, can be a potential solution to meet both requirements, speed and power handling, at the same time. A second electrode, being attached onto the top silicon cap and sitting above the diaphragm, can be implemented as a second means to pull-up the diaphragm if necessary.
- Theoretical analysis and experimental evaluation on the influences factors such as the location of damping holes and number of holes in the base substrate, which play an important role in increasing switching speed.

Appendix A Pressure Deflection Curve of Corrugated Diaphragm

The basic equation of performance characteristic for stress-free corrugated diaphragm is given by [114],

$$\frac{PR^4}{Et_d^4} = a_p \frac{z}{(1-\nu^2)t_d} + b_p \frac{z^3}{(1-\nu^2)t_d^3} \quad (\text{A-1})$$

where P is uniform pressure on the diaphragm, R is the radius of the diaphragm, t_d is the thickness of the diaphragm, E is Young's modulus, ν is the Poisson's ratio, and z is the centre deflection of the diaphragm, refer to **Figure 18**. In Equation (A-1), the first term on the right is a linear flexural term contributed by bending while the second term is a nonlinear tension term contributed by tension force. Here a_p is dimensionless stiffness coefficients, and b_p is dimensionless tension coefficients. a_p and b_p are expressed by the following equations, respectively,

$$a_p = \frac{2(q+1)(q+3)}{3\left(1 - \frac{\nu^2}{q^2}\right)} \quad (\text{A-2})$$

$$b_p = 32 \frac{1-\nu^2}{q^2-9} \left[\frac{1}{6} - \frac{3-\nu}{(q-\nu)(q+3)} \right] \quad (\text{A-3})$$

where q is written as,

Appendix A Pressure Deflection Curve of Corrugated Diaphragm

$$q = \sqrt{\frac{S}{\lambda} \left[1 + \frac{3}{2} \left(\frac{h_c}{t_d} \right)^2 \right]} \quad (\text{A-4})$$

λ , S , h_c are the spatial period, arc length and depth of corrugations, respectively. The q is termed as the corrugated profile factor. It is a figure of merit. A high q indicates high rigidity and long linear displacement. While a very low q approaches the performance of a flat diaphragm whose q equals 1. The corrugated profile factor (q) completely governs the deflection of the diaphragm.

Rearrange Equation (A-1), we obtain,

$$P = a_p \frac{E}{(1-\nu^2)} \frac{t_d^4}{R^4} \frac{z}{t_d} + b_p \frac{E}{(1-\nu^2)} \frac{t_d^4}{R^4} \frac{z^3}{t_d^3} \quad (\text{A-5})$$

For the case when initial stress in diaphragm must be considered, the deflection of a corrugated diaphragm can be obtained by “method of superposition”. The linear model of a corrugated diaphragm without initial stress is added to a linear membrane model with a high initial stress. Jerman derived the following equation to describe the pressure-deflection of a corrugated diaphragm with stress due to stretching of the middle plane of the diaphragm [115],

$$P = 4 \frac{t_d^2}{R^2} \frac{z}{t_d} \left[\sigma_0 + \frac{2.83}{4} \frac{E}{(1-\nu^2)} \frac{t_d^2}{R^2} \frac{z^2}{t_d^2} \right] \quad (\text{A-6})$$

where σ_0 , is initial stress in the diaphragm. It should be noted that the second term in the brackets represents the stress due to stretching of the middle plane of the diaphragm.

Rearrange Equation (A-5) which describes the pressure-deflection of a stress-free corrugated diaphragm, we obtain,

$$P = 4 \frac{t_d^2}{R^2} \frac{z}{t_d} \left[\frac{a_p}{4} \frac{E}{(1-\nu^2)} \frac{t_d^4}{R^2} + \frac{b_p}{4} \frac{E}{(1-\nu^2)} \frac{t_d^2}{R^2} \frac{z^2}{t_d^2} \right] \quad (\text{A-7})$$

Appendix A Pressure Deflection Curve of Corrugated Diaphragm

Comparing the second term in the brackets of Equation (A-6) and (A-7), it is obvious that the stress due to the middle plane has been reduced by a factor of $b_p/2.83$ with the introduction of corrugations in diaphragm. In order to describe the performance of a corrugated diaphragm with initial stress by superposition of a stress-free corrugated diaphragm and a flat diaphragm with initial stress, the flat diaphragm with initial stress of $\sigma_0 b_p/2.83$ rather than σ_0 , should be used. Furthermore, the superposition is only valid for linear system. Only the linear terms of Equation (A-6) and (A-7) should be used. We, therefore, obtain the pressure-deflection curve for a corrugated diaphragm with initial stress of σ_0 ,

$$P = 4 \frac{t_d z}{R^2} \left[\sigma_0 \frac{b_p}{2.83} + \frac{a_p}{4} E \left(\frac{t_d}{R} \right)^2 \right] \quad (\text{A-8})$$

Appendix B Stress Reduction Ratio by Corrugation Technique

As shown in Figure B-1, one half of the corrugation consists of three cantilevers with lengths of $w_c/2$, h_c and $b_c/2$, respectively. It is assumed that the height of the corrugation (h_c) is much smaller than the bottom width of corrugation (b_c). As a result, the deflection of the short cantilever can be negligible.

Figure B-1 Model of corrugated diaphragm with details of corrugation loaded by lateral force.

For the long cantilever with length of $w_c/2$ and moment of inertia of $I = W_{cant} t_d^3 / 12$, its bending angle α , under a lateral force F , can be calculated using the moment $M_{max} = F h_c \sin\beta$ [75]

Appendix B Stress Reduction Ratio by Corrugation Technique

$$\begin{aligned}\alpha &= \frac{1}{EI} \int_0^{w_c/2} M(x) dx = \frac{1}{EI} \frac{M_{\max}}{w_c/2} \int_0^{w_c/2} x dx \\ &= \frac{M_{\max} (w_c/2)}{2EI} = \frac{6 \sin(\beta) F (w_c/2) h_c}{EW_{cant} t_d^3}\end{aligned}\quad (B-1)$$

where W_{cant} , t_d are the width and thickness of cantilever, respectively. If the angle α is small, the total displacement Δx_c for one corrugation can be expressed by,

$$\begin{aligned}\Delta x_c &= 2 \sin(\alpha) h_c \approx 2 \alpha h_c \\ &= \frac{6 \sin(\beta) F w_c h_c^2}{EW_{cant} t_d^3}\end{aligned}\quad (B-2)$$

Figure B-1 above illustrates a model of a corrugated diaphragm which is composed of a middle planar region with a length of a , and N_c corrugations. Under thermal stress, the sum of the displacements of the whole diaphragm, which includes the corrugated (index c) and the planar (index a) region, must be zero. Here the displacement includes elastic (suffix e) displacements and thermal (suffix t) displacements. The sum of the displacements of the whole diaphragm is given by,

$$\Delta x_c^e + \Delta x_a^e + \Delta x_c^t + \Delta x_a^t = 0 \quad (B-3)$$

where Δx_c^e , the elastic displacement of N_c corrugations, is $N_c \frac{6 \sin(\beta) F w_c h_c^2}{EW_{cant} t_d^3}$ by

Equation (B-2). In addition, the elastic displacement of the cantilever (Δx_a^e) is expressed by [75],

$$\Delta x_a^e = \frac{Fa}{EW_{cant} t_d} \quad (B-4)$$

Appendix B Stress Reduction Ratio by Corrugation Technique

The thermal displacement of the corrugated region ($\Delta x'_c$) can be neglected, since $\Delta x'_c \ll x'_a$. The linear thermal displacement of the cantilever ($\Delta x'_a$) is expressed by,

$$\Delta x'_a = \mathcal{G} \Delta T a \quad (\text{B-5})$$

where $\mathcal{G}$, ΔT are thermal expansion coefficient of cantilever material, and temperature change, respectively. Substituting Equation (B-4) and (B-5) in Equation (B-3),

$$N_c \frac{6 \sin(\beta) F w_c h_c^2}{E W_{cant} t_d^3} + \frac{F}{W_{cant} t_d} \frac{a}{E} + \mathcal{G} \Delta T a = 0 \quad (\text{B-6})$$

It should be noted that the equilibrium stress in a corrugated diaphragm $\sigma = -F / (W_{cant} t_d)$ and the thermal stress $\sigma_0 = \mathcal{G} \Delta T E$. Thus, Equation (B-6) becomes,

$$-\sigma N_c \frac{6 \sin(\beta) w_c h_c^2}{E t_d^2} - \sigma \frac{a}{E} + \sigma_0 \frac{a}{E} = 0$$

Therefore, the equilibrium σ as a function of the thermal stress σ_0 (the initial residual stress) is expressed by,

$$\sigma = \frac{\sigma_0}{1 + 6 \sin(\beta) + \frac{h_c^2}{t_d^2} \frac{N_c w_c}{R - N_c (w_c + b_c)}} \quad (\text{B-7})$$

where R is the radius of the diaphragm which is $R = a + N_c (w_c + b_c)$. As a result, the stress reduction ratio (η) by the introduction of corrugated diaphragms is given by,

$$\eta = \frac{\sigma_0}{\sigma} = 1 + 6 \sin(\beta) \left(\frac{h_c}{t_d} \right)^2 \frac{N_c w_c}{R - N_c (w_c + b_c)} \quad (\text{B-8})$$

Appendix C Calculation of Damping Coefficient

Refer to the microphone as shown in

Figure 43 with a cylindrical coordinate system (r, θ, Z) , the vibration motion of the diaphragm and air layer is governed by the four equations as follows [107], [108]:

- Equation of motion

$$\nabla^2 y(r, \theta) + K^2 y(r, \theta) = -\frac{p_i}{T} + \frac{p(r, \theta, 0)}{T} \quad (\text{C-1})$$

- Navier-Stokes equation

$$j\omega\rho_o\mathbf{v} = -\nabla p + \mu(\nabla^2\mathbf{v} + \frac{1}{3}\nabla\nabla\cdot\mathbf{v}) \quad (\text{C-2})$$

- Continuity equation

$$\rho_o\nabla\cdot\mathbf{v} = -j\omega\rho \quad (\text{C-3})$$

- Equation of state

$$p = \rho c_T^2 \quad (\text{C-4})$$

where $y(r, \theta)$ is the deflection of the diaphragm, p_i is the incident acoustic pressure, $p(r, \theta, 0)$ is the reaction pressure on the diaphragm, ω is the angular frequency of the incident acoustic pressure, $\mathbf{v}$ is the air particle velocity, ρ_o is the static air density (1.205 kg/m^3), ρ is the time-varying air density, μ is the absolute viscosity of air ($17.9 \times 10^{-6} \text{ Ns/m}^2$), c_T is

Appendix C Calculation of Damping Coefficient

the isothermal speed of sound in air (290.2 m/s), and K is the wave number of sound in the diaphragm,

$$K = \omega \left(\frac{\sigma_M}{T} \right)^{1/2} \tag{C-5}$$

where σ_M is the mass surface density of the diaphragm.

A number ($k = 1, 2, \dots q_{hole}$) is assigned to each acoustic hole in the backplate for identification, where q_{hole} is the total number of acoustic holes. If an acoustic slot is present around the circumference of the backplate, it is assigned as $k = 1$.

Figure C- 1 Equivalent circuit of the backchamber and backplate with acoustic slot and holes

Figure C- 1 depicts an equivalent circuit of the backplate and the backchamber. The equations of the impedance circuit can be written in a matrix form

Appendix C Calculation of Damping Coefficient

$$\mathbf{P} = \mathbf{Z}\mathbf{U} \quad (\text{C-6})$$

where $\mathbf{P}$ is the $(q_{hole} \times 1)$ pressure matrix, $\mathbf{U}$ is the $(q_{hole} \times 1)$ volume velocity matrix and $\mathbf{Z}$ is the $(q_{hole} \times q_{hole})$ acoustic impedance matrix,

$$\mathbf{P} = \begin{bmatrix} p_1 \\ p_2 \\ \cdot \\ \cdot \\ \cdot \\ p_q \end{bmatrix} \quad \mathbf{U} = \begin{bmatrix} U_1 \\ U_2 \\ \cdot \\ \cdot \\ \cdot \\ U_q \end{bmatrix}$$

$$\mathbf{Z} = \begin{bmatrix} Z_1 + Z_C & Z_C & \cdot & \cdot & Z_C & Z_C \\ Z_C & Z_2 + Z_C & & & \cdot & \cdot \\ \cdot & Z_C & & & \cdot & \cdot \\ \cdot & \cdot & & & \cdot & \cdot \\ \cdot & \cdot & & & Z_{q-1} + Z_C & Z_C \\ Z_C & \cdot & \cdot & \cdot & Z_C & Z_q + Z_C \end{bmatrix} \quad (\text{C-7})$$

Furthermore, the acoustic impedance Z_C of the backchamber can be modeled as

$$Z_C = \frac{\gamma_{air} \rho_o c_T^2}{j\omega V_{vo}} \quad (\text{C-8})$$

where γ_{air} is the specific heat ratio of air (1.403) and V_{vo} is the volume of the backchamber. The acoustic impedance of the k th opening of the backplate can be expressed by,

$$Z_k = \frac{(8\omega\rho_o\mu)^{1/2}}{\pi r_k^2} \left(1 + \frac{l_k}{2r_k} \right) + j \frac{\omega\rho_o(l_k + 1.7r_k)}{\pi r_k^2} \quad (\text{C-9})$$

where r_k is the radius of the k th hole. The acoustic impedance of the slot in the backplate is given by,

Appendix C Calculation of Damping Coefficient

$$Z_1 = \frac{(2\omega\rho_o\mu)^{1/2}}{\pi a_1 r_1} \left(1 + \frac{l_1}{2r_1} \right) + j \frac{\omega\rho_o l_1}{2a_1 r_1} \quad (C-10)$$

where r_1 is the width of the slot.

Without going into the details of further mathematical derivations, of which can be found in [107], [108], the solution to Equation (C-1), the deflection of the diaphragm $y(r)$ that is independent of θ , can be expressed as,

$$y(r) = \frac{p_i}{TK^2} \cdot \frac{J_2(Ka)}{J_0(Ka) + D(\omega)} \quad (C-11)$$

where $J_0(Ka)$ and $J_2(Ka)$ are the zero and second order Bessel functions of Ka respectively and D is given by

$$D(\omega) = \frac{j4\omega\rho_o J_o(Ka)}{\pi T J_2(Ka)} \sum_{m=0}^{\infty} \left[-j\omega \left(\frac{y_m}{y_o} \right) + \sum_{s=1}^q \left(\frac{f_s}{y_o} \right) s_s \Gamma_m J_o(\xi_m a_s) \right] \quad (C-12)$$

$$\times \frac{1}{T_m J_0(\xi_m a)} \left\{ \frac{J_2(Ka) \delta(m)}{4K^2 a^2} + \frac{J_1(Ka) [1 - \delta(m)]}{2Ka (K^2 a^2 - \xi_m^2 a^2)} \right\}$$

Rearrange Equation (C-11), we obtain the familiar form as follows,

$$y(r) = p_i \left[\frac{1}{TK^2} \cdot \frac{J_2(Ka)}{J_0(Ka) + D(\omega)} \right]$$

$$y(r) = \left[\frac{p_i}{j\omega Z_m \pi a^2} \right] \quad (C-13)$$

where Z_m is the acoustic impedance of the diaphragm-air layer system, and is given by,

Appendix C Calculation of Damping Coefficient

$$Z_m = \frac{TK^2}{j\omega\pi a^2} \left[\frac{J_0(Ka) + D(\omega)}{J_2(Ka)} \right] \quad (C-14)$$

At frequencies that are well below the first resonant frequency of the diaphragm, the Bassel function in Equation (C-14) can be approximated by a few leading terms in their power series expansions. Z_m is then written by,

$$Z_m \approx j\omega \frac{4\sigma_M}{3\pi a^2} + \frac{8\pi T}{j\omega(\pi a^2)^2} + \frac{8\pi TD(\omega)}{j\omega(\pi a^2)^2} \quad (C-15)$$

Figure C- 2 Equivalent circuit of the microphone with lumped elements

Equation (C-15) actually can be explained by an acoustical lumped-element equivalent circuit of the microphone as shown in Figure C- 2. The first and second terms in Equation (C-14) represent the diaphragm mass M_M and diaphragm compliance C_M , respectively,

$$M_M = \frac{4\sigma_M}{3\pi a^2} \quad (C-16)$$

$$C_M = \frac{(\pi a^2)^2}{8\pi T} \quad (C-17)$$

Appendix C Calculation of Damping Coefficient

and the last term in Equation (C-15) represent the air compliance $C_A(\omega)$ and air resistance $R_A(\omega)$, expressed respectively as,

$$C_A(\omega) = \frac{(\pi a^2)^2}{8\pi T \operatorname{Re}(D)} \quad (\text{C-18})$$

$$R_A(\omega) = \frac{8\pi T \operatorname{Im}(D)}{\omega(\pi a^2)^2} \quad (\text{C-19})$$

The air resistance R_A , also termed as damping coefficient, dependent on the air damping in the air gap and acoustic holes.

Appendix D Calculation of Switching Times

The squeeze film damping of the switch, as shown in Figure 45, is generally described by the simplified Reynolds equation as follows [103], [116], which is obtained from the Navier–Stokes equations under the conditions that the air gap is small compared to the diaphragm diameter; inertial effects of the gas can be neglected; the gas is isothermal and acts like an ideal gas; and the diaphragm stays approximately flat and the pressure variations in the squeeze film are considerably smaller than the ambient pressure,

$$\nabla^2 p(x, y) = \frac{\partial^2 p}{\partial^2 x^2} + \frac{\partial^2 p}{\partial^2 y^2} = -\frac{12\mu_e v}{z^3} \quad (\text{D-1})$$

where $p(x, y)$ is the reaction pressure on the diaphragm, μ_e is the effective viscosity of air, v is the air particle velocity, and z is the air gap between the two electrodes. Since the right-hand side of Equation (D-1) is independent of the lateral position, $P(x, y) = -(12\mu_e v/z^3)\Pi(x, y)$, where $\Pi(x, y)$ only depends on the lateral geometry of the switch and satisfies the Poisson's equation $\nabla^2 \Pi = 1$. As a result, the squeeze film damping force ($F_{damping}$) exerted on the diaphragm is expressed by [103],

$$F_{damping} = \int_A p(x, y) dx dy = -12\mu_e \frac{v}{z^3} \int_A \Pi(x, y) dx dy = -b_{damp} (A^2 g_0^3) \frac{v}{z^3} \quad (\text{D-2})$$

where b_{damp} is damping coefficient of squeeze film, A is the diaphragm area, and g_0 is the initial air gap. When the air gap z reduces to the order of the mean free path of the gas

Appendix D Calculation of Switching Times

molecules λ , the no-slip boundary condition ($v_{\text{edge}} = 0$) at the interface between solid and gas becomes invalid and the slip-flow effect should be taken into consideration. A modification of the effective viscosity to account for slip-flow was given by Veijola [117],

$$\frac{\mu_e}{\mu} = \frac{1}{1 + 9.638 K_n^{1.159}} \approx \frac{1}{1 + \gamma g_0 / z} \quad (\text{D-3})$$

where μ is the viscosity of air, K_n is the Knudsen number ($K_n = \lambda/z$), γ is the slip-flow constant ($\gamma = 9\lambda / g_0$), λ is the mean free path of gas molecules that is about 70 nm under atmospheric pressure at room temperature. The presence of slip-flow effects can be approximated by the expression on the right-hand side of Equation (D-3). Therefore, Equation (D-2) can be modified as the following equation to account for slip-flow effect by using Equation (D-3),

$$F_{\text{damping}} = \int_A p(x, y) dx dy = -12\mu_e \frac{v}{z^3} \int_A \Pi(x, y) dx dy = -\frac{b_{\text{damp}} (A^2 g_0^3)}{1 + \gamma g_0 / z} \frac{v}{z^3} \quad (\text{D-4})$$

However, this approach assumes the diaphragm stays approximately flat and the air gap is constant during the damping operation. It does not take in account of the location of damping holes in the backplate, the thickness of the backplate, and the influence of the backchamber. On the other hand, Equation (43) considers all these factors and provides more accurate squeeze film damping coefficient B_a , which is based on Zuckerwar's model. As such, B_a ($B_a = 8\pi T \text{Im}(D)$) can be used to replace b_{damp} in Equation (D-4),

$$F_{\text{damping}} = \int_A p(x, y) dx dy = -\frac{B_a (A^2 g_0^3)}{1 + \gamma g_0 / z} \frac{v}{z^3} \quad (\text{D-5})$$

In addition, the electrostatic force (F_{el}) generated by actuation voltage V across the parallel plates of area A as shown in Figure 45 can be obtained by Equation (5),

Appendix D Calculation of Switching Times

$$F_{el} = \frac{dC}{dz} \frac{V^2}{2} \quad (D-6)$$

where C is the capacitance between the parallel plates which can be expressed by $C = \epsilon_0 A/z$. Here ϵ_0 is the vacuum permittivity, and z is the gap between the two electrodes. However, to accurately calculate the capacitance, fringing fields need to be taken into account. For simplification, it is assumed that the fringing fields of the top electrode is approximated by a microstripline with a width of W_s and a length of L_s , suspending a gap of z above the bottom electrode. The capacitance increase with regards to the parallel plate capacitance (C) due to fringing fields can be described by a factor $\psi_f(z)$, which is given by Morse by using conformal mapping techniques [118],

$$\psi_f(z) = \frac{C_{fringe}}{C} = 1 + \frac{2z}{\pi W_s} \left[1 + \ln \left(\frac{\pi W_s}{2z} \right) \right] \quad (D-7)$$

To replace C by C_{fringe} in Equation (D-6) using Equation (D-7), the electrostatic force F_{el} becomes,

$$\begin{aligned} F_{el} &= \frac{V^2}{2} \frac{d}{dz} \left[\frac{\psi_f(z) A \epsilon_0}{z} \right] = \frac{A \epsilon_0 V^2}{2} \frac{d}{dz} \left\{ \frac{1 + \frac{2z}{\pi W_s} \left[1 + \ln \left(\frac{\pi W_s}{2z} \right) \right]}{z} \right\} \\ &= -A \epsilon_0 V^2 \left(\frac{1}{2z^2} + \frac{1}{\pi W_s z} \right) \end{aligned} \quad (D-8)$$

Figure 45 (c) shows a schematic drawing of one-dimensional model of the diaphragm.

The equation of motion of the diaphragm is

$$F_{spring} + F_{damping} - F_{electra} = m \frac{d^2 z}{dt^2} \quad (D-9)$$

where F_{spring} is spring force of the diaphragm governed by $F_{spring} = k(g_0 - z)$, k is the equivalent spring constant of the diaphragm. By substituting Equation (D-5) and

Appendix D Calculation of Switching Times

Equation (D-8) in Equation (D-9) and rearrangement, we can obtain the following differential equation of motion for the one-dimensional system:

$$m \frac{d^2 z}{dt^2} + \frac{B_a (A^2 g_0^3)}{(1 + \gamma \frac{g_0}{z}) z^3} \frac{dz}{dt} + k(z - g_0) + \varepsilon_0 A V_{eff}^2 \left(\frac{1}{2z^2} + \frac{1}{\pi W_s z} \right) = 0 \quad (D-10)$$

The switching time can be obtained from Equation (D-10) by integration, if inertial effects and fringe fields are neglected. For the pull-in motion ($V > V_{pi}$), from the up-position ($\bar{z}_1$) to the down-position ($\bar{z}_0$), the switching time is [103],

$$t_{pull-in}(\bar{z}) \Big|_{\bar{z}_1}^{\bar{z}_0} = \frac{-8B_a(A^2 g_0^3)}{A\varepsilon_0 V_{pi}^2 f_1(-\gamma)f_2(-\gamma)f_3(2\delta)} \times \left[f_3(2\delta) \ln(\bar{z} + \gamma) - \frac{f_1(-\gamma)}{3} \ln(f_2(\bar{z})) \right. \\ \left. + \frac{f_1(-\gamma) - 3f_3(2\delta)}{6} \ln(f_1(\bar{z})) - \frac{f_2(-\gamma)(f_2(-\delta\gamma) - 3\delta)}{\sqrt{3f_3(\delta)}} \arctan \frac{f_2(\bar{z}) - 3\delta}{\sqrt{3f_3(\delta)}} \right] \Big|_{\bar{z}_1}^{\bar{z}_0} \quad (D-11)$$

where the normalized position $\bar{z} = z / g_0$, and

$$\delta = \cosh \left[\frac{1}{3} \arccos h \left(\frac{2V^2}{V_{pi}^2} - 1 \right) \right] \quad (D-12)$$

$$f_1(x) = f_2(x)[f_2(x) - 6\delta] + 3f_3(2\delta) \quad (D-13)$$

$$f_2(x) = 3x + 2\delta - 1 \quad (D-14)$$

$$f_3(x) = x^2 - 1 \quad (D-15)$$

For the switching-up motion ($V = 0$), from the down-position ($\bar{z}_0$) to the up-position ($\bar{z}_1$), the switching time is [103],

$$t_{release}(\bar{z}) \Big|_{\bar{z}_0}^{\bar{z}_1} = \frac{-8B_a(A^2 g_0^3)}{27A\varepsilon_0 V_{pi}^2 (1 + \gamma)} \times \left[\frac{1 + \gamma}{\gamma \bar{z}} + \ln \left(\frac{1}{\bar{z}} - 1 \right) - \frac{1}{\gamma^2} \ln \left(1 + \frac{\gamma}{\bar{z}} \right) \right] \Big|_{\bar{z}_0}^{\bar{z}_1} \quad (D-16)$$

List of Publications

Journal Papers

1. Feixiang Ke, Jianmin Miao and Joachim Oberhammer, "A ruthenium-based multi-metal contact RF MEMS switch with a corrugated diaphragm", *Journal of Microelectromechanical Systems*, volume 17, number 6, December 2008, pp 1447-1459.
2. Feixiang Ke, Jianmin Miao and Zhihong Wang, "Ohmic series radio-frequency microelectromechanical system switch with corrugated diaphragm", *Journal of Micro/Nanolithography, MEMS, and MOEMS (JM3)*, volume 8, issue 2, pp 02112-1-5, April 2009.
3. Feixiang Ke, Jianmin Miao and Zhihong Wang, "A wafer-scale encapsulated RF MEMS switch with a stress-reduced corrugated diaphragm", *Sensors & Actuators: A, Physical*, volume 151, issue 2, April 2009, pp 237-243.
4. Feixiang Ke, Jianmin Miao, and Chee Wee Tan, "A wafer-level encapsulated DC contact MEMS shunt switch with perforated substrate". (Pending submission, *Sensors & Actuators: A*)

Conference Papers

1. Feixiang Ke, Jianmin Miao, and Chee Wee Tan, "Performance enhancement by substrate perforation for a wafer-level encapsulated RF MEMS DC shunt switch", *22nd IEEE International Conference on Micro Electro Mechanical System*, January 2009, pp 876-879.
2. Feixiang Ke, Jianmin Miao and Joachim Oberhammer, "Ruthenium/gold hard-surface/low-resistivity contact metallization for polymer-encapsulated microswitch with stress-reduced corrugated SiN/SiO₂ diaphragm", *22nd IEEE International Conference on Micro Electro Mechanical System*, January 2009, pp 860-863.
3. Feixiang Ke, Jianmin Miao and Zhihong Wang, "A RF MEMS switch with high reliability", *Asia-Pacific Conference on Transducers and Micro-Nano Technology 2008*, June 2008.

List of References

-
- [1] H. J. De Los Santos, J. Hector, G. Fischer, H. A. C. Tilmans, and J. T. M. van Beek, "RF MEMS for ubiquitous wireless connectivity," *IEEE Mmicrowave Magazine*, December 2004, pp. 36-65.
 - [2] C. T.-C. Nguyen, "Vibrating RF MEMS for low power wireless communications (invited)," *Proceedings, 2000 International MEMS Workshop (IMEMS'01)*, Singapore, July 4-6, 2001, pp. 21-34.
 - [3] G. M. Rebeiz, J. B. Muldavin, "RF MEMS switches and switch circuits," *IEEE Microwave Magazine*, December 2001, pp. 59-71.
 - [4] J. Oberhammer, *Novel RF MEMS switch and packaging concepts*, Doctoral thesis, Sweden, 2004.
 - [5] T. Vaha-Heikkila, G.M. Rebeiz, "A 4-18-GHz reconfigurable RF MEMS matching network for power amplifier applications," *International Journal of RF And Microwave Computer-Aided Engineering*, volume 14, issue 4, pp. 356-372, Jul 2004.
 - [6] Q. Shen, N.S. Barker, "Distributed MEMS tunable matching network using minimal-contact RF-MEMS varactors," *IEEE Transactions on Microwave Theory And Techniques*, volume 54, issue 6, pp. 2646-2658, June 2006.
 - [7] G. L. Tan, R. E. Mihailovich, J. B. Hacker, J. F. DeNatale, G. M. Rebeiz, "A 2-bit miniature X-band MEMS phase shifter," *IEEE Microwave and Wireless Components Letter*, volume 13, issue 4, pp. 146-148, April 2003.
 - [8] S. Barker and G. M. Rebeiz, "Distributed MEMS true-time delay phase shifters and wideband switches," *IEEE Transactions on Microwave Theory and Techniques*, volume 46, issue 11, pp. 1881-1890, November 1998.

List of References

-
- [9] A. R. Brown, P. Blondy, G. M. Rebeiz, "Microwave and millimeter-wave high-Q micromachined resonators," *International Journal and Microwave Computer-Aided Engineering*, volume 9, issue 4, pp. 326-337.
 - [10] F. Torres et al., "Nanometer scale gaps for capacitive transduction improvement on RF-MEMS resonators," *Microelectronic Engineering*, volume 84, issue 5-8, pp. 1384-1387, May-Aug 2007.
 - [11] J. H. Park, S. Lee, J. M. Kim, H. T. Kim, Y. Kwon, Y. K. Kim, "Reconfigurable millimeter-wave filters using CPW-based periodic structures with novel multiple-contact MEMS switches," *Journal of Microelectromechanical Systems*, volume 14, issue 3, pp. 456-463, June 2005.
 - [12] A. Fukuda, H. Okazaki, T. Hirota, Y. Yamao, "Novel band-reconfigurable high efficiency power amplifier employing RF-MEMS switches," *IEICE Transactions on Electronics*, volume E88c, number 11, pp. 2141-2149, November 2005.
 - [13] C. W. Jung, M. J. Lee, G.P Li, F. F. De, "Reconfigurable Scan-beam Single-arm Spiral Antenna Integrated with RF-MEMS Switches," *Antennas and Propagation, IEEE Transactions on*, volume 54, issue 2, Feb. 2006, pp. 455 – 463.
 - [14] G. M. Rebeiz, *RF MEMS Theory, Design, and Technology*, John Willey & Sons Publication, 2003.
 - [15] J. J. Yao, "RF MEMS from a device perspective", *Journal of Micromechanics and Microengineering*, volume 10, number 4, 2000 , pp. R9-R38
 - [16] J. A. Wright, Y. Tai and S. Chang, "A large-force, fully-integrated MEMS magnetic actuator", *Transducers'97, 1997 International Conference on Solid-state Sensors and Actuators, Chicago, June 16-19, 1997*
 - [17] K. E. Petersen, "Micromechanical membrane switches on silicon", *IBM Journal of Research and Development*, volume 23, issue 4, July 1979, pp. 376-385
 - [18] L. E. Larson, R. H. Hackett, M. A. Melendes, and R. F. Lohr, "Micromachined microwave actuator (MIMAC) technology-a new tuning approach for microwave integrated circuits", *Microwave and Millimeter-Wave Monolithic Circuits Symposium, Digest of Papers, IEEE*, 1991, pp. 27-30.

List of References

-
- [19] J. J. Yao and M. F. Chang, "A surface micromachined miniature switch for telecommunications applications with signal frequencies from DC up to 4 GHz", in International Conference on Solid-State Sensors and Actuators Digest, Stockholm, Sweden, June 1995, pp. 384–387.
 - [20] R.E. Mihailovich, et al., "MEMS relay for reconfigurable RF circuits", *IEEE Microwave and Wireless Components Letters*, vol.11 no. 2, pp53-55, 2001.
 - [21] D. Hyman, and M. Mehregany, "Contact physics of gold microcontacts for MEMS switches", *IEEE Trans. Comp. Packaging Technology*, Vol. 22, No3, pp 357-364, 1999.
 - [22] Hyman, et al., "Surface micromachined RF MEMS with a view toward microwave application" *Int. J. RF Microwave CAE*, Vol.9 No.4 pp348-361, 1999.
 - [23] P. M. Zavracky, S. Majumder, and N. E. McGruer, "Micromechanical switches fabricated using nickel surface micromachining", *Journal of Microelectromechanical Systems*, volume 6, issue 1, March 1997, pp. 3-9.
 - [24] P. M. Zavracky, N. E. McGruer, R. H. Morrison, and D. Potter, "Microswitches and microrelays with a view toward microwave applications", *International Journal RF Microwave CAE*, volume 9, issue 4, pp. 338–347, 1999.
 - [25] S. Duffy, C. Bozler, S. Rabe, J. Knecht, L. Travis, P. Wyatt, C. Keast, and M. Gouker, "MEMS microswitches for reconfigurable microwave circuitry", *Microwave and Wireless Component Letters*, Vol. 11, No. 3, pp. 106–108, March 2001.
 - [26] B. Schauwecker, K. M. Strohm, W. Simon, J. Mehner, and J. F. Luy, "A new type of high bandwidth RF MEMS switch -toggle switch", *Journal of Semiconductor Technology and Science*, volume 2, issue 4, December 2002, pp. 237-245.
 - [27] W. Simon, B. Schauwecker, A. Lauer, A. Wien, and I. Wolff, "EM design of broadband RF multiport toggle switches," *International Journal of RF and Microwave Computer- Aided Engineering*, volume 14, issue 4, July 2004, pp. 329-337.
 - [28] W. Simon, T. Mack, B. Schauwecker, K. M. Strohm, J.-F; Luy, "Toggle switch: investigations of an RF MEMS switch for power applications," *Microwaves*,

List of References

-
- Antennas and Propagation, IEE Proceedings*, volume 152, issue 5, 7 Oct. 2005, pp. 378 – 384.
- [29] J. Oberhammer and G. Stemme, “Low-voltage high-isolation DC-to-RF MEMS switch based on an S-shaped film actuator,” *IEEE Transactions on Electron Devices*, volume 51, issue 1, 2004, pp. 149-155.
- [30] J. Oberhammer and G. Stemme, “Design and fabrication aspects of an S-shaped film actuator based DC to RF MEMS switch,” *Journal of Microelectromechanical System*, volume 13, issue 3, June 2004, pp. 421-428.
- [31] L. L. W. Chow, J. L. Volakis, K. Saitou, K. Kurabayashi, “Lifetime extension of RF MEMS direct contact switches in hot switching operations by ball grid array dimple design,” *Electron Device Letters, IEEE*, volume 28, issue 6, June 2007, pp. 479 – 481.
- [32] CL Goldsmith, et al., “Characteristics of micromachined switches at microwave frequencies”, *IEEE. Int. Microwave Symp. Dig.*, pp1141-1144, 1996.
- [33] CL Goldsmith, et al., “Performance of low-loss RF MEMS capacitive switches”, *IEEE Microwave Guided Wave Lett*, vol. 8, pp 269-271, 1998.
- [34] C, Chang, and P. Chang, “Innovative micromachined microwave switch with very low insertion loss”, *Sensors and Actuators*, Vol. 79, pp71-75, 2000.
- [35] Pacheco, C.T. Nguyen, and L.P.B. Katehi, “Micromechanical electrostatic K-band switches,” *IEEE MTT-S Int. Microwave Symp. Dig., Baltimore, MD*, 1998, pp. 1569-1572.
- [36] J. B. Muldavin and G. M. Rebeiz, “Inline capacitive and DC-contact MEMS shunt switch switches”, *IEEE Microwave and Wireless Components Letter*, vol. 11, no. 8, August 2001.
- [37] G. L Tan, G. M. Rebeiz, “A DC-contact MEMS shunt switch,” *IEEE Microwave and Wireless Component Letters*, volume. 12, number 6, June 2002, pp. 212-214.
- [38] J. Tsaur, et. al., “Broadband MEMS shunt switches using PZT/HfO₂ multi-layered high *k* dielectrics for high switching isolation”, *Sensors and Actuators A*, volume 121, issue 1, 2005, pp.275-281,

List of References

-
- [39] Yo-Tak Song, Hai-Young Lee and Masayoshi Esashi, "A corrugated bridge of low residual stress for RF-MEMS switch", *Sensors and Actuators A: Physical*, volume 135, issue 2, 15 April 2007, pp. 818-826
 - [40] J. Schimkat, "Contact measurement providing basic design data for microrelay actuators," *Sensors and Actuators A: Physical*, volume 73, issue 1–2, pp. 138–143, March 1999.
 - [41] J. Oberhammer and G. Stemme, "Active opening force and passive contact force electrostatic switches for soft metal contact materials", *Journal of Microelectromechanical Systems*, vol. 15, no. 5, October 2006, pp. 1235-1242.
 - [42] P. G. Steeneken, et. al., "Dynamics and Squeeze Film Gas Damping of a Capacitive RF MEMS Switch," *Journal of Micromechanics and Microengineering*, 15 (2005), pp. 176-184.
 - [43] T. Veijola, et .al., "Gas Damping Model for a RF MEMS Switch and its Dynamic Characteristics", *Microwave Symposium Digest, 2002 IEEE MTT-S International*, volume 2, 2002, pp. 1213 – 1216.
 - [44] R. Holm, *Electric Contacts: Theory and Applications, Fourth Edition*, Berlin: Springer-Verlag, 1967.
 - [45] M. Braunovic, N. Myshkin, V. Konchits, *Electrical Contacts: Fundamentals, Applications and Technology*, Taylor & Francis Group, New York, 2007.
 - [46] D. Hyman, M. Mehregany, "Contact physics of gold microcontacts for MEMS switches," *IEEE Transactions on Components And Packaging Technologies*, volume 22, issue 3, pp. 357-364, Septembet 1999.
 - [47] J. Schimkat, "Contact materials for microrelays," *Micro Electro Mechanical Systems, MEMS 98 Proceedings, The Eleventh Annual International Workshop on*, 25-29 January 1998, pp. 190-194.
 - [48] J. Schimkat, "Contact measurement providing basic design data for microrelay actuators," *Sensors and Actuators A: Physical*, volume 73, issue 1–2, pp. 138–143, March 1999.
 - [49] W. Johler, "Precious metal-reduced contact materials in telecom and signal relays," *Electrical Contacts, 2001, Proceedings of the 47th IEEE Holm Conference on*, 10-12 September 2001, pp. 104-116.

List of References

-
- [50] T. Umemoto, T. Takeuchi, R. Tanaka, "The behavior of surface oxide film on ruthenium and rhodium plated contacts," *IEEE trans. on Component, Hybrids, and Manufacturing Technology*, volume 1, issue 1, March 1978, pp. 103-107.
- [51] W. Jahn, "Contact Metals for Reed Switches," *Electrical Contacts, 1990, Proceedings of the 36th IEEE Holm Conference on, and the 15th International Conference on Electrical Contacts*, 20-24 August 1990, pp. 53-58.
- [52] E. Walczuk, S. Stolarz, K. Wojtasik, "Experimental study of Ag-W-Re composite materials under high-current conditions," *IEEE Transactions on Component, Hybrids, and Manufacturing Technology*, volume 10, issue 2, June 1987, pp. 283-289.
- [53] S. Umemura, K. Yasuda, T. Aoki, "Contact resistance characteristics of noble metal alloys for connector contacts," *IEEE Transactions on Component, Hybrids, and Manufacturing Technology*, volume 14, issue 1, March 1991, pp. 181-186.
- [54] G. S. Paul, "The use of Ag-W-CdO and AgSi₃N₄ as contact materials," *IEEE Transactions on Parts, Hybrids, and Packaging*, volume 12, issue 1, March 1976.
- [55] J. A. Augis, L. L. Hines, "Sputtered ruthenium as a contact materials for sealed reeds," *IEEE Transactions on Component, Hybrids, and Manufacturing Technology*, volume 1, issue 1, March 1978, pp. 46-53.
- [56] W. Johler, "Impact of lead-free soldering processes on the performance of signal relay contacts," *IEEE Transactions on Components and Packaging Technologies*, volume 27, issue 1, March 2004, pp.30-41.
- [57] P. G. Slade, *Electrical Contacts Principles and Applications*, Cutler-Hammer, Horseheads, New York, 1999.
- [58] S. Majumder, N. E. McGruer, G. G. Adams, P. M. Zavracky, R. H. Morrison and J. Krim, "Study of contacts in an electrostatically actuated microswitch", *Sensors and Actuators A: Physical*, volume 93, issue 1, 2001, pp. 19-26.
- [59] L. L. W. Chow, S. A. Schrader, and K. Kurabayashi, "Transition from multiple to single microcontact conduction during hot switching of microelectromechanical switches with ball-shaped dimples," *Applied Physics Letters*, volume 89 issue 13, article number 133501, 2006.

List of References

-
- [60] J. Oberhammer, M. Tang, A. Q. Liu and G. Stemmel, "Mechanically tri-stable, true single-pole-double-throw (SPDT) switches," *Journal of Micromechanics and Microengineering*, volume 16, 2006.
 - [61] F. P. Bowden, D. Tabor, *Friction and Lubrication of Solids, Vol. II*, Oxford University Press, 1964.
 - [62] B. Nikolic and P.B. Allen, "Electron transport through a circular constriction," *Physics Rev. B*, vol. 60, no. 6, pp. 3963-3969, 1999.
 - [63] L. Chen, H. Lee, Z. J. Guo, N. E. McGruer, K. W. Gilbert, S. Mall, K. D. Leedy, G. G. Adams, "Contact resistance study of noble metals and alloy films using a scanning probe microscope test station," *Journal of Applied Physics*, volume 102, issue 7, 2007
 - [64] O. H. Blackwood, W. C. Kelly, and , R. M. Bell, *General Physics*, 4th Edition, Wiley, 1973.
 - [65] D. Dubuc et al., "Smart MEMS concept for high secure RF and millimeterwave communications," *Microelectronics Reliability*, volume 44, issue 6, June 2004, pp. 899-907.
 - [66] J. Miao, R. Lin, L. Chen, Q. Zou, S. Y. Lim, and S. H. Seah, "Design considerations in micromachined silicon microphones," *Microelectronics Journal*, volume 33, issue 1, January 2002, pp. 21-28.
 - [67] Xinxin. Li, Rongming Lin, Huatsoon Kek, Jianmin Miao, Quanbo Zou, "Sensitivity-improved silicon condenser microphone with a novel single deeply corrugated diaphragm", *Sensors & Actuators: A. Physical*, 2984 (2001), pp. 1-6.
 - [68] W. J. Wang, R. M. Lin, X. Li and D.G. Guo, "Study of single deeply corrugated diaphragms for high-sensitivity microphones," *Journal of Micromechanics and Microengineering*, 13, 2003, pp. 184-189.
 - [69] R. Kressmann, M. Klaiber, G. Hess, "Silicon condenser microphones with corrugated silicon oxide/nitride electret membranes," *Sensors and Actuators A*, 100, 2002, pp. 301-309.
 - [70] Q. Zou, Z. J. Li, and L. T. Liu, "Design and fabrication of silicon condenser microphone using corrugated diaphragm technique," *Journal of Microelectromechanical Systems*, volume 5, issue 3 September 1996, pp. 197-204.

List of References

-
- [71] Y. Zhang, and K. D. Wise, "Performance of non-planar silicon diaphragms under deflections," *Journal of Microelectromechanical Systems*, volume 3, issue 2, June. 1994, pp. 59-68.
 - [72] O. C. Jeong, S. S. Yang, "Fabrication of a thermopneumatic microactuator with a Corrugated p+ silicon Diaphragms," *Sensors and Actuators*, volume 80, 2000, pp. 62-67.
 - [73] P. R. Scheeper, W. Olthuis, and P. Bergveld, "The design, fabrication, and testing of corrugated silicon nitride diaphragms," *Journal of Microelectromechanical Systems*, volume 3, issue 1, March 1994, pp. 36-42.
 - [74] M. Ying, Q. Zou, S. Yi, "Finite-element analysis of silicon condenser microphones with corrugated diaphragms," *Finite Element in Analysis and Design*, volume 30, 1998, pp. 163-167.
 - [75] M. Fuldner, A. Dehe, and R. Lerch, "An analysis and finite element simulation of advanced membranes for silicon microphones," *IEEE Sensors Journal*, volume 5, issue 5, October 2005, pp. 857-863.
 - [76] Y. Tang, K. Stanley, J. Wu, D. Ghosh, and J. Zhang, "Design consideration of micro thin film solid-oxide fuel cells," *Journal of Micromechanics and Microengineering*, volume 15, 2005, pp185-192.
 - [77] S. Chowdhury, M. Ahmadi, W. C. Miller, "Nonlinear effects in MEMS capacitive microphone design," in *Proceedings of International Conference on MEMS, NANO and Smart Systems (ICMENS'03)*, 20-23 July 2003.
 - [78] J.-E. Wong, J. H. Lang, M. A. Schmidt, "An electrostatically-actuated MEMS switch for power applications," *Micro Electro Mechanical System, 2000, MEMS 2000' The Thirteenth Annual International Conference on*, 23-27 January 2000, pp. 633-638.
 - [79] P. M. Osterberg, S. D. Senturia, "M-TEST: a test chip for MEMS material property measurement using electrostatically actuated test structures," *Journal of Microelectromechanical Systems*, volume 6, issue 2, June 1997, pp. 107-118.
 - [80] C. P. Wen, "Coplanar waveguide: a surface strip transmission line suitable for nonreciprocal gyromagnetic device applications", *IEEE Trans, on Microwave Theory and Technology.*, volume 17, October 1969, pp.1087-1090.

List of References

-
- [81] T. C Edwards, M. B. Steer, *Foundations of Interconnect and Microstrip Design*, John Wiley, 2000.
 - [82] W. Hilberg, "From approximations to exact relations for characteristics impedances", *IEEE Trans. on Microwave Theory and Techn.*, vol 17, May 1969, pp.259-265l.
 - [83] M. Houdart, "Coplanar lines: application to broadband microwave integrated circuits", *Proceedings of 6th European microwave conference*, September. 1976, pp. 49-53.
 - [84] H. Holden, "Sepcifying controlled impedance and communicating stickups", *CircuiTree*, January 2005, pp.24-28.
 - [85] G. M. Rebeiz and J. B. Muldavin, "RF MEMS switches and switch circuit", *IEEE Microwave Magazine*, December 2001, pp.59-71.
 - [86] J. Iannacci, et.al., "Electromagnetic optimization of an RF-MEMS wafer-level package", *Sensors and Actuators A*, volume 142, issue 1, March 2008, pp. 434-441.
 - [87] Jie Wu, Shao Wang, and Jianmin Miao, "A MEMS device for studying the friction behavior of micromachined sidewall surfaces", *Journal of Microelectromechanical Systems*, volume. 17, number. 4, August 2008, pp. 921-933
 - [88] J. X. Gao, L. P. Yeo, M. B. Chan-Park, J. M. Miao, Y. H. Yan, J. B. Sun, Y. C. Lam, and C. Y. Yue, "Antistick Postpassivation of High-Aspect Ratio Silicon Molds Fabricated by Deep-Reactive Ion Etching", *Journal of Microelectromechanical Systems*, volume. 15, issue 1, February 2006 pp.84-93
 - [89] S.M. Sze, *VLSI Technology*, McGraw-Hill Book Company, 1998.
 - [90] Marc Madou, *Fundamentals of Microfabrication*, CRC Press, 1997.
 - [91] Gregory T. A. Kovacs, *Micromachined Transducers Sourcebook*, WCB McGraw-Hill, 1998
 - [92] T. Tsutsumino, et. al., "Seismic power generator using high-performance polymer element", *MEMS 2006, Istanbul, Turkey*, January 2006, pp. 22-26.
 - [93] Zhihong Wang , Jianmin Miao, Chee Wee Tan and Ting Xu, "Fabrication of piezoelectric MEMS devices-from thin film to bulk PZT wafer ", *Journal of Electroceramics*, March 2008.

List of References

-
- [94] D. Xiaoyi, "Behavior and application of silicon diaphragms with a boss and corrugations," *Solid-State Sensor and Actuator Workshop, 1992. 5th Technical Digest., IEEE*, 22-25 Jun 1992, pp. 166-169.
 - [95] Longqing Chen, Jianmin Miao, Lihui Guo and Rongming Lin, "Control of stress in highly doped polysilicon multi-layer diaphragm structure," *Surface and Coatings Technology*, volume 141, vssue 1, June 2001, pp. 96-102.
 - [96] Hyukjae Lee et al., "Characterization of metal and metal alloy films as contact materials in MEMS switches", *Journal of Microelectromechanical System*, volume 16, issue 3, March 2003, pp. 557-563
 - [97] N. E. McGruer, G. G. Adams, L. Chen, Z.J. Guo, Y. Du, "Mechanical, Thermal, and Material Influences on Ohmic-Contact-Type MEMS Switch Operation", *Micro Electro Mechanical System 2006*, January 2006, pp230-233
 - [98] J. Maciel, S. Majumder, R. Morrison, and J. Lampen, "Lifetime characteristics of ohme MEMS switches", *Reliability, Testing, and Characterization of MEMS/MOEMS III, Proceedings of the SPIE*, Volume 5343, 2003, pp. 9-14.
 - [99] G.M. Rebeiz, *RF MEMS Theory, Design, and Technology*, 1st ed New Jersey, Wiley, 2003.
 - [100] C. Siegel, V. Ziegler, C. V. Wächter, B. Schönlinner, U. Prechtel, H. Schumacher, "Switching speed analysis of low complexity RF-MEMS switches", *German Microwave Conference, GeMiC 2006*, March 28 - 30, 2006.
 - [101] D. Peroulis, S. P. Pacheco, K. Sarabandi, and L. P. B. Katehi, "Electromechanical considerations in developing low-voltage RF MEMS switches", *IEEE Transactions on Microwave and Techniques*, volume 51, issue 1, January 2003, pp. 259-270
 - [102] R. K. Gupta, and S. D, Senturia, "Pull-in time dynamics as a measure of absolute pressure", *IEEE Tenth Annual International Workshop on Micro Electro Mechanical Systems, 1997, MEMS '97, Proceedings*, 26-30 Jan. 1997, pp. 290 – 294.
 - [103] P. G. Steeneken, et.al., "Dynamics and squeeze film gas damping of a capacitive RF MEMS switch," *Journal of Micromechanics and Microengineering*, 15 (2005), pp. 176-184.

List of References

-
- [104] T. Veijola, et .al., "Gas damping model for a RF MEMS switch and its dynamic characteristics", *Microwave Symposium Digest, 2002 IEEE MTT-S International*, volume 2, 2002, pp. 1213 - 1216
 - [105] S. C. Shen, D. Caruth, and M. Feng, "Broadband low actuation voltage RF MEMS switches," *Proc. IEEE GaAs IC Symp.* Seattle, WA, 2000.
 - [106] J. Bergqvist, "Finite-element modelling and characterisation of a silicon condenser microphone with a highly perforated backplate", *Sensors and Actuators A*, 39 (1993). pp 191-200.
 - [107] A. J. Zuckerwar, "Theoretical response of condenser microphones," *J. Acoust. Soc. Am.* **64**, 1278–1285 (1978).
 - [108] A. J. Zuckerwar, *AIP Handbook of Condenser Microphones: Principles of Operation of Condenser Microphones* (Edited by G. S. K. Wong and T. F. W. Embleton.), New York, American Institute of Physics, 1995, pp. 37-69.
 - [109] Z. Škvor, "On the acoustical resistance due to viscous losses in the air gap of electrostatic transducers," *Acoustica*, Vol. 1067, pp 295-299 (1967).
 - [110] J. B. Starr, "Squeeze-film damping in solid-state accelerometers" *IEEE Workshop in Solid-state Sensor and Actuator 4th Technical Digest*, 1990, pp.44-47
 - [111] C. W. Tan and J. M. Miao, "Analytical modeling of bulk-micromachined condenser microphones", *Journal of the Acoustical Society of America* 120, No. 2, 2006, pp. 750-761.
 - [112] C. W. Tan, Z. H. Wang, J. M. Miao, and X.F. Chen, "A study on viscous damping effect for diaphragm-based acoustic MEMS applications," *Journal of Micromechanics and Microengineering*, 17 (2007), pp. 2253-2263.
 - [113] S. Braun, J. Oberhammer, and G. Stemme, "Single-chip MEMS 5×5 and 20×20 double-pole single-throw switch arrays for automating telecommunication networks", *Journal of Micromechanics and Microengineering* 18, 015014, pp. 1-11, December. 2007.
 - [114] M. D. Giovanni, *Flat and Corrugated Diaphragm Design Handbook*, New York and Basel, 1982, pp 255-262.
 - [115] J. H. JERMAN, "The fabrication and use of micromachined corrugated silicon diaphragms", *Sensors and Actuators*, A21-A23, 1990, pp. 988-992

List of References

- [116] Minghang Bao, et al, "Squeeze-film air damping of thick hole-plate", *Sensors and Actuators A*, Volume 108, 2003, pp. 212-217.
- [117] T. Veijola, H. Kuisma, J. Lahdenperä, and T. Ryhänen, "Equivalent-circuit model of the squeezed gas film in a silicon accelerometer," *Sensors and Actuators: A. Physical*, vol. 48, no. 3, pp. 239-248, 1995.
- [118] P. M. Morse and H. Feshbach, *Methods of Theoretical Physics*, New York: McGraw-Hill, 1953