Design and fabrication of MEMS optical switches

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Design and Fabrication of MEMS Optical Switches

Li Jing

School of Electrical & Electronic Engineering

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

2006

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2006

Dedicated to,

My Dear Parents and Sweet Husband

“The most ordinary things are to philosophy a source of insoluble puzzles. With infinite ingenuity it constructs a concept of space or time and then fines it absolutely impossible that there be objects in this space or that processes occur during this time ... the source of this kind of logic lies in excessive confidence in the so-called laws of thought.”

Boltzman, Ludwig

(1844 – 1906)

Abstract

This thesis focuses on the research related to the microelectromechanical systems (MEMS) optical switch consisting of three major areas, micromachined actuator, deep reactive ion etching (DRIE) fabrication, and total internal reflection (TIR) optical switch.

Firstly, a stable micromachined actuator with large displacement has been designed and demonstrated. It consists of comb-finger-sets and compliant microstructure to amplify the displacement efficiently and lock the output by bifurcation effect. The amplification obtained is 54.2 when the input displacement is only 0.96 μm and it is locked thereafter.

Subsequently, a DRIE fabrication process for silicon on insulator (SOI) wafers has been investigated. Based on the study of DRIE process chemically and physically, the notching effect on SOI substrate is eliminated and utilized to realize dry release resolving the stiction problem by developing a spacer oxide thin film technique.

Lastly, a TIR prism optical switch based on the thermo-optic (TO) effect has been studied. It takes the merits of robustness of thermo-optic prism and the precise control and batch fabrication of MEMS. The optical properties including insertion loss, polarization dependent loss and cross-talk are theoretically simulated and proven by experiments.

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SUMMARY

This doctoral study focuses on research related to a microelectromechanical systems (MEMS) based optical switch. In particular, the study focused on three areas. First, a stable micromachined actuator with large displacement for a two-dimensional (2D) optical switch is designed and demonstrated. Second, a deep reactive ion etching (DRIE) fabrication process based on silicon-on-insulator (SOI) wafers is investigated. Third, a total internal reflection (TIR) prism optical switch based on the thermo-optic (TO) effect is studied.

In the actuator study, a compliant microstructure incorporated with comb-drive is designed, theoretically modeled, deep-etch fabricated and experimentally measured. This configuration provides a large ratio of output to input displacements via storing the elastic energy, deforming the microbeams and releasing the energy to amplify the displacement. The simulation results show that a magnification larger than $100\times$ can be obtained and the output direction can be altered with a proper design. Self-limitation is achieved by utilizing the bifurcation effect which is numerically simulated. This concept is proved by the device with optimized configuration fabricated by DRIE. The measured amplification is 54.2 with output displacement of $52.0\text{ }\mu\text{m}$ which is stabilized by the bifurcation effect of the microbeams. Then, the effects of fabrication tolerances, including the slanted profile of the comb fingers and the compliant microbeams, the uneven depth of different portions of the same comb fingers, and the undercuts occurred to the microbeams, are modeled.

The principles of DRIE are theoretically explained followed by an analysis on the effects of different process parameters verified by the experimental results. Based on this, a vertical, fast and high selective process recipe is provided by optimizing the

Summary

process conditions. Then the pattern effects are investigated with special focus on the loading and the verticality effects. All these phenomena then lead to the notching effect on the SOI wafers due to the buried dielectric layer and are also supplemented by the stiction problem from the wet release. Therefore, a novel spacer oxide thin film technique is developed to eliminate this notching problem. More importantly, the lateral etching effect is used to etch the device silicon instead of oxide layer in dry method. Hence, a reliable dry release method is realized by combining an oxide layer deposition and anisotropic etching.

A new total internal reflection (TIR) thermo-optic optical switch is developed by utilizing both the robustness of thermo-optic switching method and the merits of fine tuning and batch precise fabrication in MEMS technology. A silicon prism is designed based on Snell's law. The thermo-optic coefficient effect is derived using the single oscillator model of the thermo-optic effect. The optical performances of the switch are theoretically determined by employing electromagnetic wave theory and Maxwell Equations. The mechanisms of the insertion losses are analyzed in theoretical simulations of the main phenomena of interests such as Fresnel reflection, coupling loss, partial transmission at the TIR surface, F-P cavity effect, and the loss due to surface roughness. The polarization dependent loss (PDL) is simulated as a function of incident angle for both s and p polarizations respectively. The dispersion of silicon's refractive index (i.e. its variation with the wavelength) can be compensated by MEMS thermal actuators. The optical cross-talk between the two alternative outputs is studied by separately analyzing the s and p polarization components. This TIR prism optical switch based on the thermo-optic effect is fabricated by the DRIE process. The insertion losses are explained by the theoretical simulation of different

Summary

sources of loss. The optical cross-talk from TIR to transmission output is negligible, but the leakage from transmission to TIR output is -28.06 dB due to partial transmission where the complementary portion is directed to the TIR channel.

This newly developed DRIE fabrication technique plays an important role in providing a platform for an SOI wafer based process applicable to different devices and systems. The implementation of the MEMS optical switch in this study has again proven and highlighted the merits of the MEMS technology with respect to low power consumption, small size, transparency in a large range of wavelengths and signal format, scalability and batch fabrication. It paves a new path to integrate the individual merits from different principles in physics together to achieve a more functional, stable, and reliable system.

CHAPTER ONE

INTRODUCTION

1.1 Motivation

When conventional microelectronics goes beyond the incremental improvements of a well-established technology, a new frontier in micro technology has appeared. It challenges the way the devices are done and compels the designer to explore new approaches and methods, even exploring into the third dimension and also to acquiring and combining unusual multi-disciplinary skills in what it now called Micro-Electro-Mechanical Systems (MEMS). MEMS technique strives to integrate mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. Though this revolution borrows some techniques from the world of microelectronics, it applies them in new ways that revolutionize nearly every product category by bringing silicon-based microelectronics together with micromachining technology, making the complete systems-on-a-chip (SOC) possible. MEMS is an enabling technology allowing the development of smart products,

augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators, and expanding the space of possible designs and applications. As a breakthrough interdisciplinary field, there are numerous possible applications for MEMS technology. Since it allows unparalleled synergy between previously unrelated fields such as biology and microelectronics, many new MEMS systems emerge, expanding the know-how beyond that which is currently identified or known, including pressure sensor and inertial measurement units (IMU) [1, 2], communication devices such as radio frequency (RF) filter and optical components, and bio micro total analysis system (μ TAS) on chip. These devices will not only lead to interesting new applications, but also foster the emergence of a new breed of researchers with a broader knowledge and also more room for revolution in various forms.

Among these diversified applications, the Micro-Opto-Electro-Mechanical System (MOEMS), also commonly known as optical MEMS, is a promising optically-related sub segment that meets the needs of various optical applications, especially for telecommunications such as integrated optics and optical networks [3]. Various kinds of optical components can be fabricated and integrated into one system by using such technology, for instance, optical switches to selectively route various channels, variable optical attenuators (VOA) to equalize the optical power in dense wavelength division multiplexed (DWDM) systems, optical modulators and filters based on Fabry-Perot cavity to select a specific wavelength channel while block the others [4], and tunable lasers to emit various wavelength laser light. These MOEMS devices process light in miniature free-space optical beams. The prominent advantages of MOEMS components including low loss, low cross talk, scalability and insensitivity to data

format, small size, low cost, and the easy integration with large-scale systems outweigh the disadvantages such as the relatively slow speed and large operation voltage. The MOEMS applies efficiently the underlying physics and develops cost-effective processing to achieve high precision components and systems. Besides the telecommunication applications, these optical systems also show great potential for use in several other industry segments, including displays and biomedicine [5].

Among these MEMS optical devices, the optical switch is one of the key components because of the vast expansion in the use of the Internet, where the speed of information transmission and routing acts as a critical slowing down bottleneck. To address this problem, new means to switch light signals rapidly and efficiently to different routes have to be developed. Though the electrical hub was introduced into such informational network systems, the traditional conversion between optical and electrical slows down the entire chain of response. An all optical switching is replacing this electrical switch to provide signal protection, allow provisioning, increase network capacity, and generally reduce the system cost [6]. Therefore, several categories of optical switches are being developed, namely thermal-optical [7], liquid crystal [8], electro-optical [9], acousto-optical, MEMS, opto-optical, and others such as semiconductor optical amplifier (SOA) and ferro-magnetic switches, each with their own pros and cons in terms of basic performance, network requirements and system requirements [10]. Among them, the optical MEMS switch might be one of the most promising techniques due to its advantages of low insertion loss, negligible cross talk, low polarization dependent loss, insensitive to wavelength changes and applicable in a large range of wavelengths, transparent for bit rate and protocol and good scalability. Therefore, it may prove promising and very meaningful to develop such devices.

However, the stability and robustness are deteriorated as a result of the frequent motion and external disturbance. Therefore, finding the right approach to provide a stable large displacement to drive the functional components of a MOEMS microsystem is a significant and challenging task. A thorough solution is to realize an optical switch without any frequent motion at all.

MEMS devices are highly process dependent and as such they may severely be constrained by the integrated circuit (IC) process technology employed in order to achieve the final aim of realizing fully three-dimensional structures. There are two main types of microfabrication used in MEMS, namely surface micromachining and bulk micromachining. Surface micromachining is closer related to standard IC technology as it builds thin film structures on top of the substrate. Typically, polysilicon is used as structural material and silicon dioxide as sacrificial layer. However, the thickness of the deposited polysilicon layer and of any Chemical Vapor Deposition (CVD) thin film in general, is limited in surface micromachining. To address this problem, bulk micromachining was developed to obtain high aspect ratio microstructures made of single crystalline silicon that offers better mechanical properties and potential thickness than polycrystalline silicon. However, the fabrication is individually optimized for each specific device and therefore is difficult to standardize, which is the major drawback of the MEMS technology. Therefore, it is the most important to develop a universal fabrication process suitable for optical, RF and bio MEMS devices.

The stationary robustness of the material physics and the finely tuning ability of a micromachined actuator has their own merits and drawbacks. Therefore, an ideal hybrid optical switch will be the one that utilizes the merits of both and simultaneously

overcomes their drawbacks. For instance, silicon exhibits a good thermo-optic characteristic where the refractive index is a function of temperature. Utilizing this unique feature it is possible to switch the input signal without physical movements to direct the input signal, making it highly practical, attractive and achievable. Therefore, a sensitive, robust, and reliable optical switch that combined the merits of both techniques is targeted in this present work.

1.2 Objective

In this thesis, the ultimate objective is to employ the fundamental principles of MEMS technology in order to design and implement practically low power consumption, fast, stable, scalable, and reliable optical switches. To achieve this particular goal, three main objectives must be set. The first objective is to design and demonstrate a novel actuator that provides a stable and large displacement. The second objective is to develop a universal deep reactive ion etching (DRIE) fabrication process for various applications. The third objective is to fabricate a robust and sensitive thermo-optic switch.

A MEMS actuator consisting of a compliant mechanical microstructure and comb-drive was designed, theoretically analyzed, and fabricated to provide a stable and large displacement. By using this actuator, a 2D MEMS optical switch was obtained. The chemical and physical properties of DRIE process were studied, where the DRIE etching related problems such as the loading, the notching, and the profile effects are investigated and addressed. Furthermore, a total internal reflection thermo-optic switch associated with two thermal actuators was demonstrated. This optical switch is more robust, reliable, sensitive and adaptive to silicon substrate with different refractive

index. The optical properties of the optical switches are theoretically simulated and characterized. These include the insertion loss, polarization dependent loss (PDL) and optical cross talk between the two alternative output channels.

1.3 Major contributions

The major contributions in this study are summarized as follows.

In this study, a *self-locked actuator* with large displacement ratio realized by a compliant microstructure incorporated with comb-drive is investigated. A theoretical model is built up to analyze the linear amplification and the bifurcation effect used to realize self-locking. The geometrical parameters of the actuator are optimized based on these models and the actuator is fabricated using DRIE process and experimentally measured. An output displacement of 52.0 μm was obtained by amplifying the input displacement of 0.96 μm , afterwards the output displacement is stabilized using the bifurcation effect. The resonant frequency is 2.395 kHz with negligible deviation from the designed value of 2.398 kHz.

The *tolerances between design and fabrication*, which affect the performance of the switch, are unsurpassable. In this thesis, various kinds of tolerances, including the profile of the comb fingers and compliant beams, uneven depth of the different portions of individual comb finger, and undercuts of the microbeams, are discussed in terms of origins and effects on the electrostatic force and displacement amplification.

The *DRIE process* used in the fabrication of the devices is also theoretically and experimentally investigated in this study. The etching conditions, such as chamber pressure, gas flow rate, platen and coil power, and cyclic durations, are analyzed

accordingly to the etch profile, etch rate and etch selectivity to the mask layer. The loading effect is carefully studied by varying the trench width, exposure area and the locations. The effect of the process conditions and trench width on the microbeam profile is experimentally studied. The study shows that a 10.0 μm wide trench gives a nearly perfect vertical beam.

A *new spacer oxide thin film technique* is developed to eliminate the severe notching effect on SOI wafer based on the analysis of the mechanisms of the notching phenomenon. The notching depth is thoroughly investigated as a function of over etch time and trench width. This specific lateral etching is controlled and used to release either uniform or non-uniform wide beams formed by trenches of identical or different widths eliminating the stiction problem.

A *novel total internal reflection (TIR) thermo-optic switch* based on the material properties of silicon is studied and demonstrated. The selection between the alternative output channels is realized by tuning the refractive index of the localized silicon associated with the specially designed prism. In the transmissive state, the input signal is transmitted through the prism, while the incident optical beam is reflected into the other channel due to the total internal reflection. Based on the physical study of both thermo-optic effect and total internal reflection, the architecture of the TIR thermo-optic switch is designed by combining the optical properties of silicon and Snell's law. The adaptation to substrate with a slight deviation of the refractive index is compensated using two thermal actuators to finely tune the incident angle. The thermo-optic effect of silicon is theoretically explained by the single oscillator model to obtain the coefficient of $1.8 \times 10^{-4} \text{ K}^{-1}$.

The *optical properties* of the optical switch, including insertion loss, polarization dependent loss, and optical cross talk between the two output channels, are theoretically analyzed and simulated using the electromagnetic wave theory and Maxwell's equations. The dispersion of the prism at different wavelengths is discussed and balanced by the thermal actuators. The concept of this novel optical switch is experimentally proved and the measured insertion losses, cross-talks and polarization dependent loss agree well with the developed theory.

1.4 Organization of the thesis

This thesis emphasizes on the theoretical design and DRIE fabrication of various MEMS optical switches. It is composed of six chapters.

Chapter 1 provides a general introduction to the MEMS optical switch and summarizes its merits and the achievements of this study.

Chapter 2 outlines the historical achievements of MEMS technology. Various MEMS optical switches, including 2D and 3D mirrors, are reviewed. Different MEMS fabrication technologies are compared and different kinds of actuators with various applications are discussed by showing their individual pros and cons as the background of this study.

Chapter 3 focuses on the actuator analysis for 2D planar optical switch applications. The actuator using the compliant microstructure provides a stable and large motion. Theoretical models are set up to analyze the linear displacement amplification and the bifurcation effect employed to self-lock the movement of the output point. The amplification and self-locking of the actuator together with the

resonant frequency are demonstrated whilst the effects of the fabrication tolerances onto the actuator are analyzed in this chapter.

Chapter 4 analyzes the fabrication related issues from the DRIE principles to the contributions of the process conditions including the chamber pressure, gas flow rate, platen and source powers, and cycle durations. The DRIE etching related issues such as loading effect with various trench widths, exposed area, and wafer location are investigated. The profiles of various beams are experimentally measured and the etching procedure along the etching is carefully studied. The process on SOI wafer is developed to make use of the merits of single crystal silicon and to realize high aspect ratio microstructures. The mechanisms of the notching effect are analyzed, based on which the notching effect is either eliminated or it is employed to release the movable structures. The detailed processes and the factors that influence the notching are described in this chapter.

Chapter 5 demonstrates an innovative TIR thermo-optic switch based on the physics of thermo-optic effect and total internal reflection, which is fabricated by the process developed in Chapter 4. The switching between transmission and reflection is realized by locally adjusting the temperature leading to the change of refractive index, so that the TIR condition is met. Therefore, such a switch is highly sensitive to the switching temperature while the output is independent to other temperatures. The optical performances including insertion loss, polarization dependent loss (PDL), dispersion of various wavelengths, and optical cross-talk are theoretically analyzed by employing the electro-magnetic theory and experimentally characterized.

Finally, conclusions and some recommendations for future researches are presented in Chapter 6.

CHAPTER TWO

LITERATURE SURVEY

In this chapter, the literature overview related to MEMS, especially optical MEMS devices are presented. After reviewing the various types of MEMS optical switches, from 3D micromirror to 2D torsional mirror, optical switch based on 2D translational micromirror is concentrated and different configurations of switch matrices are investigated. Then, because micromachined actuators is one of the key features related to the proposed switch, different principles are presented and compared with focus on the electrostatic mechanism which is the most relevant for this proposed device. Finally, numerous MEMS fabrication processes are compared, our attention being in particular focused on the deep reactive ion etching (DRIE) approach.

2.1 Review of optical switch

“The unique capability of optical MEMS to integrate optical, mechanical, thermal, and electrical components onto a single chip allows for the implementation of various

key optical network elements in a compact, low-cost form,” says Technical Insights’ Analyst James Smith [11], “it is not only an emerging technology but an engineering principle with a myriad of far-reaching applications.” With the increase of bandwidth and transmission speed of the optical network, the realization and integration of high performance optical devices becomes increasingly important, optical MEMS being capable to provide promising characteristics such as miniaturization, high integration, high reliability, and low cost. Optical MEMS plays an important role in optical domains [12] and its great potential makes it very attractive for both research and industrial.

2.1.1 Types of optical switches

Optical switching is replacing electrical switching functions [13] because the conversion between optical and electronic signal is a critical bottleneck in optical networks when a huge amount of information needs to be switched through various nodes [14]. Therefore, optical switching without electrical-based traffic protocols is promising and is a keystone in a dynamic reconfigurable all optical networks. Several techniques as to how to implement optical switching have been proposed and studied. These include realizations based on optical MEMS [15-32], thermal optical [33-35], semiconductor optic amplifiers (SOA) [36], liquid crystals [37], electro-holography [38], electro-optical LiNbO_3 [39], electronically waveguide Bragg grating [9], acousto-optical [40-43] and opto-optical switches [44-49], respectively.

A liquid crystal optical switch is changing the molecules’ orientation by applying an external voltage to the liquid crystal materials due to the permanent electrical dipole moment [50]. Thermo-optic switches utilize the thermo-optic (TO) effect of the

dielectric material whose refractive index is a function of the temperature. A Mach-Zehnder based polymer waveguide switch is one such example [51, 52]. The holographic switch is based on controlling the reconstruction process of volume holograms by an external voltage [53]. All these mechanisms have their own pros and cons in terms of characteristics including basic performances (insertion loss, switching speed, cross-talk, polarization dependent loss, bit rate and protocol transparency, operation bandwidth), network requirements (multicast, switching device dimensions, scalability and nonblocking), and system requirements (stability, repeatability, power consumption and cost) [54], where the performances depend on each other.

Compared to the other types of optical switches, MEMS technique is favorable due to low polarization sensitivity, independence on the data rate or format, insensitivity to the wavelength, miniaturization, low power consumption, low cost of batch fabrication, middle to fast speed, expandability to large matrices and integrability with the control circuits. Additionally, this kind of optical switch can be customized for different applications such as high capacity backbone networks, optical cross connects, and optical add/drop multiplexers with the assistance of other optical components which can be easily realized using MEMS [55, 56].

2.1.2 The MEMS optical switch

According to the type of the movable element, MEMS optical switches can be divided into two main categories, namely switches with moving fibers and switches with moving mirrors or lenses. The former transfer light into different fibers by moving the fibers [32], whereas the latter shift light between different output fibers [15-31, 57] by moving mirrors or lenses. The switch with moving fibers consists of

two major components [20, 26, 32], an H-shaped buckling platform for fiber clamping and two coupled U-shaped cantilevers for lateral movement of the input fibers. Both actuators are thermally driven and use the thermal expansion of locally heated silicon. Originally, the fiber is fixed in one stable state and all fibers are clamped between the V-grooves of the H-shaped buckling platform and an upper cover. For switching, the fiber clamp is opened by heating the lower part of the clamp. Thus, the input fiber relaxes to the middle position. Heating one arm of both U-shaped input cantilevers results in a lateral bending of the input cantilever structure. When the fiber reaches another stable state, the heaters of the H-shaped cantilever are switched off and the fiber clamp closes. After this, the input actuators are turned off and the fiber is fixed in a stable position. However, such a switch has very poor expandability to large matrixes, and the switching speed is another critical limitation.

The switches with moving mirror or lenses involves a micromirror which directs the input signal into the targeted outputs. For this purpose, their structure employs either a 2D mirror, in which light signals are routed within a plane, or a 3D one, where the light travels in a 3-dimensional space according to its design architectures.

2.1.2.1 The 2D MEMS optical switch

The 2D MEMS optical switch has its own advantages over the 3D mirror switch, such as low cost and simple fabrication. Additionally, the reliability and repeatability are higher than 3D switches. Though the scalability is a problem for this 2D MEMS optical switch, it is still beneficial for small and medium matrices. According to the requirement in the market, small (such as 2×2 and 4×4) and medium (such as $16 \times$

16) sized matrices are dominating and this 2D switch can be used in matrices with size up to 64×64 .

For the torsional 2D [22, 24, 29, 30] MEMS switch cell, a high reflective mirror is driven to realize a torsional motion about a certain axis (or several axes), e.g. vertical, diagonal, or cantilever torsional micromirrors. The micromirror is suspended over the substrate by microbeam(s) along the axial direction, which are in turn supported by anchors at the ends. Opposite electrodes lie under the micromirror. In this way, the micromirror can be driven to rotate around the beam axis by the electrostatic force.

As most of the above 2D torsional switches are fabricated by surface micromachining, the air gap between the bottom of the micromirror and the substrate cannot be too large due to the thickness limitation of the sacrificial layers leading to a very limited rotation angle. Worse still, the flatness of the mirror is degraded by the stress of mismatched materials and warp may occur resulting from the non-uniform distribution of the electrostatic attractive force and the elastic balancing force. The other critical weakness of this type of switch is the stiction problem caused by either wet release or the increased electrostatic attractive force between the mirror and substrate.

Compared to 2D rotational mirrors, the translation 2D mirror based optical switches [24, 31] are easier in terms of fabrication, especially when SOI substrates are used, because the micromirror and the actuator are fabricated by DRIE process together with the fiber grooves. The performance of this switch is inherently better because the movement of the mirror is translational, where no deformation may occur to the mirror. Additionally, there is no stress induced by the fabrication process as the mirror is coated on both sides and the built-in stress can be cancelled out. This type of

optical switch is developed by using either an SOI [24] or a plane silicon substrate [31]. When the mirror is in the beam path, the incident lights are reflected into the orthogonal outputs realizing the cross state. When the mirror is driven out of the beam path, the incident lights can travel through to the opposite output fibers realizing the bar state.

2.1.2.2 The 3D MEMS optical switch

The 3D MEMS optical switch is best exemplified by Lucent optical cross connects, which can scale to thousands of ports with low loss and high uniformity. Its Micromirror can be tilted along two orthogonal axes when a proper driving voltage is applied to the stationary and movable electrodes. There are clear and critical drawbacks including (1) complex feedback mechanisms are necessary to position the mirrors, (2) bundles of input and output fibers are to be aligned, and (3) the production processes are complicated and costly. Another common perception is that this type of MEMS optical switch is extremely complicated in terms of manufacturing that requires sophisticated analog control mechanisms and intricate packaging to connect the wires onto the electrodes [58].

2.1.3 The optical switch matrix

The small 2D translational switch cell can be expanded to 4×4 matrix integrated with a waveguide [36] with 16 micromirrors. As a Gaussian beam diverges with propagation, either a collimator should be employed or a waveguide is introduced to confine the beam size. However, the mirror number is N^2 for an $N \times N$ switch matrix. Therefore, this type of configuration is modified to L-shape to reduce the mirror

number by 25% [57] where an actuator that can provide a stable and large displacement is required.

2.2 Review of actuator for MEMS optical switches

Microactuators are specific structures of MEMS technology. Though lithography, etch and deposition were developed and used in IC technology, there is no any movable structure in IC chip and circuits. In contrast, in MEMS devices, movement is introduced, recognized and controlled by various kinds of mechanisms including electrostatic [59-65], thermal [66-69], piezoelectric [70-74], magnetic [75, 76], scratch drive actuators (SDA) [77, 78], and so on [79, 80]. Table 2-1 compares the different types of microactuator in terms of driving voltage, efficiency, and maximum possible frequency [81].

Table 2-1 Comparison of MEMS actuation mechanisms

Mechanism	Max. Energy Density (Ws/m ³)	Max. frequency (Hz)	Driving Voltage (V)	Efficiency
Electrostatic	1.8×10^5	< 10,000	5 - 500	0.5
Magnetic	4.0×10^5	< 1,000	~ 20	< 0.01
Piezoelectric	1.2×10^5	< 5,000	5 – 100	0.3
Bimetallic	4.0×10^5	< 100	~ 5	0.0001
Thermo pneumatic	5.0×10^5	< 100	~ 10	0.1
Conductive polymer	3.4×10^6	< 1,000	~ 5	0.6
Shape memory alloy (SMA)	2.5×10^7	< 100	2 - 5	0.01

The table shows that thermal actuators are highly sensitive to the ambient temperature, whereas the magnetic or SDA ones are much more complicated in terms of fabrication and require in the device structure special materials that are not compatible with the complementary metal oxide semiconductor (CMOS) fabrication. The comb-drive actuator based on the electrostatic principle is the most attractive, with widespread applications in MEMS systems such as optical, inertial gyroscope, accelerometer, RF and etc.

2.2.1 The electrostatic comb-drive actuator

The electrostatic comb-drive actuator combined with a folded suspension beam was first demonstrated by Tang et al. [59, 60], providing an amazing transducer for MEMS applications. Actuator with large static displacement and stable motion capability has always attracted the interest of researchers and scientists. This is particularly true for MEMS optical devices, because the large displacement is crucial for practical applications such as micro XY stages, two dimensional lens scanners, and variable optical attenuators, while the stability is more important to assure the long-term performance of the MEMS optical switch and tunable lasers.

As the driving force generated by the comb sets is proportional to square of the applied voltage or it can be linearly to the magnitude of the voltage by other modifications [82], high voltage is typically required in order to achieve a large displacement, which increases the power consumption as a drawback. Several approaches are then conducted to reduce the driving voltages and to increase the electrostatic force of the comb-drive actuator. Efforts have been made to narrow down

the gap distance between the comb fingers [83], to increase the aspect ratio of the microstructure [84–86] and to utilize angled comb fingers [86, 103].

However, the above methods are still suffering from the side pulling effect between adjacent comb fingers [83, 89, 90] if the voltage is above the critical value [91], because the slight deviations of the comb finger leads to an unbalanced force caused by fabrication [92]. The transverse force leads to the side-to-side instability and the stability of the actuator will deteriorate when the overlap length of the comb fingers increases. The worst case occurs when the movable fingers permanently stick to the fixed fingers. Therefore, how to design and obtain a low voltage driven actuator that can provide large displacement with more robustness and immune to external vibration is very attractive and challenging.

2.2.2 Modified comb-drive actuator

Some researchers emphasized new driving scheme [93] in order to solve the requirement for a high driving voltage and the problem of instability. Additional circuitry to achieve a larger displacement under the same voltage [94-96] and incorporating an onboard folded capacitor on the device [97] were investigated. The use of an active control law was first proposed [98] for the electrostatic actuator and the first fabricated device with extended travel range was conducted by Chan [104] and modified by D. Piyabongkam *et al.* [99]. Guardia *et al.* presents a current-controlled method for extending the stable travel range [100], which in effect is equivalent to employing charge control as described in [101]. However, the position of the actuator beyond the pull-in point either cannot be maintained or periodical

refresh current pulses have to be applied to maintain it due to the inherent current leakage problem.

Thinned three-folded beam flexures were derived by modifying a DRIE process on SOI wafer, so that the stiffness of the system is reduced and hence, the displacement increases when the same voltage is applied [102, 103]. Their relationship depends on the ratio of the thickness of the folded beam to that of comb finger as expressed as

$$V_{\text{modify}} = \sqrt{\frac{2}{3\alpha}} V_{\text{orig}}$$

where V_{modify} is the voltage required to obtain the same displacement with a modified folded beam and V_{orig} is the voltage corresponding to the conventional double folded beam whose thickness is equal to that of the comb fingers. It shows that the driving voltage can be decreased to $\sqrt{2/3}$ for a triple folded beam and it can be reduced further by decreasing the thickness of the folded beams to $1/\alpha$ of comb finger thickness. Therefore, a larger static displacement can be provided by this actuator.

The stability regarding to the translational disturbance or process induced misalignment have also been considered. A multiple linear comb-drive actuators were developed and used for a $1 \times N$ optical switch [104, 105], where the actuator consists of suspended pre-bent spring beams followed by the modification into a tilted folded beam [106] where the spring comprises of four tilted beams. Recently, a hybrid spring with an N-shaped joint for comb-drive was developed to enhance the lateral stiffness against lateral mechanical disturbances and shocks [107].

2.2.3 Displacement amplification actuator

Although these improvements are significant to achieve a stable actuator that can provide a relatively large displacement, the obtained improvement is limited and the increase of the overlap of the comb fingers also raises the transverse force which, in its turn, degrades the stability. Hence, another mechanism was introduced to realize large displacement based on the mechanical principle of prior displacement multiplying [108-111]. It is based on a lever arm moving about a pivot joint, but exhibits several critical disadvantages. The movement is circular, executing along a circular arc rather than linear, and the stability of the output displacement is also influenced by small input vibrations.

Therefore, the design and realization of an electrostatic actuator that provides a stable large displacement is a big challenge and is addressed in this thesis. The limited displacement obtained by the comb-drive together with normal folded beam is amplified by a novel compliant microstructure, where the actuator is immune to external lateral disturbances by employing the bifurcation effect of the compliant microstructure.

2.3 Review of fabrication technologies for the realization of MEMS optical switches

The optical MEMS is primarily employing current IC techniques for the realization of mechanical, optical and electrical characters and developing the appropriate fabrication processes is the key factor in obtaining the desired structure and functionality. Hence, except for the steps employed in conventional micro-electronic processes, such as oxidation, deposition, lithography, metallization and

etching, special attention is paid, among other methods, to the etching technology to form three dimensional moving structures. Compared to the IC fabrication, due to the large range of methodologies that need to be used for various devices, the MEMS fabrication process has a wide spectrum with various approaches. Though lacking of standardization leads to longer design and fabrication period, it enriches the process domain and application fields.

2.3.1 Surface micromachining

The characteristic of surface micromachining is that both the functional structure layer and the sacrificial layer to form the movable structure are deposited instead of using the substrate itself [112]. The selection of proper materials is critical for the process. Usually polycrystalline silicon is used as the structural layer while silicon dioxide is used as the sacrificial material. A good example of surface micromachining based fabrication standard is the well developed Multi-User MEMS Process (MUMPs) [113]. Another combination is InP as the structure layer and InGaAs as the sacrificial layer [114].

Apart from the releasing step, this process is similar to the traditional IC processes. This process is commonly adopted in the fabrication of many optical devices such as digital micromirror devices (DMD) [4], MEMS optical switches [115], Fresnel lenses [116] and etc. The main problems identified in this process include time consuming and low yield assembling of the various components that limits the usage of the surface micromachining. Other problems include stress arising from the mismatch of the thermal expansion coefficient of the materials, and thickness limitations due to the restriction imposed by the fabrication process. Stiction is

another key problem due to wet sacrificial layer release and rinse. More importantly, the deformation of the key component, such as the micromirror of the optical switch, during the switching is a fatal disadvantage of this process.

2.3.2 The deep RIE process

Deep reactive ion etching (DRIE) has been developed and widely used for MEMS fabrication as a dry bulk micromachining technique because its directional etching is independent of the silicon crystal orientation and thus aids in preventing the unintentional prolongation of etching.

2.3.2.1 Dry etching process

Dry etching is a process where the material removal is due to reactions that occur in the gas phase. It includes both non-plasma and plasma based dry etching. The former is typically an isotropic etch that uses the spontaneous reaction of an appropriate reactive gas mixture with the material to be removed, e.g. fluorine contained gas mixture for etching Si. This etch provides high selectivity to many masking layers including Al, SiO₂, Si₃N₄, photoresist (PR), and phosphorus silicon glass (PSG). This etching can be highly controlled via the temperature and partial pressure of the reactants without the need of a specialized plasma processing equipment. One of the most employed reactant gas is XeF₂, which chemically reacts to silicon according to,

The other type of dry etching is the plasma based anisotropic etch, which is more widely used in MEMS fabrication thanks to the directional etching without using the

crystal orientation of silicon and better control preventing the unintentional prolongation of etching. The plasma based dry etching can be categorized into four types, namely, chemical etching, physical etching, reactive ion etching (RIE) and deep reactive ion etching (DRIE), with the last two being the most commonly used.

RIE process is a chemical etching accompanied by ionic bombardment (i.e. ion assisted etching). The plasma is the source of both ions and chemical etchant agents. The combined effect of both etchant atoms and energetic ions in producing etching products can be much larger than that produced by either pure chemical reaction or by sputtering alone. The etching is chemical in nature without directionality while with a reaction rate determined by the energetic ion bombardment. The anisotropic property results from ion-enhanced reaction. Though RIE can provide good directional etching, the etching rate and anisotropic profile conflict with each other. A faster etching rate needs higher reactive species concentration which leads to higher gas pressure and more collision, which is in contradiction with what is required for an increased anisotropy of the etched feature. Another conflict exists between the damage inflicted by a high etching rate and the anisotropy of the etched profile because the higher kinetic energy of the ions necessary for a good profile of high anisotropy decreases the etching rate. In other words, the etch depth is limited by the requirement for a high anisotropy. Therefore, in order to address all these issues, DRIE was introduced for the fabrication of high aspect ratio microstructures. This process employs lower energy ions with less damage and higher selectivity.

2.3.2.2 Deep RIE etching processes

Firstly, simultaneous etching and sidewall passivation processes have been successfully employed in MEMS applications [117] where the removal of passivation and proceeding of silicon etching occur at the same time and they are balanced to maintain a vertical profile. Then, cryogenic enhancement [118] was developed to address the passivation-related problem by keeping the substrate temperatures as low as -110°C and is attractive for the optical applications [119]. As a blocking layer of oxide/fluoride (SiO_xF_y) with a thickness of 10–20 nm is formed on the sidewall, the lateral etching with the radical fluorine is inhibited associated with the cryogenic temperatures suppressing the chemical reaction in which fluorine radicals would be involved. However, such extreme low temperature leads to the thermal cracking of PR. The DRIE eliminates all these issues by alternating the etching and passivation deposition steps [120–122] in order to achieve deep and almost vertical silicon structures. The process temperature is not as low as that of the cryogenic approach, hence, there is no PR cracking issue and the process efficiency is higher.

In this DRIE approach, the passivation is deliberately separated from the etching by sequentially alternating the etching and deposition steps rather than integrating the sidewall protection within the etching process. After the deposition of a polymer passivation layer over all the surfaces of the etched trenches, the polymer is etched only from the base of the trench to expose its bottom silicon while maintaining the lateral sidewall protection layer to ensure that the etching will proceed directionally. In this way, the etching and deposition could be independently controlled accurately for high anisotropy. The main reaction gases are typically SF_6 for etching and C_4F_8 for passivation. The two steps are switched using a hardware method.

Therefore, a microstructure with high aspect ratio can – in principle- be easily realized. However, the whole process is much more complicated, with numerous parameters influencing the final etch properties such as etch rate, etch profile and etch selectivity to mask materials. This complexity makes it difficult to establish a new suitable recipe that satisfies certain requirement and its development must be carried out based on the chemistry and physics of etching and the individual contributions of each process parameters. Process results also depend on the feature dimensions and distributions over the whole wafer. Hence, the loading effect has to be studied to guide the design of the desired etching recipe.

2.3.2.3 DRIE on SOI substrate process

Silicon-on-insulator (SOI) wafer is more commonly used for MEMS because the structure height is a significant advantage compared to the limited thickness of the polysilicon films employed in surface micromachining. Besides, SOI substrates are commercially available and are becoming cheaper. The device, handle and buried insulating layers are all pre-formed in an SOI substrate so that the process is relatively simple. The single crystal silicon (SCS) mechanical layer thickness is significantly greater and more uniform. Additionally, the reliability is high due to the elastic behavior continuing far up to the high yield stress of the SCS which has very few defects. Therefore, the design is flexible and it gives improved performance for some applications, such as to provide higher edge capacitance. Moreover, it is compatible with complementary metal oxide semiconductor (CMOS) process. There are, however, two significant problems for the SOI microstructure fabrication. One is the

notching problem during deep etching of the thick device layer, the other is the stiction problem caused by the wet release process.

Several ways are available to address the notching problem, but each method has its own limitations. One such solution is to adjust the process parameters dynamically, but this is time consuming and difficult to control. Surface Technology Systems (STS) has developed a deep plasma-etching machine, which has two different platen frequency sources; 13.56 MHz and 380 Hz, respectively. By employing low frequency, the ions are allowed to escape after the etching cycle, preventing the charge accumulation. However, this method is limited by the hardware itself and it is difficult to detect the end point, especially for trenches with different aspect ratios. Another method is to prevent the ions scattering at the price of non-vertical profile.

The permanent stiction problem due to the capillary forces that occurs during the rinsing and drying of wet release is another major problem. This effect has been studied heavily both theoretically and experimentally. Several modified release approaches such as the hydrofluoric acid (HF) vapor etching, liquid HF etching combined with freeze drying, photoresist assisted methods, or surface modification-based solutions had been reported. Unfortunately, these processes are not faultless, some suffering from problems such as bubbles in the liquid, low yield, less thermal stability, etc. To solve these problems, attention was given to dry release, and hence the development of dry isotropic silicon etching and dry etching of silicon dioxide. The single crystal reactive etching and metallization (SCREAM) together with the disadvantages of RIE lag may cause different etching depths at both sides of a vertically etched beam. Another attempt is the silicon micromachining by single step plasma etching (SIMPLE), but it strongly depends on the dosage the buried layer and

the release rate is very low, at about 50 nm/min. The black silicon method (BSM) involving multi-step one-run includes both BSM SOI and BSM SISI (silicon on insulator on silicon on insulator) methods. The last approach, BSM SISI, tried to solve the issue of high silicon loading problem of the BSM SOI. However, the cost of double SOI wafers for BSM SISI process is high. The other disadvantage is the low speed involved during wall passivation and oxide etching, which are at 20 nm/min and 50 nm/min respectively.

Therefore, developing a universal DRIE process on SOI substrate eliminating the notching and stiction problems is significant and serves as one of the objectives of this thesis.

2.3.3 Other fabrication techniques

In addition to these main MEMS fabrication techniques, some other technologies have been studied and employed to process on specific materials and for various applications with their own advantages and drawbacks. Some of the other fabrication techniques with special applications to optical MEMS devices are listed here.

Wet bulk micromachining [123-131] is widely used for the fiber groove fabrication [126, 127] and vertical smooth optical surfaces [130, 131]. The LIGA (Lithographie, Galvanoformung, Aboformung) process developed by Wolfgang Ehrfeld, et al. at Karlsruhe, Germany [132, 133], is used to achieve very high aspect ratio (up to 100) microstructures. This technique is used in the optical MEMS applications to fabricate the optical components including waveguides, gratings, and Fresnel lenses [134]. To realize sub-micron patterning, optical machining employing femtosecond lasers was developed but its speed is constrained by the serial process

[135, 136]. Non-conventional mechanical machining techniques, including ultrasonic [137, 138] and abrasive jet machining [139] methods, are employed for micromachining on glass or silica. A micromachining resolution as high as 20 nm was obtained by using focused ion beam machining [140, 141]. Detailed information about other microfabrication technologies for optical applications can be found in [132].

CHAPTER THREE

A NOVEL LARGE DISPLACEMENT ACTUATOR

The objective of this chapter is to demonstrate a micromachined actuator which can provide a stable large displacement and is immune to the external disturbance in order to satisfy the requirements of a reliable optical switch which can be practically used in a switch matrix. The microactuator plays an important role in controlling the position of the micromirror of the MEMS optical switch so that the incident signal can be selectively and steadily guided into the targeted output. The power consumption, resonant frequency, displacement and the stability of the system depend on the actuation mechanism. In this chapter, a novel actuator consisting of compliant microstructure and comb-drive realizes a large displacement ratio and self-locking by employing the bifurcation effect.

This chapter starts with the architecture of the MEMS optical switch and the requirements of the actuator. The linear displacement amplification of the compliant

microstructure is theoretically analyzed followed by the simulation of the bifurcation effect that accomplished the self-locking. All these theoretical simulation results are used to optimize the actuator design and are then verified by the experimental results of the DRIE fabricated actuator. However, the fabrication process leads to some tolerances of the physical dimensions and profile from the initial design features. Therefore, the effects of the fabrication tolerances, including the slanted beam profile, the uneven depth of a comb finger and the undercut effect on the actuator performances are all discussed in terms of electrostatic force and amplification in order to explain the deviation of the experimental displacements from the corresponding designed values and also to serve as a guidance to design a predictable actuator.

3.1 Architecture of MEMS optical switch

The MEM optical switch plays an important role in various optic communication networks thanks to its application in direct optical signal routing, protection and provisions [142-144], where the actuators are employed to provide translation or rotation to the micromirrors so that the incident optical signals can be directed to the expected outputs. The movement direction of the actuator depends on the architecture of the switch cell and the configuration of the switch matrix.

3.1.1 Architecture of 2×2 switch cell

The architecture of the MEMS optical switch is schematically shown in Figure 3-1. It consists of three major components, namely, actuator, micromirror and optical conduction media. In this study, the actuation is provided by a comb-drive actuator and the effective displacement of the micromirror is amplified and self-locked by the compliant microstructure. The motion of the actuator and thereby the micromirror, are oriented along the x axis. The optical conduction media is optical single mode fibers which are passively aligned and assembled easily and precisely by fiber grooves obtained by DRIE. The micromirror is a vertical mirror with a high reflectivity metal coating that decides the output directions of the incident signals.

There are two alternative states of such a MEMS switch, *cross* and *bar* states respectively, depending on the position of the micromirror. The *cross state* is shown in Figure 3-2 (a), where the micromirror is in the beam path. The two incident light beams I_1 and I_2 are blocked by it and reflected to the orthogonal outputs O_1 and O_2 , respectively. When the driving voltage is applied to the actuator, an electrostatic force is generated between the two sets of comb fingers and thereby the micromirror is

driven out of the beam path. The *bar state*, as shown in Figure 3-2 (b), enables the input signals to pass through the gap between the optical fibers to the in-line outputs. The inputs of I_1 and I_2 are guided to outputs of O_2 and O_1 , respectively.

Figure 3-1 Schematic view of our proposed 2×2 MEMS optical switch.

Figure 3-2 Schematic view of the two states of the optical switch: (a) *cross state*, (b) *bar state*.

3.1.2 Architecture of optical switch matrix

Based on this MEMS optical switch cell, a large matrix can be achieved. The configuration of the matrix is either conventional $N \times N$, where N^2 switch cells have to be employed (see Figure 3-3 (a)), or L -shape matrix (see Figure 3-3 (b)) can be used to reduce the number of switch cells. The input light is switched to the desired output port by setting a selected micromirror in the beam path with the actuator. When the input I_i is targeted to output O_j , the micromirror of switch cell at row i and column j is set to be in the beam path (*cross state*), the incident signal I_i is reflected into output O_j by the micromirror.

3.1.3 Requirements of the actuator

Achieving a large displacement is the first requirement which must be satisfied for the optical switch in order to ensure that the entire beam can be either blocked or allowed to pass through. As the beam path is different from one input to different outputs, the beam diameter varies accordingly. To resolve this problem, collimators are widely used to expand the beam waist so that it can propagate for a longer distance

Figure 3-3 Configuration of switch matrix: (a) $N \times N$ matrix, (b) L shape matrix.

without significant divergence. However, the expanded beam diameter is larger than the original Gaussian beam waist from the single fiber. Therefore, to reflect the expanded or diverged beam, the micromirror must be large enough while the displacement provided by the actuator must be large enough to block or release the incident signals entirely.

Stability is the second concern for such a switch and a matrix composed of such switches. As the micromirror and actuator are both suspended by the flexure beams, external disturbances influence the position of the micromirror. Hence, the optical properties of the switch are deteriorating. Slight alterations of the applied driving voltage also affect the performance of the switch. Therefore, it is important and meaningful to design and fabricate an actuator that is immune to external disturbances.

The third requirement is to ensure stability without side stiction problem. The overlap of the comb fingers can not be too large, because the larger the overlap distance, the higher the probability for the movable fingers to stick to the stationary fingers as a result of an unbalanced normal force. The linear relationship between the electrostatic force and the displacement will not be maintained as a consequence of a stronger fringe effect.

Therefore, it is both challenging and attractive to realize an actuator that can provide a stable and large displacement for a functional micromirror while keeping a relative small overlap length of the comb finger sets. In the following sections, a novel actuator that satisfies all these requirements is presented and discussed in detail including the theoretical analysis of the amplification of the displacement and self-locking by bifurcation effect, both verified practically with proven experimental

results. The fabrication tolerances effects onto the properties of actuator due to the DRIE process are analyzed as well.

3.2 Design and theoretical analysis of large displacement actuator

In this section, a stable self-locked actuator with large displacement ratio (output to input) is designed and theoretically analyzed. This actuator is a linear displacement device with adjustable displacement ratio ranging from 5 to 100 through the elastic deformation of the compliant microstructure. Self-locking is achieved by the bifurcation effect, whereby the output displacement maintains stable even when the input displacement changes. Therefore, the drawbacks of the previous actuators in terms of instability and small displacement are eliminated. Consequently, a stable output is ensured by the self-locking eliminating the effects of the vibration. Moreover, many benefits such as prevention of assembly, avoidance of stiction, elimination of joint friction, precision, accuracy, repeatability, absence of backlash and etc. [145, 146], can be achieved by this design. Additionally, the fabrication is entirely compatible with surface and bulk micromachining.

3.2.1 Design of actuator with stable and large displacement

The scanning electron microscope (SEM) micrograph of the self-locked micromachined actuator with a large displacement ratio is shown in Figure 3-4. In this self-locked micromechanical actuator, the driving force is generated by a comb-drive and the displacement amplification is realized by the compliant microstructure consisting of six beams that can receive the input force, store the energy as the strain energy by the deformation of the beams, and finally release the energy with

Figure 3-4 Configuration of novel actuator.

predetermined displacement. The self-locking is obtained by the compliant microstructure when the loading force is above the critical value. The folded suspension beam provides a very stiff flexure along the y direction to ensure the stability of the entire system. Whilst, the stiffness along the motion direction of the folded beam is so small compared to that of compliant microstructure that most of the force generated by the comb-drive actuator falls on the compliant microstructure.

The electrostatic force is generated by the comb-set associated with folded beam when the external voltage is applied to the electrodes, which has been studied and discussed by other researchers [59, 60]. The novelty of this study is the displacement amplification compliant structures as schematically shown in Figure 3-5 (a). It consists of 6 beams with axial symmetry along the x axis. Beams c and c' are fixed to substrate at Q and Q' respectively, Beams a , b and c are connected at point P_3 . The electrostatic

force is applied to P_1 along $+x$ direction while the amplified output displacement is achieved at point P_2 along either positive or negative x direction. In the linear amplification range, the input displacement of point P_1 is amplified by the compliant microstructure to achieve a large output displacement at point P_2 as shown in Figure 3-5 (b). With the rise in the driving force, the bifurcation conducts leading to the self-locking of the output displacement at point P_2 (see the schematic view of Figure 3-5 (c)). Afterwards, the output point P_2 remains fixed even though the input point P_1 goes further, whereby a stable output displacement is achieved. When the driving voltage is unloaded, all the microbeams are released back to their original positions proving that the deformation is elastic. The linear displacement amplification and bifurcation effect of the compliant microstructure are analyzed in the following sections.

Figure 3-5 Schematic compliant structure of the actuator: (a) original configuration, (b) linear amplification, and (c) self-locking position.

3.2.2 Theoretical analysis of linear displacement amplification

Since the compliant microstructure is planar symmetric along the x -axis to assure the motion stability, only half of the model as shown in Figure 3-6 is used to analyze the amplification. Every half compliant microstructure is composed of three beams denoted as a , b and c . The left end of beam a is connected to the driving part which provides the input displacement at point P_1 . The final amplified output point P_2 is at the right end of beam b . The left end of beam c is fixed to the substrate at point Q . The other ends of the three beams are connected together at point P_3 . The cross-sectional areas, lengths and inertial moments of the three beams are A_i (product of thickness h_i and width w_i), l_i , and I_i ($i = 1, 2$ and 3 representing beam a , b , and c), respectively, with the relative position represented by the angles α , β , and γ .

When point P_1 is actuated, an input displacement of δ_1 is obtained and the final output displacement at point P_2 reaches δ_2 . The displacement ratio is defined as

$$R = \frac{\delta_2}{\delta_1} \quad (3-1)$$

Figure 3-6 Schematic drawing of compliant microstructure.

The sign of R depends on the relative motion directions of the input and output points. If they move in the opposite directions, R is negative and vice versa. The amplitude of the displacement ratio is the absolute value of R .

In general, such a compliant design is governed by the relationship between the input and output forces, and the displacements. A multi-criterion optimization-based method can be used for the topological synthesis of the compliant microstructure, taking into account the kinematical and the structural requirements while maximizing the mechanical efficiency. The advantage of this approach is that precise control over the mechanical and geometric merit of the structure can be enforced during the optimization process to obtain a quantitative determination of an optimized design for the actuator. In this study, the main criterion considered for the geometric design is to maximize the amplitude of the stable displacement ratio defined in Eq. (3-1). As illustrated in Figure 3-6, the driving force applied to half of the microstructure along the displacement direction of point P_1 is half of the total driving force F according to the symmetric characteristics of structure system. The generalized reacting forces and moments that come from the other half are denoted as F_1 , F_2 , M_a and M_b respectively. The internal forces N_i and moments M_i (i is 1, 2 and 3 representing beam a , b and c) of the individual beams in the linear amplification range can be expressed as

$$N_1 = F_1 \sin \alpha - \frac{F}{2} \cos \alpha \quad (3-2a)$$

$$M_1 = M_a + F_1 \cos \alpha \cdot x_1 + \frac{F}{2} \sin \alpha \cdot x_1 \quad (3-2b)$$

$$N_2 = F_2 \sin \beta \quad (3-3a)$$

$$M_2 = M_b - F_2 \cos \beta \cdot x_2 \quad (3-3b)$$

$$N_3 = \frac{F}{2} \cos \gamma - F_1 \sin \gamma - F_2 \sin \gamma \quad (3-4a)$$

$$M_3 = M_a + M_b + \frac{F}{2} l_1 \sin \alpha - F_2 l_2 \cos \beta + F_1 l_1 \cos \alpha - \frac{F}{2} \sin \gamma \cdot x_3 - (F_1 + F_2) \cos \gamma \cdot x_3 \quad (3-4b)$$

The elastic energy of the beam system is expressed as

$$U = \sum_{i=1}^3 \left(\int_{l_i} \frac{N_i^2}{2EA_i} dx_i + \int_{l_i} \frac{M_i^2}{2EI_i} dx_i \right) \quad (3-5)$$

where E is the Young's modulus of the structure material.

Based on the Castigliano theory [147], the input and output displacements of point P_1 and P_2 under the loading force F can be deduced. The well known Castigliano's theorem states that if a structure is subjected to system external forces $f_1, f_2, \dots, f_n$ and if only one virtual displacement $\Delta \delta_i$ is applied in the direction of the i^{th} displacement δ_i , the expression for δ_i is

$$\delta_i = \frac{\partial U}{\partial f_i} \quad (3-6)$$

According to the boundary conditions of the compliant microstructure, the relative generalized translational displacements in the y direction and rotational displacements at points P_1 and P_2 should be zero. Therefore, for the compliant microstructure, the strain energy and generalized force should satisfy the following relations

$$\frac{\partial U}{\partial F_m} = 0 \text{ and } \frac{\partial U}{\partial M_n} = 0 \quad (3-7)$$

where m is 1 and 2 representing the reacting forces and n is a and b representing moments come from the other half. Thus, the relationship is described as

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ F_2 \\ M_a \\ M_b \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \end{bmatrix} \quad (3-8)$$

where the elements of the coefficient matrix $[C]$ are the functions of the geometric configurations and the structure stiffness of the beam system while the column matrix $\{D\}$ depends on the external loading force F . These elements can be deduced from Eqs. (3-2) to (3-4) and the detailed formulations are listed in the Appendix I. Therefore, the general reacting forces F_m and the moments M_n can be expressed by the loading force F , the structure configuration and individual stiffness of beams. As such, the displacements of points P_i under the loading force F can be expressed as,

$$\delta_1 = \frac{\partial U_T}{\partial F} = 2 \frac{\partial U}{\partial F} \quad (3-9a)$$

$$\begin{aligned} \frac{\partial U}{\partial F} = & \frac{l_1}{EA_1} \left(-\frac{F_1}{2} \sin \alpha \cos \alpha + \frac{F}{4} \cos^2 \alpha \right) + \frac{l_3}{EA_3} \left(\frac{F}{4} \cos^2 \gamma - \frac{F_1}{2} \sin \gamma \cos \gamma \right. \\ & \left. - \frac{F_2}{2} \sin \gamma \cos \gamma \right) + \frac{1}{EI_1} \left(\frac{M_a}{4} l_1^2 \sin \alpha + \frac{F_1}{6} l_1^3 \cos \alpha \sin \alpha + \frac{F}{12} l_1^3 \sin^2 \alpha \right) \\ & + \frac{l_3}{EI_3} \left(\frac{M_a}{2} l_1 \sin \alpha + \frac{M_b}{2} l_1 \sin \alpha + \frac{F}{4} l_1^2 \sin^2 \alpha - \frac{F_2}{2} l_1 l_2 \sin \alpha \cos \beta \right. \\ & + \frac{F_1}{2} l_1^2 \sin \alpha \cos \alpha - \frac{F}{8} l_1 l_3 \sin \alpha \sin \gamma - \frac{F_1}{4} l_1 l_3 \sin \alpha \cos \gamma - \frac{F_2}{4} l_1 l_3 \sin \alpha \cos \gamma \\ & - \frac{M_a}{4} l_3 \sin \gamma - \frac{M_b}{4} l_3 \sin \gamma - \frac{F}{8} l_1 l_3 \sin \alpha \sin \gamma + \frac{F_2}{4} l_2 l_3 \sin \gamma \cos \beta \\ & \left. - \frac{F_1}{4} l_1 l_3 \sin \gamma \cos \alpha + \frac{F}{12} l_3^2 \sin^2 \gamma + \frac{F_1}{6} l_3^2 \sin \gamma \cos \gamma + \frac{F_2}{6} l_3^2 \sin \gamma \cos \gamma \right) \end{aligned} \quad (3-9b)$$

To obtain the displacement of point P_2 , a virtual force P is assumed to act upon point P_2 , as shown in Figure 3-6. Hence the internal forces and moments are functions of this virtual force. The displacement of point P_2 is therefore expressed as

$$\delta_2 = \frac{\partial U_T}{\partial P} = 2 \frac{\partial U}{\partial P} \quad (3-10a)$$

$$\begin{aligned}
 \frac{\partial U}{\partial P_i} = & \frac{l_2}{EA_2} \left(\frac{F_2}{2} \sin \beta \cos \beta \right) + \frac{1}{EI_2} \left(\frac{M_b}{4} l_2^2 \sin \beta - \frac{F_2}{6} l_2^3 \cos \beta \sin \beta \right) \\
 & + \frac{1}{EA_3} \left(\frac{F}{4} l_3 \cos^2 \gamma - \frac{F_1}{2} l_3 \sin \gamma \cos \gamma - \frac{F_2}{2} l_3 \sin \gamma \cos \gamma \right) \\
 & + \frac{l_3}{EI_3} \left(\frac{M_a}{2} l_1 \sin \alpha + \frac{M_b}{2} l_1 \sin \alpha + \frac{F}{4} l_1^2 \sin^2 \alpha - \frac{F_2}{2} l_1 l_2 \sin \alpha \cos \beta \right. \\
 & + \frac{F_1}{2} l_1^2 \sin \alpha \cos \alpha - \frac{F}{8} l_1 l_3 \sin \alpha \sin \gamma - \frac{F_1}{4} l_1 l_3 \sin \alpha \cos \gamma - \frac{F_2}{4} l_1 l_3 \sin \alpha \\
 & \cdot \cos \gamma - \frac{M_a}{4} l_3 \sin \gamma - \frac{M_b}{4} l_3 \sin \gamma - \frac{F}{8} l_1 l_3 \sin \alpha \sin \gamma + \frac{F_2}{4} l_2 l_3 \sin \gamma \cos \beta \\
 & \left. - \frac{F_1}{4} l_1 l_3 \sin \gamma \cos \alpha + \frac{F}{12} l_3^2 \sin^2 \gamma + \frac{F_1}{6} l_3^2 \sin \gamma \cos \gamma + \frac{F_2}{6} l_3^2 \sin \gamma \cos \gamma \right)
 \end{aligned} \tag{3-10b}$$

By substituting the aforementioned relationship between F_m , M_n and loading F , the displacements of the input point P_1 and output point P_2 are obtained. By using (3-1), the displacement ratio is obtained.

The configuration can also be represented by the coordinates x_1 , x_2 , x_3 , h_1 and h_2 (see Figure 3-7), which is easier to provide understanding on design parameters and their effects on the amplification properties. The effects of the individual parameter on the amplification are analyzed based on the dimensions listed in Table 3-1.

Figure 3-7 shows the effect of lateral position of output point x_2 on the displacement ratio when x_2 sweeps from $-100.0 \mu\text{m}$ to $+400.0 \mu\text{m}$ while the other parameters and loading force are fixed. The most significant phenomena is that the ratio R changes from positive to negative when $x_2 = 0.0$, which means that the motion direction of output point P_2 alters at this critical point though the input displacement

Table 3-1 Dimensions of the compliant mechanical amplifier

Parameters	x_1	x_2	x_3	h_1	h_2	w_i	h_i
Dimensions	1002.5	51.5	1014.0	1432.5	317.5	3.0	25

keeps its moving direction. This implies that the output displacement direction can be adjusted by the location of the output point when the driving force is maintained. When the output point P_2 is designed at the right side of the original point O , x_2 is positive and the ratio is negative. The maximum amplitude of the negative ratio is obtained when x_2 is equal to $20.0\ \mu\text{m}$ and it decreases with the rise of x_2 . The amplitude of the displacement ratio decreases significantly from 112.0 to 26.5 when x_2 increases from $20.0\ \mu\text{m}$ to $200.0\ \mu\text{m}$ while it maintains nearly a constant of 14.6 afterwards. This relationship can be illustrated by the deviation of the displacement ratio to the distance x_2 (see Figure 3-7 (b)). It is nearly zero when the position of P_2 is farther away from $200.0\ \mu\text{m}$ verifying that the displacement ratio remains constant after this particular location.

Figure 3-8 (a) and (b) illustrate the effect of lateral positions of input point and joint point represented by x_1 and x_3 on the performance of the amplifier. The magnification is larger when the input point P_1 is farther away from the original point in lateral direction as a result of the softer compliant microstructure. The amplitude of the amplification increases from 10 to 90 when x_1 increases from $380\ \mu\text{m}$ to $1250\ \mu\text{m}$ as shown in Figure 3-8 (a), whereas the amplitude of the amplification decreases with the increase of x_3 , which is opposite to the effect of x_1 . Figure 3-8 (b) shows that the amplitude decreases from 80 to 30 when x_3 increases from $790\ \mu\text{m}$ to $1850\ \mu\text{m}$.

The orthogonal coordinates of the joint point P_3 and fixed point Q represented by h_1 and h_2 also affect the properties of the compliant microstructure. The dependence of the amplification on the joint point position h_1 is plotted in Figure 3-9 (a), which illustrates an almost linear proportionality between them as a result of less stiffness along x direction. The influence of the fixed point denoted by h_2 is shown in Figure 3-

9 (b) implying that the amplitude of amplification decreases when the fixed points are farther away in the vertical direction.

(a)

(b)

Figure 3-7 Effect of output point location x_2 on the amplification: (a) displacement and amplification vs. x_2 , (b) deviation of amplification to x_2 .

Figure 3-8 Amplification vs. the design parameter: (a) input point location x_1 , and (b) joint point position x_3 .

Figure 3-9 Amplification vs. vertical coordinates: (a) joint point h_1 , (b) fixed point h_2 .

The analytical solutions are verified by ANSYS numerical simulations. Two cases corresponding to a fixed x_1 of 1000 μm and two different x_2 of 50 and 80 μm are simulated, which shows that the displacement ratio is -49.7 and -32.6 respectively, thus agreeing with the analytical results. This particular difference between the two cases comes from the different location of the output point P_2 . Also the displacement of point P_3 along y direction for case I is 5.4 μm , which is larger than the value of 3.9 μm obtained for case II when the input displacement is 1.0 μm . The larger

displacement along y direction is accompanied by a greater displacement ratio resulting in a greater amplification.

3.2.3 Theoretical analysis of self-locking

The local bifurcation effect occurs for this compliant microstructure with the increased input displacement under a higher loading. In order to find the critical load of the system, the bifurcation analysis of the beams system of the micromachined actuator is carried out using finite element method (FEM).

Since the beams of this actuator are slender, the Euler–Bernoulli hypothesis is valid. The beam warp is negligible and the strains are small while the displacements and rotations are moderately large in the analysis. The element stiffness matrix of beams can be derived by employing the principle of stationary potential energy Π_e which can be expressed as

$$\Pi_e = U_e - V_e \quad (3-11)$$

where U_e is the strain energy stored in the element and V_e is the external work done to the element, and the subscript e represents the element level. For a beam element, the strain energy can be expressed as

$$U_e = \frac{1}{2} \int_0^L [EA \left(\frac{\partial u}{\partial x'} \right)^2 + EI \left(\frac{\partial^2 v}{\partial x'^2} \right)^2] dx' + \int_0^L \left[\frac{F_{x'}}{2} \left(\frac{\partial v}{\partial x'} \right)^2 - F_{y'} \left(\frac{\partial u}{\partial x'} \frac{\partial v}{\partial x'} \right) \right] dx' \quad (3-12)$$

where E is the Young's modulus, L is the length of element, A is the cross-sectional area, I is the second moment of area, u is the axial displacement, and v is the lateral displacement. $F_{x'}$, $F_{y'}$ and M are the nodal forces and moments relative to the local

coordinate system of the beam element, in which x' is the axial coordinate and y' is the lateral coordinate. The first term of Eq. (3-12) leads to the linear stiffness matrix and the second term relates to the geometric stiffness matrix, which can accurately predict the lateral bifurcation.

The element nodal force vector is constrained in this study to a two-dimensional beam element, and hence is expressed as

$$\{F\} = [F_{x'1}, F_{y'1}, M_1, F_{x'2}, F_{y'2}, M_2] \quad (3-13)$$

In Eq. (3-12), the bending moment is assumed to be distributed linearly. Therefore, the forces $F_{x'}$, $F_{y'}$ and M at the internal cross-section with the coordinate of x' can be expressed in terms of those at the element ends by using

$$F_{x'} = F_{x'2} = N \quad (3-14a)$$

$$F_{y'} = -(M_1 + M_2) / L \quad (3-14b)$$

$$M = M_1(1 - x' / L) + M_2(x' / L) \quad (3-14c)$$

In the updated Lagrangian formulation [148], let $\{f\}_e$ and $\{u\}_e$ represent the incremental nodal force and incremental nodal displacement vectors at the two ends of the element. The work done by the element nodal force under nodal displacement increments is given by

$$V_e = \{u\}_e^T \{f\}_e \quad (3-15)$$

Linear interpolation functions can be adopted for the axial displacement u . Cubic interpolation functions can be employed for the lateral displacement v . Substituting these functions into the above equations, the expression for the total potential energy may be defined in terms of the incremental nodal displacements at the two ends of the element.

The beam element secant equilibrium equation can be formulated according to the principle of stationary potential energy

$$\delta \Pi_e = \delta U_e - \delta V_e \quad (3-16)$$

which leads to the element secant stiffness matrix in updated Lagrangian formulation, which can be written as

$$\{f\}_e = ([K_L]_e + [K_G]_e)\{u\}_e \quad (3-17)$$

where $[K_L]_e$ is the linear stiffness matrix, and $[K_G]_e$ is the geometric stiffness matrix, both of which are available in standard text books [148].

For this beam system of the micromachined actuator, FEM equations can be obtained by assembling the element stiffness matrix. Hence, the FEM system equation of the micromachined actuator can be expressed as

$$([K]_E + \lambda[K]_G)\{\Delta q\} = \lambda\{\Delta F\} \quad (3-18)$$

where $\{\Delta q\}$ and $\{\Delta F\}$ represent the incremental generalized displacement and load incremental vectors, respectively. λ is the scaling factor of the corresponding load. The matrix of $[K]_E$ and $[K]_G$ represent the classical first order elastic stiffness matrix and the geometric stiffness matrix of the system.

The nonlinear large displacement bifurcation analysis is carried out using commercial software MSC/NASTRAN and the critical load of the system is determined. When the load reaches the critical value, the local bifurcation takes place, in which case the stable output is achieved. This is because the stiffness of system is determined by beams a , b and c before the occurrence of the bifurcation. However, the local bifurcation of beam b takes place for the present beam system when the system's critical load is reached, case in which only beams a and c control the stiffness of

system. Although the local bifurcation takes place, the overall performance of the beam system is still stable. In such a stable state, the further horizontal displacement at P_2 is so small compared to those of beams a and c that it can then be ignored. At this stage, beam b gives a big contribution to very large longitudinal or tension stiffness to the system, which means that the driving force F does not contribute to the transversal deformation of beam b after bifurcation. Four models are built with the ramping of h_2 from 317.5 μm to 2053.5 μm (see Table 3-2) and the other parameters have the same values as listed in Table 3-1. It must be noted that the fixed point is at the outside of the joint point P_3 for Model 4. The individual amplification under the ramping loading and the resonant frequency for different models are simulated and listed in Table 3-2, with little variations among them. Their amplification properties are plotted in Figure 3-10 (a) and they coincide with the analytical simulation results. More importantly, this figure also illustrates clearly that the universal bifurcation effect occurs to all the models when the loading exceeds their corresponding individual critical value.

In normal mechanical system, the bifurcation should be avoided to prevent an unstable behavior. However, the bifurcation phenomenon is significant for this micromechanical actuator as it provides a stable self-latched output displacement.

Table 3-2 Various models with individual frequency and linear displacement ratio

Model number	M1	M2	M3	M4
h_2 (μm)	317.5	567.5	1067.0	2053.0
Frequency (Hz)	2398	2480	2632	2739
Linear ratio	-25.0	-52.0	-29.9	-14.6

(a)

(b)

Figure 3-10 Numerical simulation results of the bifurcation effect of the amplifier: (a) amplifications of the 4 models, (b) displacements of model 1.

In Figure 3-10 (a), it can be seen that the amplitude of displacement ratio for each model drops dramatically when the bifurcation effect takes place because the input motion is increasing continuously while the output displacement remains constant thereafter. For example, the amplitude is fixed at about 52.3 in the linear amplification range for Model 2 while it decreases to 50 when the loading reaches its critical value

and down to 1 rapidly. Similarly for Model 1, the input displacement increases from 0 to $0.088\ \mu\text{m}$ continuously while the output displacement increases to $-1.95\ \mu\text{m}$ when the loading reaches its critical value and this displacement remains constant even the loading and input displacement rise further as shown in Figure 3-10 (b).

Therefore, the self-locked micromachined actuator with a large displacement ratio can be realized using the linear amplification of the compliant microstructure combined with the bifurcation effect. The linear amplification provides a large output displacement as it amplifies the small input displacement effectively. Thereafter, the bifurcation effect enters in operation and realizes the self-locking. Thus, the output displacement is fixed at the targeted value without any significant variations even though the input displacement generated by the driving force fluctuates.

3.3 Experiment results and discussions

3.3.1 DRIE fabrication

In this study, the micromachined actuator is fabricated by employing a DRIE process on an SOI wafer. Compared to the surface micromachining process [149] in which five polysilicon layers are deposited as structure layers and flattened by chemical mechanical polishing (CMP) technology and multiple insulator and sacrificial layers are used, this process is simpler and the stiction problem is eliminated.

The architecture of the compliant microstructure is optimized according to the theoretical analysis as listed in Table 3-1. The SEM micrograph of the fabricated self-locked actuator with large displacement ratio is shown in Figure 3-11. Figure 3-12 (a) and (b) are the SEM micrographs of the input point P_I and the joint point of the three

beams P_3 , respectively. The solid joint point of the three beams is to prevent the beam from breaking as the stress is quite high at this point. Figure 3-13 shows the deformation of the compliance when external voltage is applied to the comb drive with comparison of the original configuration. It is clearly shown that the microbeams a and b deformed a lot and the bifurcation occurred where the output point P_2 was self locked. The detailed amplification and displacement are discussed in the next section.

Figure 3-11 SEM micrograph of the fabricated actuator.

Figure 3-12 SEM micrographs of the: (a) linking input point, (b) joint point.

Figure 3-13 Comparison of the compliant amplifier with and without deformation: (a) original configuration, (b) deformation.

3.3.2 Displacement measurement and discussions

The compliant microstructure was characterized and the output displacement versus the input displacement is plotted in Figure 3-14 including the overall experiment results with the input displacement ranging from 0 to 38.0 μm (see Figure 3-14 (a)) and the close-up input and output motion relationship with the input displacement from 0 to 4.0 μm (see Figure 3-14 (b)).

The experiment shows that a stable 52.0 μm output displacement is obtained as a consequence of the efficient amplification of the original input displacement. The output displacement is stabilized as a result of the bifurcation effect within the tolerance of the testing as indicated by Figure 3-14 (a). It illustrates that the maximum output displacement is achieved when the input displacement reaches 0.96 μm and the output displacement remains constant even when the input displacement increases further to 38.0 μm . Figure 3-14 (b) shows the linear amplification process where the output displacement depends linearly on the input displacement before the bifurcation.

(a)

(b)

Figure 3-14 Measurement results of the output displacement vs. input displacement:
(a) input ranging from 0 to 38.0 μm , (b) input ranging from 0 to 4.0 μm .

For example, the output is -17.16 μm when the input displacement is 0.24 μm , resulting in a magnification of 71.5.

The amplification as a function of input displacement is plotted in Figure 3-15 with the simulation curve plotted in the same figure for comparison. Within this movement range, the motion directions of the output and input are opposite due to the

design as discussed in section 3.2, where the output point P_2 is located at the right side of joint point P_3 in lateral direction. Before the bifurcation point where the critical input displacement is $0.96\ \mu\text{m}$, the displacement ratio of the output to input is as high as -100 and the magnification decreases with the rise in the input displacement. After the critical input value, the magnification of displacement ratio drops as a result of the self-locked output displacement, which means that the output displacement remains at a fixed maximum value even though the input displacement increases continuously. These experimental results agree well with the theoretically simulated results.

This character is repeatable in the entire motion range implying that all the deformation is elastic. All the beams can return to their initial positions when the loading is released. The amplification conducts due to the linear elastic deformation while the self-latching is due to the bifurcation effect.

3.3.3 Resonant frequency measurement and discussion

The resonant frequency is a natural frequency of vibration determined by the physical parameters of the vib

rating object. In general, it is a function of its stiffness k and effective mass m_{eff} .

Figure 3-15 measurement results of amplification vs. input displacement.

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m_{\text{eff}}}} \quad (3-19)$$

For this specific optical switch, the stiffness is determined by the compliant structure while the other functional components give various contributions to the effective mass. The theoretical resonant frequency is listed in Table 3-2 and it was measured using MEMS Motion Analyzer (MMA), which can measure motions in three dimensions at frequencies from 1 Hz to 1 MHz with nanometer resolution. When an AC signal of 2 V (amplitude) sweeping from 100 Hz to 10 kHz associated with a bias of 10 V is applied to the fabricated switch cell, the movement amplitude alters accordingly and the maximum motion occurs at the resonant frequency as shown in Figure 3-16. The phase is also recorded and analyzed simultaneously. As Figure 3-16 shows, the maximum motion occurs at a resonant frequency of 2.395 kHz and the phase changes 180° abruptly at this specific frequency, as expected.

Figure 3-16 Motion and phase change vs. driving frequency.

The simulated corresponding frequency is 2.398 KHz. The error between measurement and simulation is 0.125% due to the fabrication tolerances, which induces various errors of the width and the height of the beams at different locations.

The self-locked micromachined actuator with a large displacement ratio has been practically realized and its operation was fully demonstrated. The compliant microstructure consists of six symmetrical beams along the moving direction. A theoretical model was built up and employed to derive the optimum design. The analysis showed that the proposed actuator can realize large displacement ratio by elastic deformation of the compliant microstructure. The bifurcation effect was successfully used to attain the self-locked stable output displacement. The experimental results agree well with the analytical and numerical simulation results. The output displacement of $-52.0\text{ }\mu\text{m}$ is achieved by amplifying the input displacement of $0.96\text{ }\mu\text{m}$ with the displacement ratio of -54.2. Displacement ratio as large as -100 was obtained before this particular output displacement. Thereafter, the output displacement remained stable by the bifurcation effect even though the input displacement increased further to $38.0\text{ }\mu\text{m}$. This self-locked micromachined actuator with large displacement ratio can be used not only in an optical switch, but also in many other applications which need to provide an effective displacement amplification and a stable large output displacement.

3.4 Fabrication tolerance analysis

The compliant microstructure fulfills the amplification of the original small input displacement to a large output displacement and also stabilizes the position of the output by employing the bifurcation effect. The initial input displacement is provided

by a comb-drive that consists of two series of comb-like fingers partially overlapping with each other, as schematically shown in Figure 3-17. One set is free to move bringing about the motion of the functional component, while the other is fixed in a stationary position. The width and height of the fingers are denoted by b and H , respectively, with the gap between the adjacent overlapped fingers of g for the initial overlap length of L_1 . The driving force is constant and independent on the lateral displacement in the range of $0.3L < x < 0.7L$, and is expressed as (the detail analysis can be found in the Appendix II)

$$F_x = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{n\epsilon_0 H}{g} V^2 \quad (3-20)$$

As the stiffness along the x direction of the folded beam is much smaller compared to that of the compliant microstructure, the force applied to the compliant microstructure is almost equal to the force generated by the comb-drive actuator. Therefore, the displacements of input point P_1 and output point P_2 can be obtained by combining Eqs. (3-20), (3-9) and (3-10).

Figure 3-17 Schematic view of a set of comb fingers.

The above analyses are theoretical simulation regardless of the fabrication tolerances which affect the performances of the actuators. The tolerances caused by fabrication include (1) misalignment between different mask layers [150], (2) tapered profiles of the microbeams, (3) uneven depth of the individual beams, (4) undercut, and (5) different gaps of the adjacent fingers between the overlap and non-overlap sections unless special requirement [151, 152]. These tolerances greatly depend on the fabrication methods and conditions. With special reference to this actuator, there is no misalignment between the structures as they are patterned and deep etched together. However, the tolerances (2) to (4) exist and are significant for high aspect ratio structures. Their effects on the performances of the actuator, in terms of electrostatic force and amplification, are discussed in the following sections. These analytical results can be used to compensate the fabrication tolerances at the design stage and allow the actuators to provide a more predictable performance.

3.4.1 The effect of the beam profile

The etched profile is gauged by the angle α shown schematically in Figure 3-18 (anticlockwise from the vertical line to sidewall), which depends on the process conditions and design features as analyzed in next chapter. Generally, there are three types of profiles observed, i.e. positive, negative and vertical ($\alpha = 0$). In the actuator, the trenches of the comb fingers, the compliant microstructure and the key functional element of micromirror all have different widths, inducing various profiles, which in turn affect the electrostatic force and amplification.

Figure 3-18 Schematic of the DRIE etched slanted trench.

3.4.1.1 Effect of the profile of the comb fingers

The cross sectional view of the fabricated comb finger with a slight taper is schematically shown in Figure 3-19 (a), and Figure 3-19 (b) is the SEM micrograph of the deep etched comb fingers where the slope angle is denoted as α and the gap on the top is g_0 .

The gap between two adjacent comb fingers becomes a function of the height and is expressed as

Figure 3-19 Sloped comb fingers: (a) schematic of the sloped comb fingers, (b) SEM micrograph of the sloped comb finger.

Accordingly, the capacitance of the comb sets changes to

$$C_{slope} = \int_0^c 2ndC = \frac{n\varepsilon(L_1 + \Delta x)}{\tan \alpha} \ln\left(\frac{g_0}{g_0 - 2H \tan \alpha}\right) \quad (3-22)$$

where dC is the elementary capacitance of an infinitesimally small section with height of dh . Therefore, when the same voltage is applied, the ratio of the electrostatic force generated by the sloped comb fingers to that which would be generated by ideal vertical fingers calculated by Eq. (3-20) is

$$\frac{F_{slope}}{F_{design}} = \frac{(\partial U / \partial x)_{slope}}{(\partial U / \partial x)_{design}} = \frac{g_0}{2H \tan \alpha} \ln\left(\frac{g_0}{g_0 - 2H \tan \alpha}\right) \quad (3-23)$$

Figure 3-20 shows the relative electrostatic force as a function of the slanted angle α under the conditions of $H = 50 \mu m$ and $g_0 = 2.5 \mu m$, where α varies from -1.0° to $+1.0^\circ$. It illustrates that the electrostatic force generated by the negatively sloped comb finger is smaller, as opposed to positive sloped comb finger, which is more significant. For instance, only 75.8% of the theoretical electrostatic force is generated when α is equal to -1.0° , but this force increases by 1.716 times when α is equal to $+1.0^\circ$. The angle cannot be too large because an unwanted force along the z direction will be generated, which is even comparable with the lateral force [153].

Figure 3-20 Relative electrostatic force as a function of the finger profile.

3.4.1.2 Effect of the profile of the comb compliant microstructures

An imperfect vertical profile is also observed on the compliant beams inducing the deviation of the stiffness and amplification of the actuator. The top width and height of the trapezoidal cross section of the beam are b_0 and H respectively while the cross section profile has an angle of β as shown in Figure 3-21 (a). Figure 3-21 (b) is the corresponding SEM micrograph of the actual realized structure.

The second moment of inertia I_z can be rewritten as

$$I_{z_{slope}} = \frac{H}{12} (b_0^3 + 3Hb_0^2 \tan \beta + 4H^2 b_0 \tan^2 \beta + 2H^3 \tan^3 \beta) \quad (3-24a)$$

and the cross sectional area becomes

$$A = H(b_0 - \tan \beta) \quad (3-24b)$$

Figure 3-22 shows the effect of the sloped angle of the compliant microbeams on the displacement and amplification under the conditions of $b_0 = 3.0 \mu\text{m}$ and $H = 25.0 \mu\text{m}$ when the driving force is constant. It is clearly shown that the effect of varying β leads to just a minor change in the input displacement which can be negligible as the

Figure 3-21 Sloped compliant microbeam: (a) schematic cross sectional view, (b) SEM micrograph of the sloped complaint microbeams.

Figure 3-22 Displacement and amplification of sloped compliant microstructure.

absolute motion is too small. However, the output displacement changes dramatically resulting from the large amplification that is also a function of the sloped angle. The amplitude of the amplification increases with negative angle and vice versa. Although the maximum difference is only 0.36%, the output displacement deviates from the designed value by 56% when the beams are tapered with an angle of -1.0° .

3.4.1.3 The effect of the comb finger and compliant beam profiles

As the comb fingers and the compliant microbeams are formed by various trenches, the profile may be different after being etched under the same process conditions. As a result, the displacement along the lateral direction obtained by the slanted comb fingers and the sloped compliant beams deviates from the designed value when the same voltage is applied. The amplification as a function of the tapered angle of the comb finger, α , and that of the folded beam, β under the applied voltage V is obtained by combining the Eqs. (3-1), (3-9), (3-10), (3-23) and (3-24). Their

Figure 3-23 Relative amplification vs. profile angles of the comb finger and the compliant beam.

relationship is plotted in Figure 3-23 where both the angles of α and β is ramping from -1.0° to $+1.0^\circ$. It shows that the combining outward comb fingers with inward compliant microbeams gives a larger displacement ratio as a greater electrostatic force is generated and a softer suspension is provided. The effect of the comb fingers' profile is more significant than that of the compliant beams as this figure shows.

3.4.2 The effect of a comb finger uneven depth

RIE lag or micro loading effect [154, 155], whereby the etching rate decreases when trench width increases, is commonly observed in fluorinated plasmas etch and the etch parameters are contributory factors to the micro loading effect. Usually monolithic silicon or an SOI substrate is employed to fabricate the MEMS devices. During the fabrication process, uneven depth beams occur as a result of the different trench widths beside the beams [156, 157], as shown in Figure 3-24 where the finger

gap of the overlap part is narrower than that of the non-overlap part. Figure 3-24 (a) is the SEM micrograph of the uneven depth comb fingers and (b) is the schematic graph, where the overlap part with the gap of g_1 has the depth of H_1 and length of L_1 while the other non-overlap part has the corresponding depth and gap of H_2 and g_2 . Two kinds of uneven depth comb finger exist due to the different substrate, namely, $H_2 > H_1$ or $H_2 < H_1$.

As a result of these differences, the capacitance, electrostatic force, and corresponding displacement differ from those of the even depth finger design. The initial capacitance is expressed as

$$C_0 = \frac{2n\epsilon_a\epsilon_0 H_1 L_1}{g_0} \quad (3-25)$$

When $H_1 < H_2$ and the displacement along lateral direction is Δx , the capacitance is

$$C_1 = \frac{2n\epsilon_a\epsilon_0}{g_0} (L_1 + \Delta x) H_1 \quad (0 \leq \Delta x \leq L_1) \quad (3-26a)$$

$$C_2 = \frac{2n\epsilon_a\epsilon_0}{g_0} [(\Delta x - L_1) H_2 + 2L_1 H_1] \quad (L_1 \leq \Delta x) \quad (3-26b)$$

Figure 3-24 Comb drive with various depth parts: (a) SEM micrograph of the damaged comb finger, (b) schematic non-uniform depth comb.

When $H_1 > H_2$

$$C_1' = \frac{2n\epsilon_a\epsilon_0}{g_0} [2\Delta x H_2 + (L_1 - \Delta x)H_1] \quad (0 \leq \Delta x \leq L_1) \quad (3-26c)$$

$$C_2' = \frac{2n\epsilon_a\epsilon_0}{g_0} (L_1 + \Delta x)H_2 \quad (L_1 \leq \Delta x) \quad (3-26d)$$

When $0 \leq \Delta x \leq L_1$, the electrostatic force under the applied voltage V is

$$F_1 = \frac{\partial}{\partial(\Delta x)} \left(\frac{1}{2} C_1 V^2 \right) = \frac{n\epsilon\epsilon_0 V^2}{g_0} H_1 \quad (H_1 < H_2) \quad (3-27a)$$

$$F_1' = \frac{\partial}{\partial(\Delta x)} \left(\frac{1}{2} C_1' V^2 \right) = \frac{n\epsilon\epsilon_0 V^2}{g_0} [2H_2 - H_1] \quad (H_1 > H_2) \quad (3-27b)$$

When $\Delta x \geq L_1$

$$F_2 = F_2' = \frac{\partial}{\partial(\Delta x)} \left(\frac{1}{2} C_0 V^2 \right) = \frac{n\epsilon\epsilon_0 V^2}{g_0} H_2 \quad (3-27c)$$

Substituting the designed force as expressed in Eq. (3-20), the relative forces can be expressed as

$$\frac{F_1}{F_0} = \frac{H_1}{H_0} \quad (H_1 < H_2) \quad (3-28a)$$

$$\frac{F_1'}{F_0} = \frac{2H_2 - H_1}{H_0} \quad (H_1 > H_2) \quad (3-28b)$$

when the displacement is less than the initial overlapping length, i.e. $0 \leq \Delta x \leq L_1$. The driving force changes abruptly when the displacement is over the initial overlap to

$$\frac{F_2}{F_0} = \frac{F_2'}{F_0} = \frac{H_2}{H_0} \quad (3-28c)$$

Figure 3-25 shows the relative electrostatic force as a function of the displacement of the comb-drive actuator. The electrostatic force increases abruptly when the displacement is equal to the initial overlapping length no matter which part is deeper.

Figure 3-25 Electrostatic force vs. the displacement of comb-drive with uneven depth.

The force is weaker compared to the designed value when the initial non-overlapped section is shallower compared to the overlapped part whose depth is equal to the designed value. While the opposite fabrication result generates a greater electrostatic force when the displacement is over the initial overlapped length. Consequently, the displacement and amplification change proportionally to this driving force.

3.4.3 Effect of undercut of microbeams

The microstructure was fabricated by lithographically pattern and hard mask etching to deep silicon etching. During these pattern transfers, some deviations from the soft mask to hard mask can be observed because of imperfect anisotropic etching. This problem appears to be more serious when transferring the pattern to the high aspect ratio silicon microstructures, especially when the process starts with an etching cycle using SF_6 because it is an isotropic chemical process by nature. This effect can

be observed in Figure 3-26, where the width of the silicon beam is smaller by $0.3\ \mu\text{m}$ compared to the upper hard mask $3.0\ \mu\text{m}$ wide. When this process continues, this undercut is more serious and this phenomenon is similar to that observed by cryogenic enhancement deep etching, where an $18\ \mu\text{m}$ undercut was observed for a $275\ \mu\text{m}$ deep etch and an $8\ \mu\text{m}$ undercut is observed for a $125\ \mu\text{m}$ deep etch [158], respectively.

Let Δa and Δb denote the undercuts at each side of the comb finger and of the compliant microbeam respectively. The gap of the consequent finger increases to $g + 2\Delta a$ and the electrostatic force generated by the comb-drive with undercut decreases to

$$\frac{F_{\text{undercut}}}{F} = \frac{g_0}{(g_0 + 2\Delta a)} \quad (3-29)$$

Considering $g_0 = 2.5\ \mu\text{m}$ and an undercut change from 0.0 to $0.2\ \mu\text{m}$, the corresponding electrostatic force is normalized and plotted in Figure 3-27. It depicts that the force decreases with the rise in the undercut because the capacitance reduces resulting from the wider gap between the comb fingers. When the undercut on one

Figure 3-26 SEM micrograph of undercut of DRIE etching.

side is $0.15\ \mu\text{m}$, the electrostatic force generated is only 89.29% of the corresponding designed value. Thus, the original displacement is smaller than the designed value while the amplification and output displacement are affected accordingly.

The undercut of the compliant beams also gives its contribution to the mechanical performances of the actuator. The combined influence of the two kinds of undercut on the amplification in the linear range is shown in Figure 3-28, which clearly shows that the undercut of the compliant microbeam increases the effective magnification of the actuator while the same kind of tolerance on the comb fingers affects the performance inversely and more significantly.

The influence of the various fabrication tolerances were discussed in detail. These tolerances can be used to analyze the experiment deviation from the designed corresponding values. Such models play an important role in guiding a predictable design by allowing the designer to compensate the fabrication tolerances from the design stage.

Figure 3-27 Electrostatic force vs. comb fingers undercut.

Figure 3-28 Relative displacement vs. undercuts of comb finger and compliant beam.

The non-uniformity of etching in a device usually is due to the different designed features. If the designed trench widths are even, the non-uniformity is neglectable because neither the macroloading nor the microloading occurs. Therefore, the non-uniformity in a device strongly depends on the device itself. The effect of the non-uniformity such as the profile, depth and width lead to the deviation of the mechanical dimension and profile, tolerance of the mechanical, electrical and specific performances. The tolerable range is directly related to the application and testing structure should be employed to optimize the process conditions in order to control the non-uniformity.

3.5 Summary

The novel electrostatic actuator proposed in this work consisting of a comb-drive, a folded beam and a compliant microstructure is deeply studied in this chapter. This

actuator provides a stable large displacement to the MEMS optical switch realizing a dynamic tuning of the input signals into the expected outputs. The detailed design and theoretical analysis of the compliant microstructures was carried out to analyze the linear amplification and bifurcation effect of the system. Accordingly, models were built for simulation and design. The structure and dimensions of the compliant microstructures were optimized based on these simulations. The optical MEMS switch driven by this kind of novel actuator was fabricated by employing DRIE process and the optical fibers were passively aligned and assembled in the realized device.

The actuator was experimentally investigated, and the results showed that it provides a significant displacement amplification with magnification of 54.2 at the bifurcation critical point, before which the magnification is as large as 100. The output displacement to drive the micromirror is $52.0\text{ }\mu\text{m}$ while the input displacement is only $0.96\text{ }\mu\text{m}$. Afterwards the output motion is self-locked by the compliant microstructure even though the input displacement increases as large as $38.0\text{ }\mu\text{m}$. The resonant frequency of the switch is 2.395 kHz which matches well with the theoretical result of 2.398 kHz . The deviation is only about 0.125% as a consequence of the difference of effective mass between design and fabrication. These measurement results proved that the amplification mechanism is fully operational and demonstrated a reliable stable actuator with large displacement. The stability of the system along the transverse direction is assured using folded beams whose stiffness is much smaller along lateral direction than that of the compliant microstructures.

However, the fabrication process necessary to implement practically this structure introduces various types of tolerances such as slanted profiles of the comb fingers and compliant beams (protuberant or reentrant), uneven depths in different portions of the

individual comb finger, and various undercuts. The causes of these fabrication tolerances were analyzed from the processing point of view. The analysis of the fabrication tolerances that affects on the device performances including the generated electrostatic force, the input and output displacement of the actuator, and the amplification were carried out to explain the difference between the theoretical and experimental results. Furthermore, the analysis can be effectively used to design the device in accordance to the designer's requirements.

CHAPTER FOUR

THE DEEP RIE PROCESS

The objective of this chapter is to develop a universal and reliable deep reactive ion etching (DRIE) process on an SOI wafer to achieve high performance MEMS devices. As the performances of MEMS devices are strongly process dependent and the MEMS fabrication is not standardized, it is very important and relevant to design a flexible process which is applicable for different systems. Among the numerous process steps, etching is the most essential step, especially for bulk micromachined microstructures with high aspect ratio, where deep, highly directional etching and release from beneath are necessary and challenging. Dry gaseous etching is more advanced compared to wet etching because of its merits of independent with respect to the substrate crystalline orientation, accurate transfer of lithographically defined patterns into underlying layers, high resolution and cleanliness, ease of automation and better control. Release is a special etching employed to remove a specific layer in order to obtain the movable MEMS structures, that is never used in IC technology and where new problems like

stiction may. An SOI wafer based process simplifies the process, reduces the number of necessary masks at the price of notching effect, due to the buried insulation layer, and the micro-loading effect. These issues are addressed in this chapter and proved by process results.

This chapter starts with the process flow of an SOI based DRIE process. Then the dry etching is discussed with focus on the chemical and physical aspects of the alternative etching and passivation DRIE. The effects of the process parameters, including operating power, various gas flow rate, durations, and chamber pressure, on the structures are analyzed individually in terms of etch rate, etch profile and etch selectivity and are associated with the experiment results to optimize the process conditions.

With special attention paid to the high aspect ratio structures, the loading effects are experimentally studied. The etch rate is analyzed first as a function of the feature size, the location, the exposed area and the variations within the process itself. Then, the verticality of the microbeams as a function of trench width is investigated as guidance for a better design.

Lastly, a new spacer oxide thin film technique is developed to eliminate the severe notching issue during the processing of an SOI wafer based on the analysis of the origin of notching phenomenon. Moreover, this problem is used to selectively release microstructures, thus realizing a reliable dry release.

4.1 DRIE fabrication process flow

The universal process flow for MEMS optical components including micro-functional structures, electrodes for the actuation, fiber grooves for passive alignment, and dicing line for separation is outlined in Figure 4-1.

The electrodes are patterned and sintered to obtain good ohmic contact with silicon, as shown in Figure 4-1 (a). Then the hard mask (e.g. silicon dioxide) is deposited and the microstructures including the fiber grooves are patterned by employing lithography and a hard mask etching process (see Figure 4-1 (b)). Multi-layer patterning is employed to pattern the dicing line onto the hard mask layer, followed by the first DRIE etch through the device while protecting with photoresist (PR) the microstructures patterned on the hard mask oxide layer (see Figure 4-1 (c)). In this way, the lithography onto deep trenches is prevented and the accuracy of the functional structures is guaranteed. The dicing line is realized by a buried oxide etch followed by a second DRIE etch of the handle silicon as shown in Figure 4-1 (d). After that, the PR is stripped, exposing the patterned hard mask to proceed with the microstructures fabrication, including another deep etch to the expected depth and release the movable microstructures as shown in Figure 4-1 (e). It should be noted that the release is achieved by using a gaseous dry approach instead of the classical wet method. Lastly, the metal is deposited onto the functional optical components, such as mirror or gratings, to realize highly reflective surface as shown in Figure 4-1 (f).

The advantages of the DRIE fabrication over the other wet etching process are significant. Firstly, the vertical anisotropic etch is realized by controlling the process conditions instead of relying on the crystalline orientation eliminating the constraint of having the designed slope dependent on and oriented as a function of the substrates

crystallographic directions. Secondly, a gaseous process including etch and release prevents the stiction problem that widely exists in wet rinsing and drying processes. Thirdly, the aspect ratio of the microstructures can be increased dramatically leading to improved device performances. These merits are more significant when silicon on insulator (SOI) wafer is introduced into the MEMS fabrication due to the device silicon – buried oxide – handle silicon sandwiched substrate. The depth of device is predetermined by the thickness of the device silicon layer and thus preventing any unintentional over etching. The microstructures etching on the device layer can be stopped well at the interface of the silicon-oxide thanks to the high etch selectivity between Si and SiO₂. Additionally, the movable structures can be easily released by utilizing the buried oxide layer with either a wet or dry etch method.

Figure 4-1 Universal DRIE process flow for MEMS optical devices: (a) Electrodes patterning and sintering, (b) Microstructure patterning on a hard mask layer, (c) Dicing line patterning and first DRIE etch through the device silicon layer, (d) Buried oxide etch and 2nd DRIE etch the handle silicon, (e) Microstructures DRIE and release the movable structures, and (f) Sidewall metal coating.

The process can be simplified further in various ways according to the applications and different designs, but using DRIE etch for high aspect ratio microstructures is a must and release is unavoidable. However, there still are many issues which have to be addressed in such a fabrication process, particularly for an SOI based one. These issues are analyzed and resolved in the following sections.

4.2 Chemistry-physics of DRIE

Dry silicon etching is the process where the material removal reactions occur in the gas phase, including both non-plasma and plasma based methods, which can be used to realize isotropic and anisotropic etch respectively. A specific technique of this type, deep reactive ion etching (DRIE) is the focus of this study. In our practical experiments we used a Surface Technology Systems (STS) Multiplex inductively coupled plasma (ICP) deep etch machine as shown in Figure 4-2 to accomplish high aspect ratio microstructures.

Figure 4-2 Multiplex ICP Process Module.

This equipment employs a process based on the technique invented by Larmer and Schilp [120] and the passivation is deliberately separated by sequentially alternating the etching and deposition steps. This technique uses a high density low pressure (HDLP) system which reduces the ion collision probability as the sheath thickness decreases at higher ion density and the ion mean free path increases at lower pressure [159]. The ion directionality is improved and this in turn enhances the control of anisotropy. The ICP source offers the most stable and widest operating window which operates at 13.56 MHz.

The main reaction gases are SF_6 for etching and C_4F_8 for passivation. The process involves the introduction of a short polymer deposition cycle immediately after each etch cycle. The formal polymer-forming step deposits a layer of passivation (C_xF_y) on the sidewall and the base of the feature by ionization and dissociation of a precursor gas, i.e. C_4F_8 . The deposition gas is dissociated by the plasma to form ion and radical species first

The species undergo polymerization reactions to generate a polymeric layer

where the suffix *(ads)* means CF_2 adsorbs onto the surface and *(f)* implies that the passivation film is a deposited film. Then the etch cycle starts with the dissociation of the reactive gas SF_6

followed by the bottom passivation layer removal [160]

The silicon to be etched is exposed and the etch can proceed as described by

Similarly, both the polymer deposition and silicon etching steps are repeated successively to achieve passivation and etch cycles. Thus, the final result is that the anisotropy is enhanced by protecting the sidewall from radical, atomic and neutral etch species and the vertical etch is controlled mainly by the ion bombardment aiding the removal of the surface polymer.

Based on this principle, etching can be carried out to obtain high aspect ratio microstructures. However, the characteristic etching performance parameters such as etch rate and selectivity, as well as surface morphology and post-etch mechanical behavior (including pattern profile and anisotropy) have a strong dependence on processing variables [161, 162]. For instance, the profile and etch surface are not a concern in realization of the dicing line, whilst a fast etch rate is important to obtain the deep trenches. However, as previous sections showed, achieving a perfectly vertical profile of the microstructures is much more important compared to having a fast the etch rate. The verticality and surface smoothness are two key issues necessary to be achieved in order to ensure a high performance micromirror. Therefore, understanding the effects of the individual processing parameters allows to optimize both etch and deposition rates so when both of them are combined, the entire DRIE efficiency is maximized.

The factors that influence the process include the concentration of etchant species generated in the plasma, the flux of etchant species to the silicon surface, the reaction

rates at the surface, the temperature of the silicon, the removal rate of reaction products, and the consumption of etchant by other species in the plasma or by products formed during etching. Consequently, the macro parameters to be adjusted and monitored during the processes are the gas flow rate, coil and platen RF power, chamber pressure, wafer temperature and the individual cyclic times. The effects of these conditions are discussed based on the experiments carried out on 6" silicon (100) wafers in terms of etch rate, etch profile and etch selectivity.

4.2.1 Effect of platen power

The platen power plays an important role in this deep etching process to remove the base passivation polymeric layer. This RF power is used to accelerate the ions to a sufficiently high potential (typical greater than 20eV) to bombard the trench bottom while maintaining the sidewall passivation intact thereby promoting the anisotropy. Therefore, the etching rate, etching selectivity to the mask material and etching profile are functions of the platen power. The platen power rises the etch rate as the energy of the reactive ions is higher and it also makes the mask erosion rate faster, thus degrading the selectivity. A comparison of these effects is shown in Table 4-1 with the following etch conditions, etching cycle of 8.0 seconds and passivation cycle of 5.0 seconds, gas flow during the etching of 30 sccm of C_4F_8 , 100 sccm SF_6 and 10 sccm O_2 , and gas flow for passivation of 160 sccm C_4F_8 , the coil RF power and process pressure of 600 W and 20 mTorr, respectively, while the platen power changed from 14 W to 23 W. It is shown that the etch rate is increased and the etch selectivity to hard mask silicon dioxide is reduced with higher platen power.

Table 4-1 Comparison of the etch rate, etch selectivity, feature profile and undercut for various platen power.

Specifications	14 w	18 w	20 w	23 w	Remark
Undercut (μm)	0.37	0.32	0.28	0.24	Decrease
Beam top width (μm)	1.02	1.02	1.08	1.10	Increase
Beam bottom width (μm)	1.77	1.54	1.15	1.08	Decrease
Beam depth (μm)	53.6	56.0	55.3	55.8	Deeper
Beam profile (θ°)	0.80	0.53	0.07	-0.01	More Vertical
Etch rate (μm/min)	1.34	1.40	1.38	1.398	Increase
Selectivity Si:SiO ₂	160:1	165:1	143:1	94:1	Lower

The profile of the etched trench also alters from positive to vertical and to negative with the ramping platen power. The feature with high aspect ratio is even close towards the base if the platen power is low.

Undercut is another phenomenon relying on platen power revealed by Table 4-1 , where the relevant definition of the undercut is schematically shown in Figure 4-3. The beam profile is presented by the angle θ between the contour of the etched side and the ideal vertical edge. The etch rate, undercut and profile angle are plotted in Figure 4-4, which verifies that the etch rate increases whereas the undercut decreases with higher platen power, respectively.

One of the most important parameters for optical devices is the verticality which changes from a positive slope to nearly 90° when the power is set at 23 W, while at

the same time, the etch selectivity between silicon and hard mask silicon dioxide is sacrificed with the higher platen power as shown in Figure 4-5.

Figure 4-3 Schematic DRIE etched beam.

Figure 4-4 Platen power effect on etch rate, undercut, and profile of the deep etched beam, respectively.

Figure 4-5 Platen power effect on etching rate selectivity.

4.2.2 Effect of gas flow with source power

The precursor of the reactive species during the etch cycle is SF_6 which is dissociated in the plasma, providing neutral particles, reactive ions and other highly reactive compounds whereas the alternative passivation cycle uses C_4F_8 . The gas flow rates and the source power influence significantly the deep etching process.

Figure 4-6 Variation in silicon etch rate as a function of coil power and SF_6 flow rate.

When the flow rate of etching gas, SF_6 , is fixed at either 100 sccm or 130 sccm and the coil RF power ramps from 600 W to 1000 W, the Si etch rate is source power limited, as evidenced by Figure 4-6. It illustrates that the etch rate increases with the coil power as a consequence of more reactive etchant species (F^*) being generated. The relationship between the etch rate and the gas flow rate is also deduced from this figure. Figure 4-6 also shows that the etch rate is precursor gas flow limited if insufficient precursor gas is available. In these two cases, the main etch rate limiting mechanism is the insufficient generation of etchant species (F^*) due to either an insufficient gas flow rate or a too low source power. However, it does not mean that etch can be speeded up infinitely by rising the gas flow and/or coil power.

A similar phenomenon was also observed by other research group and a kinetic scheme for the generation and loss of atomic fluorine was employed to explain this relationship. The generation of the F^* species from SF_6 is the result of the dissociation reaction characterized by a reaction speed of k_G :

There are several mechanisms for the consumption of the species F^* as follows.

- (a) Recombination with SF_n (n is 3, 4 or 5) species: as Eq. (4-2) expressed, SF_n are generated with the reactive etchant F^* . In the process chamber, it is possible for these species to recombine with F^* at the combination rate of k_R .

where T denotes the termination species.

- (b) Recombination with other F^* species: when the reactive F^* meet each other, they will combine to F_2 at the rate of k_F .

(c) Reaction with silicon (the effective consumption): the reactive species react with the surface silicon at the etch reaction rate of k_E .

As the generation and consumption of the etchant species must be balance, the overall process will be expressed as

$$k_G[SF_6] = k_R[SF_n][F^*] + k_F[F^*][F^*] + k_E[F^*][Si] \quad (4-7)$$

where the symbol $[]$ represents the concentrations of the various species. It is noted that the contribution of the three mechanisms to the consumption of the species is different. The limiting silicon etch rate is due to the equilibrium between the etchant generation from SF_6 and its recombination with dissociated SF_n . The recombination between the reactive species F^* plays a marginal role, if any. The third contribution is related to the exposed area of silicon denoted as $[Si]$, which does not affect the absolute value of the etch rate while does make the etch rate saturate at a lower $[SiF_6]$ level. The fluorine species concentration $[F^*]$ is an increasing function of $[SiF_6]$ if the generation constant k_G is several orders of magnitude greater than the recombination constant k_R . In other words, the etch rate is limited by the etchant species $[F^*]$ loss due to its recombination with SF_n . Therefore, reducing the recombination possibility by using a precursor gas that has a lower recombination rate with atomic fluorine species is one approach to reduce the loss. The other method to increase the etch rate is to quickly remove the potential recombination particles from the process chamber.

The passivation cycle is another key step to realize a high aspect ratio microstructure, and this cycle influences the anisotropy, aspect ratio, undercut and

overall etching rate. Therefore, achieving a fast polymeric film deposition rate is essential in order to improve the profile control. This speed relies on the passivation gas flow rate and the source power as well. Extra energy is necessary to dissociate the passivation precursor gas C_4F_8 to accomplish the deposition as expressed by Eq. (4-1a), and for this reason, the source power is critical since it provides the kinetic power starting and maintaining all the chemical processes. However, an increased source power in pursuit of a higher deposition rate of the polymer film increases the wafer surface temperature, thereby decreasing the polymer deposition rate. Therefore, a better wafer cooling is necessary to optimize the overall etching rate.

In conclusion, the coil RF power raises the etching rate as a result of more etching species. Also the insufficient precursor gas flow rate decreases the etch rate. In general, the gas flow rates of etch etchant of SF_6 and passivation precursor of C_4F_8 are about 100 sccm and 160 sccm, respectively.

4.2.3 The effect of the duration of the cyclic etch/passivation cycles

DRIE is a cyclic process of etch and passivation. The various combinations of etch and passivation cycle affect the overall etch rate, the trench profile and the etched surface roughness. A Longer duration of etch cycle and a shorter passivation cycle definitely increase the etch rate as pro while the anisotropy is sacrificed resulting in bowing sidewalls, which is not desirable. Another more serious problem is the sidewall scallops. Since the lateral etch is restricted by the polymeric film deposited during the separate passivation cycle, the scallops arises unavoidably as schematically shown in Figure 4-7 (a) and in the SEM micrograph picture of Figure 4-7 (b). The etched beam sidewall surface is roughened by this effect.

Figure 4-7 Scallops on the trench sidewall: (a) schematic representation, (b) SEM micrograph of an actual structure.

Hence, the durations of etch and passivation cycles influence the quality of the sidewall. A trade-off between the etch rate, beam profile and sidewall quality must be carefully selected.

4.2.4 Effect of process pressure

The process pressure affects the overall etch results including etch rate, etch selectivity and profile. Generally, the number of fluorine radicals increases initially when the pressure is higher as more reaction gas leads to higher etch rate. However,

when the pressure increases further, the DRIE etch rate does not improve anymore because the dissociation efficiency for the plasma is lower and the number of reactive species reduces. Eventually when the pressure continues to increase, the reactive ions suffer more collisions because their mean free distance is drastically reduced, leading to a higher recombination in the plasma which results in a lower etch rate.

The process pressure also affects the profile of the etched feature. The bowing and closing up of the features towards the bottom in high aspect ratio trenches are observed as a result of high pressure. This is because more collisions between the reactive species at higher pressure induce more significant isotropy. It can also be accounted as the decrease of ion bombardment directionality due to higher pressure resulting in lower energy ions arriving at the trench bottom normally onto it due to increased scattering. Hence, reducing the chamber pressure can provide a more vertical trench at the price of a reduced etch selectivity between silicon and the mask material because the mask etch rate increases as a consequence of the increased mean free distance at lower pressures. Higher pressure can reduce the photoresist etch rate, but sputtering and redeposition of the mask material promotes the formation of the so-called silicon grass, i.e. microscopic needles etched in silicon due to localized micro-masking by the deposited mask material. Therefore, a compromise between the trench profile against etch rate and selectivity to mask has to be taken.

The STS ICP DRIE process is a very complicated process where the etching of silicon is the result of chemical and physical reactions and the anisotropy is guaranteed by the separated passivation deposition on the sidewalls combined with the lateral polymer removal. The process conditions, including the RF coil power, RF platen power, gas flow rate, process pressure, durations of the etching and passivation,

and the substrate temperature affect the macroscopic etch characteristics such as etch rate, etch profile, etch selectivity and etch surface. The dependence of the characteristics on the process conditions is not isolated from each other. Some are even conflicting with others and therefore, compromises have to be found in order to optimize the specific process.

4.3 The loading effect

Apart from the process conditions that affect the deep etching results, the microstructures design together with the distributions of the overall structures may lead to different consequences under the same etching conditions. In this section, the etching issues related to the feature design are studied.

4.3.1 The loading effect dependence on the design of various features

The loading effect is a well-known phenomenon originated from the non-uniform plasma distribution, non-vertical pattern profile of the soft and hard masks, and the various pattern densities. The micro-loading is the result of the local variations in the exposed area on the wafer, which causes faster etching onto the larger exposed feature.

Table 4-2 Process conditions used to investigate the loading effect

Gas flow (sccm)			Power (Watts)		Process time (s)
C ₄ F ₈	SF ₆	O ₂	Coil	Platen	
30	100	10	600	14	8
160	0	0	600	0	5

This phenomenon is also widely known as the RIE lagging effect. It is generally caused by the local depletion of etchants on the region of a wafer [163]. The etching is also a function of global variation in the exposed surface area of a wafer. It means that the etch rate is dependent on the overall exposed area and the pattern distribution on the wafer. This is known as the macro-loading effect where it is caused by the global etching difference. To investigate such loading effects, a specific mask was designed with 24 trenches of different widths from 0.4 to 200 μm . In this research, the process conditions are fixed as listed in Table 4-2.

In these processes, the hard mask was a 2.0 μm thick Plasma Enhanced Chemical Vapor Deposition (PECVD) oxide with precursor of tetraethyl silicate (TEOS). After patterning, the designed trenches with different mappings, were etched in the 6" silicon wafers. The results were obtained by taking the scanning electron microscope (SEM) pictures in several positions on the wafer, which is labeled as Figure 4-8.

4.3.1.1 Etch rate vs. trench width

The DRIE was carried out for 30 minutes under the process conditions listed in Table 4-2 and the sample examined below was measured at the center of the wafer. Very significant micro-loading effect is observed among the narrow trenches as it can be seen in the SEM micrographs shown in Figure 4-9. The etched depth varied dramatically among the trenches with widths from 0.4 to 20.0 μm while the variation is negligible for wider trenches, as plotted in Figure 4-10. The etched depth increases from 23.70 μm for the 0.4 μm -wide trench to 31.7 μm for the 2.0 μm -wide trench and to 40.0 μm for 20.0 μm -wide trench, respectively. Thereafter, the depth increases only by 1.6 μm for larger widths, up to 200.0 μm .

Figure 4-8 Position labels on the 6" wafer for the loading effect experiments.

(a)

(b)

Figure 4-9 SEM micrographs of the various trenches etched in a location at the centre of the wafer: (a) Trenches with widths from 0.4 to 10.0 μm, (b) Trenches with widths from 10.0 to 75.0 μm.

Figure 4-10 Etched depth of various wide trenches.

The overall average etch rate in this process is plotted in Figure 4-11 (a), which demonstrates that the rate increases from $0.80 \mu\text{m}/\text{min}$ for the trench $0.4 \mu\text{m}$ wide to $1.39 \mu\text{m}/\text{min}$ for the $200.0 \mu\text{m}$ wide trench. However, the acceleration of the etch rate is not constant or linearly proportional to the trench width. The etch rate increases dramatically for the narrow trenches, i.e. when the widths alter from $0.4 \mu\text{m}$ to $20.0 \mu\text{m}$ as shown in Figure 4-11 (b), while the difference can be ignored when the trenches become wider. This lagging effect and the tapered bottom of narrower trench are due to the narrow opening that hinders the arrivals of reactive ions and diffusion of reaction by products. It is also related to the higher aspect ratios as it is more difficult for the plasma etch species to physically reach the bottom of the trench.

This micro-loading effect makes MEMS fabrication a tricky task, as it produces different depths for different features. Additionally, the micro-loading effect changes for different etch conditions, which makes it harder to control the aspect ratio needed in MEMS. Changing the process conditions, for example, increasing the gas flow rate, increasing the chamber pressure to optimum, or decreasing the electrode power during

the etch cycle, may be helpful to reduce the micro-loading effect. It would be a breakthrough if the same depth can be achieved for different size features, especially those in the range of 0.4 μm to 10 μm that are widely employed in the MEMS or NEMS devices and for which the loading effect is the most significant.

(a)

(b)

Figure 4-11 Etch rate as a function of the trench width: (a) Trench widths between 0.4 μm to 200.0 μm , (b) Trench widths from 0.4 μm to 20.0 μm .

4.3.1.2 Etch rate vs. trench position on the wafer

The etch rate is not only a function of the feature design, but also of the pattern distribution on the wafer as a result of the non-uniform plasma distribution in the process chamber. The etching results of the five different positions C, R, T, L and B as denoted by Figure 4-8, representing center, right, top, left and bottom of the wafer are compared in Figure 4-12. It can be seen that the lagging effect exists universally across the wafer implying that it is the result of the localized distribution of the patterns. The narrower the trench to be etched, the slower the etch rate, due to the insufficient reactive species and difficulty for the by product to escape. This effect is the most noticeable in the trenches with width in the range of 0.4 μm to 20.0 μm . However, the lagging effect differs from one position to another. The sequence of the loading effect (difference between the maximum and minimum etched depth) in order of ascending magnitude is T (top) 14.40 μm , L (left) 16.00 μm , R (right) 16.30 μm , B (bottom) 16.60 μm and C (center) 17.90 μm . The trench at the wafer center lags the most because it is the most difficult area for the by-products inside the narrow trenches to diffuse outwards and be evacuated even if the reaction species are uniformly distributed.

For trenches with the same width, the etch rate changes according to the trench position. For example, the etching rate of the 2.5 μm wide trench at the five different positions is 1.10 $\mu\text{m}/\text{min}$ (C), 1.05 $\mu\text{m}/\text{min}$ (R), 1.12 $\mu\text{m}/\text{min}$ (T), 1.13 $\mu\text{m}/\text{min}$ (L), and 1.12 $\mu\text{m}/\text{min}$ (B) respectively. The left section is etched fastest while the center and right trenches are etched most slowly in this study.

Figure 4-12 Etch depth of various trenches located at different positions.

Therefore, the overall microstructures on the wafer and the localized patterns with different widths have various etch rate under the same process conditions. These effects bring more difficulties for the MEMS devices with various trench widths, especially for high aspect ratio structures.

4.3.1.3 Etch rate vs. exposed area of the wafer

The etch rate is affected by the local variations in the exposed surface area on the wafer represented by the trenches with different widths. The pattern at specific position has its own etching characters as discussed above. The overall exposed area is another important factor that influences the etch profile, etch depth and etch rate since the consumption of the reactive species differs according to the entire exposed area. To investigate this effect, the same mask is mapped differently to obtain various exposed areas. For instance, the exposed areas are 3.41%, 7.81%, 11.09% and 15.49%. They are etched under the same condition and the center sample is taken as

the reference gauge. The etch depths of the various trenches with different exposed areas are shown in Figure 4-13. It illustrates that the smaller the overall exposed area, the faster the etch rate and hence the deeper the trench. In general, the depth of the trenches decreases when the percentage of exposed area on wafer increases. This phenomenon is very significant for the trenches with width wider than 20.0 μm , for example, the depth differences between 3.41% and 15.49% exposed areas for trenches 20.0 and 200.0 μm wide are 5.0 μm and 7.8 μm , respectively, after 30 minutes. This is due to the depletion of reactive etching ions because the larger exposed area uses up more etchant ions and thus the depth etched reduces and the etch rate decreases.

The deviation of narrower trenches is not as significant compared to wide trenches. Figure 4-14 compares the etch depth of trenches which are narrower than 20.0 μm under the same conditions. The difference increases with the rise in the trench width because the wider trenches deplete more reactive species than the narrower trenches.

Figure 4-13 Etch depth in relation to the exposed area for various trenches.

Figure 4-14 Etch depth vs. exposed area for trenches with widths less than 20 μm

The micro-loading effect is affected by the overall etching areas as well. The loading decreases as the percentage of the exposed area increases. The difference of the etched depths between the narrowest trench (0.4 μm wide) and the widest one (200 μm wide) is listed in Table 4-3. It can be seen that this difference reduces from 17.90 μm for the smallest exposed area to 11.83 μm for the largest exposed area. This is expected as the widest trenches depend most on the percentage of the exposed area. When the overall etch area increases, the etch rate of wider trenches decreases more than that of the narrower trenches and thereby, the micro-loading effect decreases. This effect is more significant when deeper trenches are required as a result of the etch rate decrease, as listed in the same table. The average etch rate of the narrow trenches (2.5 μm wide) decreases slowly as the exposed area increases, from 1.10 μm/min for a 3.41% exposed area to 1.02 μm/min for a 15.49% exposed area. However, for the 200 μm wide trench, the difference is considerable from 1.39 μm/min for 3.41% to 1.13 μm/min for 15.49%. Less than 30% expose area is recommended for 6" process.

Table 4-3 Etch results due to the different exposed area under the same conditions.

Exposed area \ Specifications	3.41%	7.81%	11.09%	15.49%
Depth of 0.4 μ m trench (μ m)	23.70	24.12	23.48	21.97
Depth of 200 μ m trench (μ m)	41.60	38.70	36.90	33.80
Max. Depth difference (μ m)	17.9	14.58	13.42	11.83
Average etch rate of 2.5 μ m trench (μ m/min)	1.10	1.10	1.06	1.02
Average etch rate of 200 μ m trench (μ m/min)	1.39	1.29	1.23	1.13

4.3.2 Etch rate along the process

In the previous sections, the presented etch rate value was considered to be the average during the whole deep etching process. However, the rate decreases along the process. It is hard to monitor the live rate dynamically. Therefore, the deep etch is separated into several sub-steps and the average rate of every individual sub-step can be studied. Using this methodology, the variation in time of the etch rate during the whole process is achieved. As the electrostatic driven MEMS optical switch is fabricated on an SOI wafer with a device layer of 75 μ m thick, the testing process of the deep etching is divided into 3 sub-steps with periods of 40, 20 and 40 minutes, respectively. Their etching depths and individual average etch rate for different trench widths are listed in Table 4-4 and plotted in Figure 4-15, which verifies that the etch rate of a specific trench decreases with trench depth. At the first sub-step (40 minutes), the average etch rate for a 2.5 μ m-wide trench is 1.00 μ m/min and it drops to only 0.67 μ m/min for the third sub-step (another 40 minutes). This deceleration is more

significant for narrower trenches. The micro-loading effect also varies with the process. The deeper the trench, the sounder the difference in etch rate. This is because as the etching depth increases, it is accompanied by a change in the rate of cyclic etch and passivation succession due to variations in the passivation step coverage and transport of reactive and product species into and out of the trench respectively. Relatively, there is less change on the reactive species motion in and out of the wide trenches. Therefore, the fabricated pattern must deviate from the designed trench depth under various etch conditions and periods, especially for narrow trenches. As the etch rate reduces with the process, the estimated depth based on a previous sub-step is deeper compared to the real fabricated result and vice versa.

Table 4-4 Etch rate during the etching process of trenches with different widths.

<div>Trench width Time (min)</div>	2.5μm trench		7.0μm trench		30.0μm trench		120.0μm trench	
	Depth	Rate	Depth	Rate	Depth	Rate	Depth	Rate
	(μm)	(μm/min)	(μm)	(μm/min)	(μm)	(μm/min)	(μm)	(μm/min)
1 st 40	40	1.00	43.2	1.08	45.2	1.13	50.2	1.26
Estimated 20	20	-	21.6	-	22.6	-	25.1	-
2 nd 20	16.1	0.81	17.7	0.89	21.5	1.08	24.0	1.20
1 st + 2 nd	56.1	0.94	60.9	1.015	66.7	1.11	74.2	1.24
3 rd 40	26.8	0.67	33.5	0.84	44.6	1.12	47.7	1.19
Overall 100	82.9	0.83	94.4	0.94	111.3	1.11	121.9	1.22

Figure 4-15 Etch rate vs. trench width for the three sub-steps during the etch process.

4.3.3 Beam verticality

The etching profile is highly dependent on the process conditions and on the characteristic of pattern as discussed in section 4.2. The influence of the trench width on the sidewall profile is investigated experimentally. The SEM micrographs of trenches with widths between 0.4 and 200.0 μm resulted after etching continuously for 30 minutes are shown in Figure 4-9. The verticality of the trenches with different widths was analyzed and the results are shown in Figure 4-16. It indicates that the beam sides have a positive angle when the trench widths are less than 10.0 μm and have a negative angle when the trenches are more than 10.0 μm wide under the same etching conditions. For trenches with width of 10.0 μm , the deviation from vertical is smallest. Therefore, some dummy microstructures are employed to fix the trench width at this particular value in order to guarantee the verticality of the microstructure. As shown in last chapter for the MEMS optical switch, the micromirror is the key element that determines the direction of the output beam. The performance of the

Figure 4-16 Verticality of the beam vs. the trench width.

switch, expressed by parameters such as insertion loss and crosstalk, depends on the verticality of the mirror. However, the space around the mirror must be wide enough for allowing sidewall coating in order to achieve reliable metal coating and to assembly fiber optics,. In such a case, dummy microbeams are necessary, parallel to the micromirror surface and with a gap of 10.0 μm , in order to be easily removed before the metal coating. Therefore, a vertical micromirror with a good metal coating can be obtained.

4.4 The notching effect

SOI is getting more commonly adopted in MEMS fabrication due to its merits of simpler process and precise control on the depth of the device. However, the buried oxide layer which is of dielectric material brings new problems besides the issues on the DRIE etching of monolithic silicon. Severe undercutting (or notching or footing effect) of the silicon occurs at the boundary of the device silicon and buried oxide.

This effect is due to the accumulation of localized positive charge because of the oxide layer, which deflects the further incident positive high energy reactive ions towards the trench base sidewalls. In this section, the mechanisms of the notching effect are discussed and a newly developed process, multiple step deep etching associated with thin oxide spacer layer deposition and anisotropic etching, is introduced, described and experimentally verified in order to eliminate this notching problem. Additionally this notching effect is utilized to dry release the desired movable structures, thus eliminating the stiction problem caused by the wet release process.

4.4.1 Mechanisms of the notching effect

Performing DRIE etch through the device silicon layer is an essential step in the fabrication of microstructures on an SOI substrate. However, plasma etching the silicon over the insulator layer has long been recognized as the cause to the silicon notching problem at the silicon/insulator interface [164-166], as schematically shown in Figure 4-17 (a). Figure 4-17 (b) is the SEM micrograph illustrating the notching phenomenon on an SOI wafer. The poor profile caused by the notching may result in resonant frequency variations in the microstructure, leading to degraded performances. The notching effect is dependent on the aspect ratio, so the profiles and the characteristics of the final devices may further vary across the wafer affecting the repeatability and reliability, especially for the thick device wafer.

Charging Charge accumulation is the main reason for the notching. Its mechanism can be explained explicitly by three phenomena (see Figure 4-18):

- (1) An electric field effect during the charging transient when the impinging ions change direction,

- (2) Etching reactions of the energetic ions impinging on the bottom surface of the exposed silicon,
- (3) The forward scattering effects.

On the onset of lateral etching, more and more insulator layer is exposed and the notching deepens due to the forward scattering of ions. Moreover, the oxide surface charges up leading to forward deflection of ions since more oxide is exposed as etching proceeds [167]. Though the sidewall is covered by the polymeric thin film, these deflected ions quickly sputter away the thin passivation layer and the silicon beneath is exposed at the device silicon/buried oxide interface to be etched. Additionally, the significant issue that is unavoidable in a DRIE process is the micro-loading effect of the aspect ratio dependent etching (ARDE), which worsens the microstructures since different wide trenches have different etch rate under the same conditions. For SOI substrate based fabrication, the designed features may be widened or even destroyed due to the insulator layer under the device silicon. This phenomenon can be explained by the deflection, capturing, and the subsequent depletion of ions.

Figure 4-17 Notching effect: (a) schematic representation, (b) SEM micrograph.

Figure 4-18 Schematic illustrations of the notching effect: (a) charge accumulation, and (b) mechanisms of the notch formation.

Research has shown that the notching effect depends on aspect ratio, layout, whether the silicon lines are electrically connected [168], thickness of the mask layer [169], and the electron temperature [165]. The aspect ratio dependent charging is due to the directionality difference between ions and electrons when approaching the wafer surface. The positively charged ions arrive nearly normal to the wafer plane because of the effect of the sheath field, whereas the electrons face a decelerating field. The higher energy electrons tend to be deflected and the lower energy electrons are turned back though both of them start with a uniform distribution in all directions at the sheath edge. Monte Carlo simulations verified that electrons arrive at an uncharged wafer surface with a near isotropic distribution, but in a high aspect ratio structure, most of the directional ions could reach the bottom of the trenches, while the electrons end up mostly near the top of the device layer [168]. This mechanism was verified by sputtering a metal layer on the dielectric glass wafer which was electrically connected with the silicon substrate [164]. The notching effect was eliminated though the incident positive ions still bombarded onto the surface. These charges could not be

accumulated on the glass substrate because they were evacuated from this metal covered bottom to the silicon substrate due to the electric connection. Hence, no ion trajectory bending occurred in the direction of the silicon surface. However, it is impossible to carry on this pre-metal covering process for the SOI process as the buried oxide layer is sandwiched by two silicon layers. Figure 4-19 and Figure 4-20 show the cross sectional views of the DRIE etch results of an SOI wafer etched continuously for 30.3 minutes under the process conditions listed in Table 4-2. The trenches have widths ranging from 0.4 to 200 μm on SOI wafer with a 35- μm thick device layer. It is clear that the 4.0 μm trench is just etched down to the buried oxide layer since the time is set by the average etching rate on this specific trench. However, trenches narrower than 4.0 μm are not etched through to the buried oxide layer, while the trenches with widths ranging from 5.0 to 10.0 μm encountered serious notching at the interface between device silicon and insulator layer. For trenches with widths larger than 20.0 μm (see Figure 4-19) no prominent notching or other side effects are noted. This is attributed to the dependency of the notching on the aspect ratio.

This lateral attack etch is a fatal problem for SOI-based MEMS fabrication because it makes it hard, if not impossible, to have only one trench width in the device or system level design. Even if this criterion is met, the uniformity around the entire wafer may not be satisfactory. As a result, the notching issue cannot be addressed if the continuous DRIE etching is employed. This problem is worsened if the thickness of the device silicon increases as there will be an even more serious loading effect due to accumulation of more positive ions.

Figure 4-19 Trenches with widths from 0.4 to 20.0 μm etched in an SOI wafer.

Figure 4-20 Trenches with widths from 20 to 200 μm etched in an SOI wafer.

Figure 4-21 Notching of trenches etched in an SOI wafer with 75μm Si device layer.

Figure 4-21 is a very illustrative example of the severe notching occurring when trenches are etched in an SOI wafer with a device silicon 75.0 μm -thick. The widths of the trenches and silicon beams are 7.0 and 2.0 μm , respectively. The actual final height of the silicon beam is only 46.5 μm , including the seriously damaged bottom. The actual intact beam height is only 33.2 μm , which is less than half of the corresponding designed value due to the serious notching effect.

Therefore in this study, the objectives are to eliminate and utilize the notching effect.

4.4.2 Elimination of notching effect

There are several ways to address this issue [165-169], but each method has its own limitations, time consuming and difficulty in controlling [168], constraints by hardware and difficulty in detecting the end point, suitability only for bonded wafers [167], and degraded profiles [169]. A new spacer oxide thin film technique has been developed in this study and the process flow is outlined in Figure 4-22 for trenches of with three different widths. A PECVD silicon dioxide layer of 3.5 μm thick is first deposited as the hard mask. In general, its thickness has to be sufficient to protect the device silicon from being etched. Upon patterning the trenches, the major etch step of the device layer is divided into several sub-etch steps according to the etch rate of various aspect ratio trenches. The first sub-etch step focuses on the fastest etched trenches. As illustrated in Figure 4-22 (a), the widest trenches are etched through to the buried oxide layer, while the narrow trenches are still not completely etched. If the etching continues in this regime, notching would occur at the bottom of the wide trenches due to the dielectric buried oxide layer. To prevent this from happening,

PECVD dioxide is then employed to cover the surface of the trenches including their sidewalls, top surfaces and the trench bottoms. In order to continue with the etching for the other trenches, one must employ an anisotropic oxide etching step (e.g. using an Applied Materials P5000 Mark II) which removes the lateral deposited in a CHF_3 based etchant. The result is shown in Figure 4-22 (b). After this, the STS ICP DRIE is used again until the device layer is etched through for the second widest trenches (see Figure 4-22 (c)). For the narrowest trenches with the slowest etch rate, the oxide conformal coverage, lateral SiO_2 removal and the DRIE etch through steps are all repeated again. However, to ensure vertical profiles and smooth sidewalls for the beams, the previous spacer oxide is removed before the second deposition, as demonstrated in Figure 4-22 (d). In this way, the deposited oxide will not accumulate to a thick layer which may induce a step at the interface between the various etchings. Then a new oxide layer is deposited and laterally etched to protect the sidewall, as shown in Figure 4-22 (e). Finally, the last etching is carried out followed by spacer oxide removal using an isotropic oxide etch (refer to Figure 4-22 (f)).

Using this novel technique, trenches with different widths can be obtained on an SOI wafer without notching problem. This is accomplished by dividing the deep etching into more steps and associating it with auxiliary oxide deposition and lateral oxide removal steps intercalated in between the DRIE steps in order to protect the sidewalls. this process was practically verified on an SOI wafer with a device layer 35 μm thick, using a pre-designed mask with trench widths varying from 0.4 to 200.0 μm . the main focal point of attention were the trenches with widths from 2.0 to 10.0 μm , for which notching is most serious but which are typically most widely used in MEMS devices.

Figure 4-22 DRIE process flow which eliminates the notching effect: (a) First DRIE etch till the widest trenches to the buried oxide, (b) 5000Å PECVD oxide deposition and anisotropic etch the lateral deposited oxide, (c) DRIE etch the second widest trenches to buried oxide layer, (d) Etch back the deposited oxide on the sidewalls, (e) Redeposit and lateral etch another 5000Å PECVD oxide, (f) Repeat the deep etching and remove the deposited oxide after process completion.

The relationship between the etch rate and the trench width was used as basic data in deciding the proper time distribution of the multiple steps etching on the SOI wafer. Based on the rates obtained on the monolithic silicon wafer, the multiple-step etching process was carried out to etch trenches with different widths in order to fully eliminate the notching effect. The first etching is targeted for the 10.0 μm wide trench, whose etch time is expected to be 27 minutes and 30 seconds according to the rate obtained from the initial silicon wafer etching. After this step, all of the trenches are

etched to different depths whereas only the 10.0 μm -wide trench is etched through. Then, a PECVD TEOS oxide deposition is employed to cover all the exposed surfaces, followed by the anisotropic etch of silicon oxide on the lateral surfaces leaving only the protection oxide layer on the sidewalls. In this way, the sidewalls of the 10.0 μm trench are covered by oxide and the trench bottom is the buried thermal oxide. For the narrower trenches, the sidewalls are also covered by oxide while the bottom bare silicon is exposed.

The second DRIE step is carried out to etch through the trenches with widths ranging from 5.0 μm to 9.0 μm . The oxide deposition and anisotropic oxide etching expose the bottom silicon and the third deep etching step is repeated, this time targeting trenches with widths of 2.0 μm , 2.5 μm , 3.0 μm , 3.5 μm and 4.0 μm , before which the previous sidewall oxide layer is removed by isotropic oxide etching. The final cross-sectional views of the specially designed trenches are presented in Figure 4-23 (a). It clearly shows that trenches narrower than 2.0 μm are not etched through, whereas trenches with widths of 2.0 μm , 2.5 μm and from 5.0 to 10.0 μm are etched through without the notching problem. However, undercutting still exists at the foot of the trenches with widths of 3.0 μm , 3.5 μm and 4.0 μm , respectively. This is the result of the pronounced etch rate variations among patterns with critical dimensions of 2.0 μm , 2.5 μm , 3.0 μm and 3.5 μm . However, this phenomenon can be eliminated if more etching steps are employed.

Another observed phenomenon is the rounded shape of the trench bottom (see Figure 4-23 (b)), which could be due to two causes. The first one is the overetch during the anisotropic etching of the deposited oxide for the purpose of securing a very well exposed single crystal silicon (SCS) surface at the bottom from the subsequent

Figure 4-23 Improved etching results on 35 μm SOI wafer: (a) all trenches (from 0.4 to 20 μm wide), (b) Bottom of the 5.0 μm wide trench.

DRIE etching, which results in etching some of the buried oxide. The second cause could be the multiple-step silicon etching. Although the etching selectivity between silicon and oxide is larger than 65, under such conditions, the exposed buried oxide would be etched profoundly due to the long exposure to the directional high-energy plasma. It is noted that the bottom of the DRIE etched trench is cone-shaped instead of being as flat as the top surface. Nonetheless, the loss of a little buried oxide posed no side effects on the process or the property of the devices since the next process in most cases is the oxide etching to release the microstructures.

One of the most important steps for this process is the PECVD oxide coverage. This particular deposition must be conformal over all of the surfaces, especially the sidewalls and bottom of every trench. Cross-sectional SEM micrographs were taken in order to verify that oxide depositions used in this process provided such a good coverage. However, the dielectric oxide film induces charging of the electrons during scanning, making the inspection of the thin oxide layer extremely difficult. This

Figure 4-24 SEM micrographs of the deposited oxide: (a) bottom, (b) sidewall.

problem can be eliminated in the following manner. First an extra polysilicon layer is deposited on top of the oxide layer. The sample is then dipped in buffered oxide etchant (BOE) to etch the PECVD SiO_2 thin film after cutting the cross-sectional sample in order to obtain a hollow layer between the SCS and the deposited polycrystalline silicon. Figure 4-24 (a) and (b) show the hollowed oxide layers at the bottom and sidewalls that were previously covered by the polysilicon, verifying that both the bottom and the sidewalls of the trenches were all well covered by the PECVD oxide. This confirms that the process is reliable.

Another concern of this process is the thickness of the hard mask oxide layer. According to the etch rate selectivity between silicon and oxide of 50 under the conditions listed in Table 4-2, the $2.0\text{ }\mu\text{m}$ oxide is thick enough used as a hard mask for etching through the $75.0\text{ }\mu\text{m}$ device silicon layer. However, the hard mask thickness must meet the requirement of safely resisting to the practical multiple etching process. The lateral oxide removal (refer to Figure 4-22 (b)) that exposed the bottom silicon requires a certain amount of over etching. Thus, the previously deposited top hard mask is consumed unavoidably. The concrete variations of the hard

Table 4-5 Oxide thicknesses during the multiple etch process.

Process	1	2	3	4	5	6	7	8
step	Original	1 st DRIE	1 st oxide dep.	1 st oxide etch	2 nd DRIE	2 nd oxide dep.	2 nd oxide etch	3 rd DRIE
Center	3.5627	2.7511	3.3497	2.5705	2.3819	2.8051	2.1798	1.4587
Edge	3.4818	2.5029	3.0723	2.4430	2.0050	2.4070	1.7635	0.8822

mask thickness for different process steps measured at the large non-patterned areas are listed in Table 4-5. It clearly shows that the oxide depletion at the edge is faster than that at the center. The residue oxide thickness at the edge after triple DRIEs is only 8822 Å. The measured oxide layer in this figure is thicker than that in the localized patterned area because of the non-uniform distribution of the reaction chemical gases. Therefore, thicker hard mask layer is required to accomplish the multiple DRIE etching.

The above described fabrication approach plays the role as a base line for MEMS devices fabrication on SOI wafers, as it provides more flexibility for microstructure design and realization. Several different feature sizes of microstructures can be designed and fabricated at the same time, eliminating the restriction of only a single uniform size for each process. Another benefit derived from this novel process is the very much enhanced profile of the deep microstructure, which is the key requirement for the MEMS optical devices.

4.4.3 Dry release by notching effect

The permanent stiction problem due to the capillary forces that occurs during the rinsing and drying of wet release is another common problem observed in a conventional SOI process [170]. This effect has been studied theoretically and experimentally [171, 172] and several modified release approaches have been reported with their respective drawbacks. To solve these problems, special attention is paid to dry release.

In this study, a more flexible fabrication method is proposed and demonstrated to release movable structures on an SOI wafer without stiction. A thin spacer oxide thin film is utilized and the notching effect is this time exploited beneficially in order to provide a dry chemical release. This original solution entirely eliminates any problems associated with wet chemical release and other reported dry gas releases. The notching effect or undercutting is employed because this specific etching takes place laterally, hence is a very good candidate for a release process. The depth of the notching depends on many factors, such as the over-etch time, the type of the material as well as the thickness of the sidewalls passivation, and the size of the feature. Other variations include electron temperature, ion energy, and the ion/electron current at the surface.

The DRIE makes use of separated etch and passivation to attain the deep trenches. Though the sidewall is covered by the polymerized $(CF_2)_n$, this thin polymer-like layer cannot protect the silicon trench sidewall from etching by the high energy ions repelled from the exposed silicon dioxide layer, resulting in the appearance of the notching effect. However, a thin sidewall spacer oxide film could be used to eliminate the notching problem, as discussed previously in section 4.4.2. More significantly, the

Figure 4-25 Process flow for dry release employing the notching effect: (a) First DRIE etch; (b) PECVD oxide deposition; (c) Anisotropic etch the lateral deposited oxide to expose the bottom silicon; (d) 2nd DRIE etch till to the buried oxide layer and lateral release the beams by notching effect.

release depth can be controlled by adjusting the depth covered by the spacer oxide layer even if over-etching for release occurs. Incidentally, the proposed process allows beams formed by both uniform and non-uniform beams to be released

4.4.3.1 Uniform beam release

Beams with uniform trenches can be released by employing the notching effect. The process flow is outlined briefly in Figure 4-26. After patterning the trenches on the hard mask oxide layer on the SOI wafer, DRIE is employed to etch the device layer to within 1.0 – 2.0 μm from the buried oxide layer as shown in Figure 4-25 (a). The exposed surfaces are then covered by the PECVD oxide (see Figure 4-25 (b)). To etch the remaining silicon and to release the beams, the lateral deposited oxide is removed by anisotropic oxide etching while the sidewall oxide remains intact as

illustrated by Figure 4-25 (c). Then DRIE is employed again. This is a critical step for the uniform dry release as it plays two important roles: first, it etches through the device layer until the buried oxide layer is reached, and second it releases the features via the notching effect (see Figure 4-25 (d)). Compared to other dry release methods, the process time tolerance is much more flexible. In conventional dry etching, over-etching can result in sacrificing of beam depths. However, because of the sidewall oxide coverage, in this process the structures can endure longer over etch as the selectivity between silicon and silicon oxide is high.

In order to verify this process, SOI wafers with a silicon device layer 35 μm thick were used to demonstrate this novel notching-based release process. After patterning the structures, DRIE is carried out for 25 minutes to a depth of about 33.0 μm followed by the thin PECVD oxide layer deposition. The lateral oxide is etched anisotropically using the Precision 5000 Mark II (ETCH MXP) etcher from Applied Materials. Over-etching is required to ensure exposure of the bottom silicon for the subsequent vertical etching step. Finally, a DRIE etch is implemented for 12 minutes to etch through the trenches and to release the microbeams. The released structures are shown in Figure 4-26 (a) and (b), which illustrates that the beams are released well without stiction or other side effects.

In the event of insufficient etching, undercutting occurs only at the foot of both sides of the beam where the beams cannot be totally released, as is evident in Figure 4-27 (a). When the process time is appropriate, the foot of the released beam will be shaped like an upright cone that is pure SCS without oxide coverage. As for the top part of the beam, the PECVD oxide coverage remains intact. Therefore, if the DRIE

continues for a longer period, the cone part will be etched off and the top part will remain to give the final released beams as shown in Figure 4-27 (b).

(a)

(b)

Figure 4-26 SEM micrographs of the dry released beams: (a) released group of beams, (b) Released single beam with an upright cone bottom.

(a)

(b)

Figure 4-27 SEM micrographs of insufficient and over release beams: (a) group of not released beams, (b) Group of over released beams group.

The depth of the released microstructures can be adjusted by combining the DRIE etch and oxide thin film deposition and anisotropic etching steps. By allowing sufficient etch time for the second DRIE etch, the achieved beam height is equal to the depth of the initially etched trench and whose sidewall is protected by the oxide film. Therefore, by adjusting the first etching time, suspended microstructures of various depths can be obtained.

4.4.3.2 Non-uniform beam release

The notching effect is strongly related to the aspect ratios of the patterns (see Figure 4-19). Under the process conditions stated in Table 4-2, the notching effect is significant for trenches with aspect ratio greater than 1.75. No apparent undercutting for features with aspect ratios on the order of 1.5 or less is noted, as the electrons are able to bombard at the lower part of the etched structures and at the bottom of the surface. The charge buildup and the resulting notching effect are precluded. The extreme high aspect ratio patterns (greater than 20) are too narrow for the etchant gas to enter deeply and for the product gas to escape. The etch rate then drops significantly and the interface between the conductive silicon and the isolative thermal oxide is not exposed. The notching effects for the features with aspect ratios of between 1.75 and 20 (with width ranging from 20 μm to 2.5 μm on an SOI wafer with a device layer 35 μm thick) strongly depends on the pattern. This can be observed from the SEM micrographs of Figure 4-28, where various trench dimensions are illustrated. The notching is so small in Figure 4-28 (a) that it can be neglected for the 20.0 μm wide-trench. However, the notching depth defined as the distance of the lateral etch, increased as the aspect ratio increases. A notching depth of 4.335 μm for the trench with an aspect ratio of 3.50 is observed in Figure 4-28 (a), and a depth of 4.230 μm is

observed for the aspect ratio of 3.89 in Figure 4-28 (b). The depth reduces to 2.140 μm when the aspect ratio increases to 7.00 (see Figure 4-28 (d)).

The notching depth dependence on the trench width is plotted in Figure 4-29. Accordingly, this result can be used to easily control the notching depth by tailoring the aspect ratios of the etched features.

Figure 4-28 SEM micrographs of notching on trenches with various widths: (a) 20 μm and 10 μm wide trenches, (b) 9.0 μm and 8.0 μm wide trenches, (c) 7.0 μm and 6.0 μm wide trenches, and (d) 5.0, 4.0, 3.5 and 3.0 μm wide trenches.

Figure 4-29 Notching depth vs. trenches with different widths.

Different etch durations are required for different trenches in order to etch through the 35 μm SOI device layer. Trenches with different aspect ratios under the same etch conditions present different lateral undercutting as shown in Figure 4-19. The lateral etch rate (ratio of notching depth over notching time) for trenches with widths ranging from 4.0 to 10.0 μm are plotted in Figure 4-30, which is uniform within this range. This uniform notching rate is attributed to the consistent charge distribution in this aspect ratio range. Table 4-6 states the notching depth, the over-etching time and the notching rate of the series of trenches.

The amount of over-etch time is another important contributing factor for notching depth. The etch results with longer over etch times are depicted in Figure 4-31 for a series trenches with widths of 2.5 μm , 3.0 μm , 3.5 μm , to 4.0 μm under the same etch conditions, except for an additional 5.0 minutes of etching so that the obtained results can be compared with the previous ones, as shown in Figure 4-28. This figure shows that the trench 2.5 μm wide is etched through with the additional 5 minutes of DRIE etch while the final etch depth is less than 35 μm (see Figure 4-28 (d)) for the trench etched without this additional 5.0 minutes. However, the other three wider trenches suffer from notching during this additional 5 minutes etch as shown in Figure 4-31.

Figure 4-30 Notch rate vs. trenches' width.

Table 4-6 Notching depths and rates for trenches of various widths.

Trench width (μm)	Etch rate (μm/min)	Time for 35 μm (min)	Over etch time (min)	Notch depth (μm)	Notch rate (μm/min)
4.0	1.155	30.300	0	0	-
5.0	1.222	28.651	1.466	2.140	1.460
6.0	1.242	28.178	1.939	3.035	1.565
7.0	1.256	27.856	2.261	3.675	1.625
8.0	1.277	27.408	2.709	3.980	1.469
9.0	1.283	27.277	2.840	4.230	1.489
10.0	1.296	26.996	3.121	4.335	1.389

Therefore, structures with different trench widths will result in different notching depths if a single continuous etching approach is employed. However, by using the proposed multi-step plasma etching process, such non-uniform features can be etched and dry released to an equal depth. Therefore, this new improved SOI wafer fabrication technique allows a large flexibility in the design of MEMS devices with

possible variation in microstructures dimensions while at the same time presenting the geometrical and operational properties of the devices.

For a non-uniform design that includes both wide and narrow trenches, an oxide spacer coverage is employed to avoid excessive notching. The process is described as follow. Firstly, all trenches are patterned in the top mask layer as shown in Figure 4-32 (a). Then the trenches are etched but not entirely down to the silicon and oxide interface, even in the case of the widest trenches (see Figure 4-32 (b)). All the patterns are then conformal covered by PECVD TEOS oxide, followed by plasma etching of the oxide deposited on the lateral bottom in order to continue the vertical etching as well as to realize the lateral release as illustrated in Figure 4-32 (c). The last step is a crucial step as it plays several key roles. It etches through the widest trenches and deepens the narrow trenches. With the progress of etching, releasing the beams with wide trenches starts due to the notching effect which starts to take place, while the narrow trenches become deeper. When the narrow trenches are etched through to the interface with the buried oxide, the beams with wide trenches would have suffered some degree of notching or lateral etching. Hence, the beams with wide trenches are released totally while notching just begins for the beams with narrow trenches. Continuing the undercutting of the narrow beams, the repelled positive ions can not react with the spacer oxide of the beams so that the depth of the beams with wide trenches will not be etched further. The DRIE etching is stopped when the narrow beams are completely released as shown in Figure 4-32 (d). Thus, the DRIE anisotropic etching and dry gas release that makes use of the notching effect are both realized.

Figure 4-31 SEM micrograph of the notching effect on trenches with widths of 2.5, 3.0, 3.5 and 4.0 μm .

Figure 4-32 Process flow of dry release non-uniform beams using notching effect: (a) Trenches patterning, (b) First DRIE, (c) Sidewall oxide coverage, (d) Notching release.

Figure 4-33 SEM of the optical switch fabricated using our novel SOI DRIE fabrication process: (a) overview, (b) close up view of the mirror with optical fibers.

By using this novel process, the MEMS optical switch can be easily fabricated and the SEM micrographs of functional devices are shown in Figure 4-33. The overview of the MEMS optical switch is shown in Figure 4-33 (a). The trench width covers 2.5 μm of the overlapped fingers, 7.0 μm of the non-overlapped fingers, 50.0 μm of the folded beams, and 127.0 μm fiber grooves. All of these trenches with different widths are fabricated together on an SOI wafer with a device silicon layer 75 μm thick. Figure 4-33 (b) shows the central mirror together with the assembled optical fibers.

4.5 Summary

This chapter described in detail a novel DRIE SOI process flow which was used to fabricate a high performance and reliable optical switch. The principle of DRIE was first described from the chemistry and physics viewpoints, with main application for an STS ICP deep etching module, as this type of machine was utilized in this project. The effects of numerous condition factors, such as the gas flow rate, coil power, platen

power, process pressure, and duration of the separated etch/passivation cycles on the macroscopic characterizations of etch results (etch rate, etch profile, and etch selectivity to mask layer) have been analyzed experimentally. Accordingly, a proper process recipe was generated by finding the necessary compromises among the different aspects for different applications. However, the loading effects, both at localized and overall wafer level, are unavoidable, which means that different wide trenches experience different etch rates due to the different trench widths regardless of where and how they are distributed. Since the plasma does not distribute in the process chamber uniformly and the exhaustion of the by-product is not the same across the whole wafer surface during etching, the etch result of the same design alters from one position to another. Normally the patterns at the edge are etched faster than the center ones. The key deep etching characteristic that is affected by the process conditions and the design is the verticality of the mirror. In other words, positive, vertical, and negative profiles are possible by adjusting the process conditions.

The design has been carried out according to the device requirements and careful consideration on the fabrication effects must be paid at the design stage. However, specific problems occur on SOI wafer due to the buried oxide layer which is dielectric though the preformed sandwich substrate provides a lot of ease for the fabrication and assure high performance.

For instance, notching along the lateral direction at the foot of the trenches and permanent stiction between the adjacent beams after the wet releasing and drying steps are two most serious problems that degrade the performance and can even destroy the devices. Hence, a thin oxide film deposition and an anisotropic etch of the oxide deposited on the trench bottom have been introduced between two consequent deep

etch steps while maintaining the spacer oxide to prevent the notching problem. This improved process has been verified on an SOI wafer with device silicon layer 35 μm . Thick. On the other hand, the notching effect has been used beneficially to achieve a non-defect dry release for both uniform and non-uniform beams.

By using this proposed approach, the tolerance to over-etch time is much increased while maintaining the height of the beams. This process realizes even height beams for non-uniform trenches, which is the case most widely used in MEMS devices. Another merit of the process is that the depth of the microstructures can be designed and fabricated to achieve more powerful devices since the oxide coverage depth of beams with different feature sizes can be adjusted accordingly. The demonstrated process makes the design and fabrication of microstructures on thick SOI wafer much more flexible and powerful.

This process based on a spacer oxide protection has been used for the fabrication of the 2×2 optical switch. From a broader perspective, the process can be used to fabricate any high aspect ratio suspended structures for many other MEMS devices applications, such as a variable optical attenuator (VOA), a tunable laser (TS), a radio frequency (RF) switch, and so on.

CHAPTER FIVE

THE THERMO-OPTIC SWITCH

The main objective of this chapter is to develop a new optical switch that utilizes the thermo-optic (TO) effect and total internal reflection (TIR). The intention is to explore new principles in physics and engineering in designing this new optical switch. A different mechanism utilizing the MEMS technology compared to the existing optical switches is invented in this chapter. Based on the profound knowledge in MEMS fabrication and actuation developed in the last two chapters, this chapter focuses more on the principles of physics and the development of the new device.

A thermo-optic switch is an optical switch that utilizes the thermo-optic effect to switch the light between different spatially-separated outputs. The silicon material has the intrinsic property that its refractive index varies with the temperature. However, this change is too small to induce a large alteration of the refractive angle for real optical switching applications. In order to amplify this small angle alteration, the mechanism of TIR is utilized. The principle is to first adjust the incident light close to the TIR angle and then to use the temperature to change the refractive index. As a

result, the light can be switched between total internal reflection and the transmission. In the implementation of such an optical switch, a silicon prism will be used as the core switching element, and two thermal actuators will be employed to finely adjust the prism angle. Out of the three side surfaces from the prism, the first and the third ones receive and lead out the light beam at normal angles unto their planes, respectively, whereas the second one acts as the critical switching surface where the light can be either transmitted or totally reflected. The optical switching is obtained by the thermal optical effect rather than by the movement of a micromirror, as is commonly used in the micromechanical switches. As the thermal actuators can be fabricated on the same MEMS chip and the temperature control of the prism surface can be realized by localized heating, a single MEMS chip is able to provide the full switching function. When compared with the other MEMS optical switches, this optical switch possesses special advantages. For instance, it is more reliable because mechanical movement is not required. The thermal actuators make it convenient to adjust the prism without any external equipment.

This chapter starts with the physical studies of the thermal optical effect and total internal reflection, followed by the design of the optical switch, including the prism design, the fiber positioning and the thermal actuator design. Then, different optical losses are investigated, covering the insertion loss, polarization dependence loss and the cross-talk. Finally, the experimental results of the thermal optical effect and the optical switching function are presented and compared with the analysis.

5.1 Physics of thermo-optic effect

5.1.1 Thermo-optic effect of silicon material

The thermo-optic effect refers to the dependence of the optical refractive index of a material on temperature. This effect is present in all transparent materials including dielectrics, semiconductors and organic materials and it has wide applications in various optical devices [173]. The thermo-optic coefficient can be positive or negative dependent on the material property. Usually polymers such as acrylates and polyimides have negative thermo-optic coefficients [174]. In contrast, semiconductor materials such as silicon have positive coefficients. These materials are extensively used in tunable devices. In general, the sign of the coefficient is dependent on the polarizability and the density of a particular material since these two properties are function of temperature.

The polarizability is a material property which characterizes the ability of distortion of the electron cloud of a molecular entity of that respective material by an electric field [175]. As schematically shown in Figure 5-1, the dipole moment $\vec{p}$ is induced by the external electric field $\vec{E}$.

The relative distance between the positive and negative center is represented by $\vec{x}$.

The dipole moment $\vec{p}$ is expressed as

$$\vec{p} = q\vec{x} = \rho\vec{E} \quad (5-1)$$

Figure 5-1 Schematic of the polarization induced by an external electric field.

where ρ is the polarizability of the medium given by $\rho = q\vec{x}/\vec{E}$. A higher polarizability leads to a higher refractive index.

Another term affecting the thermo-optic coefficient is the of the medium's density alteration induced by a temperature change. This is indicated by the coefficient of thermal expansion (CTE), which is an intrinsic property of the material. Assuming that the medium is uniform homogenous and isotropic, the material commonly expands uniformly in all directions upon heating as schematically shown in Figure 5-2. Since the number of atoms or molecules in the material remains constant, the density decreases as the volume increases.

As the total polarization is expressed as

$$\vec{P} = N\vec{p} = N\rho\vec{E} = \epsilon\chi_e\vec{E} \quad (5-2)$$

where N is the density of the atom or molecule, ϵ is the electric permittivity and χ_e is the electric susceptibility that is expressed using the refractive index n of the material as

$$\chi_e = \sqrt{n^2 - 1} \quad (5-3)$$

Thus,

$$N\rho = \epsilon(n^2 - 1)^{\frac{1}{2}} \quad (5-4)$$

Therefore, the refractive index n can be expressed as

Figure 5-2 Schematic of the thermal expansion of the material.

$$n = \left(1 + \frac{N\rho}{\varepsilon}\right)^{\frac{1}{2}} \quad (5-5)$$

This equation shows that the refractive index is directly related to the density N and the polarizability ρ of the material.

The thermo-optic effect of silicon is explained by the single oscillator model [176]. For the critical points of the interband transitions, the transition energies decrease with higher temperature. Coupling among various types of oscillators to the electromagnetic radiation field is often employed to explain the optical properties of the material. The real part of the dielectric constant ε in the transparent range can be written as [176]

$$\varepsilon = n^2 = 1 + E_p^2 \sum_k \frac{f_{cv}(k)}{E_{cv}^2(k) - E^2} \quad (5-6)$$

where E_p is the electronic plasma energy and is expressed as $E_p = \sqrt{4\pi N \hbar^2 e^2 / m_e}$ with the effective mass of m_e and using the reduced Planck constant $\hbar$ and single electron charge e . E is the photon energy, k is the reciprocal lattice vector, and $E_{cv}(k)$ and $f_{cv}(k)$ are the transition energy and the interband oscillator strength between the valence and conduction band, respectively.

When a single oscillator occurs, Eq. (5-6) can be simplified to

$$n = \sqrt{1 + \frac{E_p^2}{E_g^2 - E^2}} = \sqrt{1 + \frac{4\pi N \hbar^2 e^2}{m_e (E_g^2 - E^2)}} \quad (5-7)$$

where E_g is the optical band gap. Thus,

$$\frac{dn}{dT} = \frac{dn}{dN} \frac{dN}{dT} + \frac{dn}{dE_g} \frac{dE_g}{dT} \quad (5-8)$$

$$\frac{dn}{dN} \frac{dN}{dT} = \frac{1}{2} \left(1 + \frac{4\pi N \hbar^2 e^2}{m_e (E_g^2 - E^2)} \right)^{-\frac{1}{2}} \frac{4\pi \hbar^2 e^2}{m_e (E_g^2 - E^2)} \frac{dN}{dT} = -\frac{3k_{ex}(n^2 - 1)}{2n} \quad (5-9)$$

where T is the temperature. k_{ex} is the thermal expansion coefficient of silicon, which is expressed as [177]

$$k_{ex}(T) = 3.725 \times 10^{-6} \left\{ 1 - \exp[-5.88 \times 10^{-3}(T - 124)] \right\} + 5.548 \times 10^{-10} T \quad (5-10)$$

The optical band gap is affected by the temperature as given by

$$\frac{dn}{dE_g} \frac{dE_g}{dT} = -\frac{n^2 - 1}{2nE_g} \frac{2}{1 - \left(\frac{E}{E_g} \right)^2} \frac{dE_g}{dT} \quad (5-11)$$

According to the empirical relationship given by Varshni [178-180],

$$E_g(T) = E_g(0) - \frac{\alpha_g T^2}{(T + \beta_g)}, \text{ where } E_g(0) \text{ is the average band gap at 0 K and the}$$

constants α_g and β_g are related to the electron-phonon interaction and Debye temperature of the silicon. With this relation, Eq. (5-11) can be further expressed as

$$\frac{dn}{dE_g} \frac{dE_g}{dT} = \frac{n^2 - 1}{2nE_g} \frac{2\alpha_g}{1 - \left(\frac{E}{E_g} \right)^2} \left[\frac{2T}{T + \beta_g} - \frac{T^2}{(T + \beta_g)^2} \right] \quad (5-12)$$

Therefore, the thermo-optic coefficient is expressed as

$$\frac{dn}{dT} = \frac{n^2 - 1}{2n} \left\{ -3k_{ex} + \frac{2\alpha_g}{E_g} \frac{1}{1 - (E/E_g)^2} \left[\frac{2T}{T + \beta_g} - \frac{T^2}{(T + \beta_g)^2} \right] \right\} \quad (5-13)$$

When the constants take the values of $E_g(0) = 4.03(\text{eV})$, $E_p = 13.31(\text{eV})$, $\alpha_g = 3.41 \times 10^{-4}(\text{eV} \cdot \text{K}^{-1})$, $\beta_g = 439(\text{K})$ [176] and $n = 3.42$, the thermo-optic coefficient can be expressed as

Figure 5-3 Relationship between refractive index change and temperature change.

$$\frac{dn}{dT} = 1.8 \times 10^{-4} + 3.47 \times 10^{-7} T - 1.98 \times 10^{-7} \times T^2 (K^{-1}) \quad (5-14)$$

By neglecting the higher order term of the thermo-optic coefficient, the relationship between the temperature change and the refractive index change is calculated and plotted in Figure 5-3. It shows that the refractive index of single crystal silicon increases linearly with the temperature.

5.1.2 Analysis of total internal reflection

To make use of the thermo-optic effect for optical switching, the TIR phenomenon plays an important role and thus needs detailed study, including the basic relations and wavelength dependence.

According to the Snell's law [181], the relationship among the incident angle α , the refractive angle θ , and the optical properties of the two media is governed by

$$n \sin \alpha = n_0 \sin \theta = \sin \theta \quad (5-15)$$

where n and n_0 are the refractive indices of the two media, respectively. In this study, the two media are assumed to be the silicon and the air. At room temperature and 1550

nm wavelength, $n = 3.42$ [182] and $n_0 \approx 1.0$. Although single crystalline silicon is anisotropic, it has inversion symmetry implying a constant refractive index. When the incident angle α meets the requirement of $\sin \alpha \leq n_0/n = 1/n$, the refraction angle θ has a real value. The utmost refractive angle is equal to 90° in which the critical incident angle α_c is given by

$$\alpha_c = \arcsin(n_0/n) = \arcsin(1/n) \quad (5-16)$$

At larger incident angles, the TIR would take place. For silicon-based prism, it has $\alpha_c = \arcsin(1/3.42) = 17.0^\circ$.

There are two methods to switch the incident light between transmission and reflection. One is to change the incident angle to values beyond the critical angle, so that the light can be changed between the TIR state and the transmission state. According to the analysis of thermo-optic effect, changing the refractive index of the material by adjusting the temperature while leaving the incident angle fixed is another possibility. The relationship between the refraction index change and the refractive angle change is expressed as

$$\Delta n = n_0 \operatorname{ctg} \theta_0 \Delta \theta \approx n_0 \cos \theta_0 \Delta \theta \approx n_0 \left(\frac{\pi}{2} - \theta_0 \right) \Delta \theta \quad (5-17)$$

Compared with the method of adjusting the incident angle, the one that changes the refractive index is more efficient and reliable because no mechanical movement is required. The stability and reliability are therefore assured. Additionally, the strong dependence of the refractive angle on the optical properties of the medium makes the switch more sensitive to the control parameters. Figure 5-4 depicts the change of the refractive index needed to realize the total internal reflection when the initial refractive angle θ varies from 86° to 90° . It is observed that the output selection is so sensitive to

Figure 5-4 Relationship between initial refractive angle and refractive index change.

the refractive index change that only a 5.2×10^{-4} increase of the refractive index is enough to switch the transmitted light at 89° to the TIR state. Therefore, changing the refractive index of the silicon is an effective way to switch the input signal between the transmission state and the TIR state.

By considering the thermo-optic effect of silicon, the relationship between the temperature change required and the initial refraction angle of the transmitted light is simulated and shown in Figure 5-5. The horizontal axis represents the initial refractive angle, while the vertical axis represents the required temperature change to make the refractive angle be increased to 90° (i.e., total internal reflection, TIR). In this way, the TIR may occur, the incident light will be reflected out to the alternative output from the transmitted output when the temperature of the optical component is increased accordingly. On the other hand, the TIR reflected light can be switched back to the transmission output by lowering the temperature. However, the optical refractive

Figure 5-5 Relationship between the required temperature change and the initial refractive angle.

index is also wavelength dependent due to the dispersion effect. The refractive index of silicon at the room temperature (293K) was derived by Edwards *et al* as [183]

$$n^2(\lambda) = \epsilon_0 + \frac{A}{\lambda^2} + \frac{B\lambda_1^2}{\lambda^2 - \lambda_1^2} \quad (5-18)$$

where $\lambda_1 = 1.1071 \mu\text{m}$, $\epsilon_0 = 11.6858$, $A = 0.939816$, and $B = 8.10461 \times 10^{-3}$. As most of the applications in optical communications utilize the S, C and L bands (corresponding to a wavelength range from 1400 nm to 1650 nm), the analysis below will focus on this wavelength range. The deviation of the refractive index is plotted in Figure 5-6 (the right side y axis). It is clearly shown that longer incident wavelength results in smaller refractive index. However, the absolute deviation value is less than 0.013 over this wavelength range.

According to Eq. (5-16), the corresponding critical angle varies with different wavelength, as expressed by

$$\theta(\lambda) = \arcsin\left[\frac{1}{n(\lambda)}\right] = \arcsin\left(\frac{1}{\sqrt{\epsilon + \frac{A}{\lambda^2} + \frac{B\lambda_1^2}{\lambda^2 - \lambda_1^2}}}\right) \quad (5-19)$$

Figure 5-6 Relationship between silicon’s refractive index and wavelength.

This relationship is also illustrated in Figure 5-6 (the primary left side y axis). In applications that use multiple wavelengths, the switching should satisfy all of three bands or even wider for wavelengths. Therefore, careful selection of the initial incident angle and the refractive index change is important.

5.2 Design of the thermo-optic switch

A practical optical switch generally requires a large angle difference between the two switching states in order to allow for the deployment of two output fibers. Although the thermo-optic effect itself cannot induce a sufficiently large refractive index change to produce the large difference of refractive angle, the involvement of TIR makes it feasible. To realize the function of the optical switching, an optical prism is used as the core element to switch an incident light between the TIR state and the transmission. The positioning of the optical fibers is also discussed.

5.2.1 Design of optical prism

The architecture of the thermo-optic effect based TIR optical switch is shown in Figure 5-7. It consists of a silicon prism, three optic fiber grooves, two thermal actuators and a high reflection mirror. The prism determines the output direction of the incident beam by thermally changing its refractive index. The high reflection mirror is employed to change the direction of the transmitted light into the output fiber 1. The two bio-directional thermal actuators are used to fine tune the incident angle of the incident light to make the switch more universal. The fiber grooves realize high precise passive alignment and assembly of the optic fibers.

The two states of the optical switch are schematically shown in Figure 5-8. The optical axis of the input beam is perpendicular to the incident surface of the prism. Therefore, the propagating direction remains unchanged at the first interface though the refractive indexes of the two media are different. Hence, the incident angle at the second interface is equal to the prism angle α .

Figure 5-7 Architecture of the TIR thermo-optic switch.

Figure 5-8 Realization of two switching states using the prism: (a) Transmission state at lower temperature and smaller refractive index, and (b) TIR state at higher temperature and larger refractive index.

At lower temperature, the refractive index is smaller and the critical angle is thus larger. When the critical angle becomes larger than the incident angle (fixed value), the input signal is directed into the output 1 at the transmission state (see Figure 5-8 (a)). Similarly, the input signal is switched into the output 2 as a consequence of total internal reflection when the temperature is sufficiently high to allow the critical angle to be smaller than the incident angle (see Figure 5-8 (b)).

The initial incident angle is selected to be close to the critical angle at room temperature in order to minimize the requirement for temperature change. However, the wavelength dependence is also taken into account as the switch is targeted to operate in a wavelength range from 1400 nm to 1650 nm. According to Figure 5-9, the tolerance of the critical angle over this wavelength range is between -0.07° and $+0.034^\circ$. The incident angle is then chosen at 16.96° as listed in Table 5-1. The temperature change required is accordingly 43.49°C .

Table 5-1 Dimension of the silicon optical prism

Specification	$\alpha (^{\circ})$	$l (\mu\text{m})$
Dimension	16.96	108.5

Additionally, the side length of the prism is also chosen after taking into consideration of a few factors. The length should be sufficiently large to allow for the deployment of two normal single mode fibers (the input and the output fiber shown in Figure 5-7) at the same side. However, in a real device, the fabricated prism should be released to allow for fine angle adjustment, therefore the prism length is limited by the release. With these considerations, the side length of the prism is selected at 108.5 μm (Table 5-1).

From the architecture of the optical switch, a few advantages of this optical switch over other techniques can be identified. Firstly, it is innovative to employ the principle of critical angle of TIR for optical switching. Secondly, the required change in refractive index is not as critical as that of the waveguide-based switch because the switching function can be realized as long as the TIR condition is satisfied. Thirdly, the mechanical instability issue is no longer a concern. Lastly, the effective volume is small and light absorption problem due to long propagation distance can be avoided.

5.2.2 Influence of the evanescent wave on output position

Considering a light ray traveling from silicon to the air, the refractive light beam would become an evanescent wave when the TIR occurs. For the output position, the evanescent wave should be considered since the incident light would enter the air by a

very small distance instead of being simply totally reflected into the silicon. The incident wave, reflected wave and refractive wave at the interface are shown in Figure 5-9. Each of them can be resolved into components parallel (denote by subscript p) and perpendicular (subscript s).

The transmitted wave E_t in term of electric field is expressed as

$$E_t = A_t \exp[-i(\vec{k}_t \cdot \vec{r} - \omega t)] \quad (5-20)$$

where A_t is the amplitude, $\vec{k}_t$ the wave vector, $\vec{r}$ the position vector, ω the angular frequency, and t the time. Taking the plane of incidence as the x - z plane, the expression of transmitted wave by three individual components can be rewritten as

$$E_t = A_t \exp[-i(k_{tx}x + k_{tz}z - \omega t)] \quad (5-21)$$

Based on Snell's law, the wave vector $\vec{k}_t$ depends on the incident wave vector and the refractive index of the medium:

$$\begin{aligned} k_{tx} &= k_i \sin \theta_i = k_i \frac{\sin \theta_t}{n} \\ k_{tz} &= k_i \cos \theta_i = \pm k_i i \sqrt{\left(\frac{\sin \theta_t}{n}\right)^2 - 1} \end{aligned} \quad (5-22)$$

Figure 5-9 Reflection and transmission at the interface of two media.

where k_{tx} and k_{tz} are the projections of k_t along the x and z directions, respectively. θ_t is the transmission angle, and k_i is the incident vector. Equation (5-22) shows that the z component of the wave vector is imaginary as a result of the relative refractive indices of the silicon and the air. However, only a positive value is valid as discussed below.

$$\text{Let } \kappa = k_i \sqrt{\left(\frac{\sin \theta_t}{n}\right)^2 - 1} \quad (5-23)$$

Then $k_{tz} = \pm i\kappa$ and the transmitted wave function described by Eq. (5-21) becomes

$$E_t = A_t \exp(\mp \kappa z) \exp[-i(k_{tx}x - \omega t)] \quad (5-24)$$

It means that the transmitted wave is not homogeneous along the boundary in the plane of incidence (in the x direction) while the amplitude decreases exponentially along the z direction. This wave is the evanescent wave. It is natural that only the negative sign corresponds to the physical situation. Otherwise, the amplitude tends to increase to infinity with the penetrating depth of z . The effective penetrating depth is defined as the depth where the amplitude reduces to e^{-1} of the initial amplitude, being of the order of a wavelength.

Let the transmitted field consist of x - and y - components, at the interface where $z = 0$, the electric and magnetic field E'_x and H'_x can be written as,

$$\begin{aligned} E'_x &= -\frac{1}{2} \left(T_p \cos \theta_t e^{-i(\omega x - k_{tx} x \sin \theta_t)} + T_p^* \cos^* \theta_t e^{i(\omega x - k_{tx} x \sin \theta_t)} \right) \\ &= -\frac{i}{2} \sqrt{\frac{\sin^2 \theta_t}{n^2} - 1} \left(T_p e^{-i(\omega x - k_{tx} x \sin \theta_t)} - T_p^* e^{i(\omega x - k_{tx} x \sin \theta_t)} \right) \end{aligned} \quad (5-25a)$$

$$E'_y = \frac{1}{2} \left(T_s e^{-i(\omega x - k_{tx} x \sin \theta_t)} + T_s^* e^{i(\omega x - k_{tx} x \sin \theta_t)} \right) \quad (5-25b)$$

$$H_x^t = -\frac{1}{2} \left(T_s \cos \theta_i \sqrt{\varepsilon_2} e^{-i(\omega x - k_y x \sin \theta_i)} + T_s^* \cos^* \theta_i \sqrt{\varepsilon_2} e^{i(\omega x - k_y x \sin \theta_i)} \right) \quad (5-25c)$$

$$= -\frac{i}{2} \sqrt{\varepsilon_2} \sqrt{\frac{\sin^2 \theta_i}{n^2} - 1} \left(T_s e^{-i(\omega x - k_y x \sin \theta_i)} - T_s^* e^{i(\omega x - k_y x \sin \theta_i)} \right)$$

$$H_y^t = -\frac{1}{2} \sqrt{\varepsilon_2} \left(T_p e^{-i(\omega x - k_y x \sin \theta_i)} + T_p^* e^{i(\omega x - k_y x \sin \theta_i)} \right) \quad (5-25d)$$

The Poynting vector is expressed as

$$S_z^t = \frac{c}{4\pi} (E_x^t H_y^t - E_y^t H_x^t) \quad (5-26)$$

The time average of the two terms is zero in the interval from $-t'$ to t' , where t' is larger than the period T of $2\pi/\omega$. For one contains the first term

$$\frac{1}{2t'} \int_{-t'}^{t'} \left\{ T_p^2 \exp[-2i(\omega x - k_y x \sin \theta_i)] - T_p^{*2} \exp[2i(\omega x - k_y x \sin \theta_i)] \right\} \quad (5-27)$$

$$= \left[T_p^2 \exp\left(\frac{2i\omega x \sin \theta_i}{nv_2}\right) - T_p^{*2} \exp\left(-\frac{2i\omega x \sin \theta_i}{nv_2}\right) \right] O\left(\frac{T}{t'}\right)$$

It is negligibly small as $t' \gg T$ and the other term with T_s is close to zero. The time average of the Poynting vector along z direction vanishes, which means the optical power flows to and fro, but there is no continuous power flowing into the air medium. Therefore, no energy flows across the interface although there is evanescent field in the air medium.

Figure 5-10 The Goos-Haenchen shift

Figure 5-11 Relative position of the input and output fibers.

The reflected power is equal to the incident power regardless of the surface roughness. However, the entrance of the incident power is different from the exit of the reflected power at the symmetric position. There is a lateral shift of about half wavelength distance, which is known as the Goos-Haenchen shift and is shown in Figure 5-10.

Therefore, the output fiber of the TIR state must not be exactly at the directly reflected direction. It has a Goos-Haenchen shift from the entrance of the incident wave as schematically shown in Figure 5-11.

5.2.3 Design of the thermal actuator

The output position of the incident signal is highly dependent on the actual refractive index of the prism. However, in practice, the refractive index of silicon may vary from device to device due to the different fabrication condition, temperature, and humidity, etc. To accommodate for this variation, a pair of MEMS thermal actuators are introduced into this optical switch to fine tune the incident angle and the position of the prism.

These two thermal actuators are located at the two tips of the prism as shown in Figure 5-12. This arrangement brings in some advantages, for instance, the incident spot of light at the interface can be fixed. When the two thermal actuators drive the prism rotation anticlockwise around the symmetric center of O , the incident light still bounces off the second interface of the prism at the spot of O . At the same time, the incident angle can be adjusted to meet the TIR condition. In this way, it compensates for the difference between the real silicon refractive index and the designed value.

The prism needs only a very small rotation (typically $< 1^\circ$) but at high accuracy. Therefore, MEMS thermal actuators are employed in this switch to provide the desired fine tuning precision. The design features are listed in Table 5-2 and the layout is shown in Figure 5-13.

Figure 5-12 Fine tuning of the prism orientation.

Table 5-2 Dimensions of the thermal actuator.

Specification	Wide beam		Narrow beam	
	Width, w_w	Length, l_w	Width, w_n	Length, l_n
Dimensions (μm)	16	290	3	400

Figure 5-13 Layout of the thermal actuator.

However, due to this rotation, the incident angle at the first interface is no longer 90° (see Figure 5-12). Fortunately the influence on the incident angle $\Delta\alpha$ at the second interface is negligible. This is because the refractive index of prism is much larger compared to that of the air, resulting in a much smaller change in the incident angle at the second interface. This effect is plotted in Figure 5-13 in which the refractive index varies from 3.40 to 3.50. The reference point is taken at $n = 3.45$. The change of the rotation angle is expressed as $\delta\alpha(n) = \sin^{-1}(1/n) - \sin^{-1}(1/3.45) \approx -5.04\Delta n \text{ (deg)}$, and the change of the incident angle $\Delta\alpha$ at the second interface can be calculated by $\Delta\alpha(n) = \frac{1}{n}\delta\alpha \approx -1.46\Delta n \text{ (deg)}$. The deviation of the incident angle at the first prism side from the designed value over the range of refractive index from 3.40 to 3.50, is

Figure 5-14 Variation of the incident angle due to the slight rotation.

$|\delta\alpha(n)| \leq 0.25$. Therefore, the change in the incident angle at the second interface is smaller than 0.073° .

5.3 Theoretical analysis of optical losses

In real applications, the optical switch has specification requirements such as insertion loss (IL), cross-talk, polarization dependent loss (PDL), wavelength dependent loss (WDL), and return loss. A detailed study of these parameters is crucial for the evaluation of the switch performance for proper applications.

5.3.1 Insertion loss (IL) of the optical switch

Insertion loss is the power loss that results from inserting a component, such as a connector, coupler or splice into a previously continuous path [185]. Hence, it is used as a gauge to measure the power lost from input to the particular output. In this thermal optical switch, there are two outputs. Their insertion losses are caused by different mechanisms. For output 1 (transmitted light, refer to Figure 5-8), the loss comes from the Fresnel reflection at the interfaces, fiber coupling loss due to the Gaussian beam divergence, partial transmission at the second interface of the prism, and the mirror scattering loss. For output 2 (reflected light), the loss is caused by the Fresnel loss, fiber coupling loss, scattered loss induced by surface roughness at the TIR surface and F-P cavity effect loss. In the following section, these losses are investigated in detail.

5.3.1.1 Loss of Fresnel reflection

When an optical beam falls onto a boundary between two homogeneous media with different optical properties, there must be a portion of the power reflected back into the first medium. This specific reflected power can be calculated by using Fresnel's formula [181],

$$IL_{Fresnel} = -10 \log \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (5-28)$$

where n_1 and n_2 are the refractive indexes of the two media, which are equal to 1.0 and 3.42 respectively at the interface of free space and silicon prism. Hence, the loss is 1.55 dB at every air-silicon interface. This kind of loss is observed at the interface of the fiber facet and free space as well, but the value is much smaller (0.18 dB per interface).

5.3.1.2 Loss of fiber coupling

The fundamental mode field distribution of single mode fiber (SMF) can be well approximated by a Gaussian function. Thus, the beam diverges after it comes out of the fiber because the diffraction causes light waves to spread transversely as they propagate. The spreading of the beam is in precise accord with the predictions of pure

Figure 5-15 The divergence of a Gaussian beam.

diffraction theory. The beam profile is schematically shown in Figure 5-15.

The following formulas describe the beam spreading and are thus used for estimation of the fiber coupling loss. Even if a Gaussian TEM₀₀ beam wavefront is made perfectly flat at some plane, it would quickly acquire curvature and begin spreading according to

$$R(z) = z \left[1 + \left(\frac{\pi n w_0^2}{\lambda z} \right)^2 \right] \quad (5-29)$$

$$w(z) = w_0 \left[1 + \left(\frac{\lambda z}{\pi n w_0^2} \right)^2 \right]^{\frac{1}{2}} \quad (5-30)$$

where z is the distance propagated from the plane where the wavefront is flat, λ is the wavelength of light, n is the refractive index of the medium, w_0 is the beam waist characterized by the radius of the $1/e^2$ irradiance contour at the plane where the wavefront is flat, $w(z)$ is the radius of the $1/e^2$ contour after the wave has propagated for a distance of z , and $R(z)$ is the wavefront radius of curvature after propagating for a distance of z . The beam size out of the single mode fiber is plotted in Figure 5-16 for

Figure 5-16 Gaussian beam waist vs. transmission distance.

the most widely used fiber with $w_0 = 5.2 \mu\text{m}$ and $\lambda = 1.55 \mu\text{m}$. The beam waist is increased to $7.04 \mu\text{m}$ and $8.74 \mu\text{m}$ after the propagation distances of $50.0 \mu\text{m}$ and $100.0 \mu\text{m}$, respectively.

This spreading leads to the insertion loss associated with three kinds of fiber misalignments, namely longitude gap z , lateral misalignment Δx and angular misalignment $\Delta\theta$. The total insertion loss developed by Nemoto and Makimoto can be calculated by the equation

$$L = -10 \log \left[\frac{4D}{B} \exp \left(-\frac{AC}{B} \right) \right] \quad (5-31)$$

where
$$A = \frac{(k \cdot w_T)^2}{2}, \quad k = \frac{2\pi n_0}{\lambda} \quad (5-31a)$$

$$B = G^2 + (D+1)^2 \quad (5-31b)$$

$$C = (D+1) \cdot F^2 + 2DFG \cdot \sin(\Delta\theta) + D(G^2 + D+1)\sin^2(\Delta\theta) \quad (5-31c)$$

$$D = \left(\frac{w_R}{w_T} \right)^2 \quad (5-31d)$$

$$F = 2 \cdot \frac{\Delta x}{k \cdot w_T^2} \quad (5-31e)$$

$$G = 2 \cdot \frac{\Delta z}{k \cdot w_T^2} \quad (5-31f)$$

in which k is the wave number, w_T and w_R represent the Gaussian mode field radii of the transmitting and receiving fibers, respectively. As the lateral and angular misalignments can be avoided by high resolution lithography and etching technology, the divergence induced by the longitudinal gap is the major factor to the IL. With another assumption that the input and output fibers are with same mode field radii w_0 , the loss due to the fiber separation is simplified to

$$L = -10 \log \left[\frac{4}{\left(\frac{\lambda z}{\pi w_0^2} \right)^2 + 4} \right] \quad (5-32)$$

The relationship between loss and propagation distance is simulated and plotted in Figure 5-17, which indicates that the separation between the two fibers leads to a larger loss, and this loss increases with the separation.

5.3.1.3 Loss of partial transmission

For the output 1 in Figure 5-7, the incident light flows across the first interface of the prism and goes through the second interface before being reflected by the high reflective mirror. In this case, the TIR condition is not met and the light comes out of the prism. However, only partial power is transmitted through the second interface while the other complementary part is reflected back into the prism and gets lost. The particular reflectivity and transmissivity depend on the polarization of the incident beam.

Figure 5-17 Coupling loss as a function of the transmission distance.

As shown in Figure 5-9, the electric field can be resolved into components parallel (denoted by subscript p) and perpendicular (subscript s) to the plane of incidence. The choice of the positive directions for the parallel components is indicated in Figure 5-9 and the perpendicular component is along the y direction (being visualized at right angles to the plane of the figure). The components of the corresponding magnetic vector are obtained using Maxwell's equations. According to the boundary conditions, we have,

$$E_{is} + E_{rs} = E_{ts} \quad (5-33)$$

$$H_{ip} \cos \theta_i - H_{rp} \cos \theta_i = H_{tp} \cos \theta_t \quad (5-34)$$

$$H_p = \sqrt{\frac{\epsilon}{\mu}} E_s = n \sqrt{\frac{\epsilon_0}{\mu_0}} E_s \quad (5-35)$$

Thus, Eq. (5-34) can be written as

$$n_1 E_{is} \cos \theta_i - n_1 E_{rs} \cos \theta_i = n_2 E_{ts} \cos \theta_t \quad (5-36)$$

By substituting the three electric waves,

$$\begin{aligned} E_i &= A_i \exp[-i(\omega_1 t - \vec{k}_i \cdot \vec{r})] \\ E_r &= A_r \exp[-i(\omega_1 t - \vec{k}_r \cdot \vec{r})] \\ E_t &= A_t \exp[-i(\omega_2 t - \vec{k}_t \cdot \vec{r})] \end{aligned} \quad (5-37)$$

It yields,

$$\begin{aligned} A_{is} + A_{rs} &= A_{ts} \\ \cos \theta_i \sin \theta_t (A_{is} - A_{rs}) &= A_{ts} \sin \theta_i \cos \theta_t \end{aligned} \quad (5-38)$$

Therefore, the ratios of the amplitude of the reflection over incident and the refraction over incident for s polarized wave are,

$$r_s = \frac{A_{rs}}{A_{is}} = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \quad (5-39a)$$

$$t_s = \frac{A_{ts}}{A_{is}} = \frac{2 \sin \theta_i \cos \theta_t}{\sin(\theta_i + \theta_t)} \quad (5-39b)$$

Similarly for the p polarized components, it yields,

$$r_p = \frac{A_{rp}}{A_{ip}} = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \quad (5-40a)$$

$$t_p = \frac{A_{tp}}{A_{ip}} = \frac{2 \sin \theta_i \cos \theta_t}{\sin(\theta_i + \theta_t) \cos(\theta_i - \theta_t)} \quad (5-40b)$$

Since the light intensity is given by $I = \frac{1}{2} \sqrt{\frac{\epsilon}{\mu}} |A|^2$, the amount of energy in the

primary wave which is incident on a unit area of the interface per second is

$W_i = I_i \cos \theta_i = \frac{1}{2} \sqrt{\frac{\epsilon_1}{\mu_1}} A_i^2 \cos \theta_i$. Similarly, the energies of the reflected and

transmitted waves leaving a unit area of the interface per second can be expressed as

$W_r = I_r \cos \theta_r = \frac{1}{2} \sqrt{\frac{\epsilon_1}{\mu_1}} A_r^2 \cos \theta_i$ and $W_t = I_t \cos \theta_t = \frac{1}{2} \sqrt{\frac{\epsilon_2}{\mu_2}} A_t^2 \cos \theta_t$, respectively.

Therefore, the reflectivity and transmissivity of the s and p polarized waves are,

$$R_s = \left(\frac{A_{rs}}{A_{is}} \right)^2 = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)} \quad (5-41a)$$

$$T_s = \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} \left(\frac{A_{ts}}{A_{is}} \right)^2 = \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} \frac{4 \sin^2 \theta_i \cos^2 \theta_t}{\sin^2(\theta_i + \theta_t)} \quad (5-41b)$$

$$R_p = \left(\frac{A_{rp}}{A_{ip}} \right)^2 = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad (5-42a)$$

$$T_p = \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} \left(\frac{A_{tp}}{A_{ip}} \right)^2 = \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} \frac{4 \sin^2 \theta_i \cos^2 \theta_t}{\sin^2(\theta_i + \theta_t) \cos^2(\theta_i - \theta_t)} \quad (5-42b)$$

As the first medium is the silicon and the second after the interface is air, $n_1 = 3.42$ and $n_2 = 1.0$. The transmissivity of the two components versus incident angle from 0.5° to 17° is plotted in Figure 5-18. It can be seen that there is some deviation between the two polarized components, while both have a less than 1.0 transmissivity when the incident angle is close to critical angle of 17.0° . Only 8.07% for s polarized wave and 63.40% for p polarized wave can penetrate the interface when the incident angle is 16.97° (corresponding to a refractive angle of about 86.6°). In such case, the complementary power is reflected back into the prism. Therefore, the loss due to the reflection is 10.93 dB and 1.98 dB for the s and p polarized waves, respectively.

As the transmitted power decreases rapidly when the incident angle approaches the critical angle, the loss for the output 1 is very high, especially for the s polarized component. The transmissivity of the p polarized wave approaches 1.0 at the incident angle of 16.3° , which corresponds to the Brewster angle

Figure 5-18 Transmissivity at the second interface.

angle of 16.3° , which corresponds to the Brewster angle $\theta_b = \tan^{-1}(n_2/n_1) = \tan^{-1}(1/3.42)$. The p polarized component is totally transmitted without any kind of loss in such case.

5.3.1.4 Loss of prism surface scattering

As the optical prism is obtained by using a DRIE-based process, the second surface of the prism, which is designed to provide total internal reflections for the input light, is not as smooth as an ideal mirror surface. There are two types of surface roughness that appear at the interface. The first is the surface roughness with a correlation length of $0.5\ \mu\text{m}$, which is the high frequency component of the roughness. The other type is called bumpiness, with a correlation length of $2.5\ \mu\text{m}$ [185, 186]. These imperfections dramatically degrade the reflection efficiency resulting in the back reflections and radiation loss, thereby increasing the power loss. This type of loss depends on the surface roughness, incident wavelength, polarization status of the incident light and also the incident angle. At the interface between air and prism, the rough surface makes the transmission deviate from Snell's law. A narrow distribution appears with its peak closer to the straight-through direction. The roughness may cause serious problems to the switching function as it scatters the light to different directions. At high roughness, the angular distribution of the incident light does not change significantly even though the thermal optical effect causes a small change of refractive index. The peak tends to grow and to become narrower as the angle of incidence increases [187-189]. This is because the local incident angle decreases as a result of the slope of the surface. The single-scattering tends to broaden the distribution of the transmitted light. This peak shifting affects the transmission when

the incident light is not normal to the interface. While in this specific design the incident angle is 0° at the first interface, the rough surface just broadens the transmission light. Hence, the received light at the output fiber will be sacrificed.

At the second interface where the TIR occurs, the random roughness makes the reflection and transmission power deviate from those of a perfect surface. When the incident light is switched to the output 2 by the TIR, the backscattering occurs in the angular distribution of mean reflected intensity. As the TIR appears only for angles above the critical value, the backscattering at the silicon-air interface is critical and disappears rapidly with the increase of incident angle. This decrease is much faster than that in metals. This phenomenon is not only related to the shadowing from ridges but also depends on the selective reflectivity.

Let the height of a rough surface of various points be a function denoted by D . It separates the two media with different properties as shown in Figure 5-19. The surface geometry is illustrated by $z = D(x)$, above which the permittivity is greater than the lower rarer medium whose refractive index is equal to 1.0.

The incident light is impinged onto the surface with an incident angle of θ_0 with the normal to the average plane of the surface. The direction of the normal is along the z axis. The incident, reflected and refracted wave vectors are K_0 , K_r , and K_t , respectively. They are expressed as

$$\begin{aligned} K_0 = K_r &= \frac{2\pi n}{\lambda} = nk_0 \\ K_t &= \frac{2\pi}{\lambda} = k_0 \end{aligned} \quad (5-43)$$

where λ is the wavelength of the light. These wave vectors can be rewritten in a Cartesian system of coordinates in the form

Figure 5-19 Illustration of the rough surface.

$$\begin{aligned}
 K_0 &\equiv nk_0(\sin \theta_0, 0, -\cos \theta_0) \\
 K_r &\equiv nk_0(\sin \theta_r, 0, \cos \theta_r) \\
 K_t &= k_0(\sin \theta_t, 0, -\cos \theta_t)
 \end{aligned}
 \tag{5-44}$$

There is no cross polarization for either the s or p polarized wave as the surface is assumed as a function of the x coordinate [190]. The TE wave is incident on to the surface represented by the electric field as

$$E^i(\mathbf{r}) = jE^i \exp(i\vec{K}_0 \cdot \vec{r}) \tag{5-45}$$

where $\vec{r} = (x, z)$, j is the unit vector along y direction and E^i is the amplitude of the field. The reflectivity at the TIR interface is the power received over the initial power around the entire surface expressed as

$$R = \frac{1}{I_0} \int_{-\pi/2}^{\pi/2} \langle I^r(\theta) \rangle d\theta = \frac{1}{I_0} \int_{-\pi/2}^{\pi/2} \langle |E^r(r, \theta)|^2 \rangle d\theta \tag{5-46}$$

where $\langle I^r(\theta) \rangle$ is the angular distributions of the mean scattered power and I_0 is the total initial power of the incident wave which is proportional to square of the incident electric field over all the illuminated surface, $I_0 \propto |E^i|^2 L \cos \theta_0$. The reflected electric

field $E^r(r, \theta)$ is a function of the surface morphology and the wave vectors. The far-zone scattered field relative to the angular distribution is expressed [191, 192] as

$$E^r(r, \theta) = \frac{e^{i(kr - \pi/4)}}{2\sqrt{2\pi kr}} \int_{-\infty}^{\infty} \{k[\cos \theta - D'(x)\sin \theta]E(x) - iF(x)\} \exp(-i\vec{K}_r \cdot \vec{r}') dx \quad (5-47)$$

in which $E(x)$ and $F(x)$ are source functions, which can be obtained using the non-local boundary conditions on the surface for the field and its normal derivative based on the theory given in [191, 192].

$$E(x) = E^i[x, D(x)] + \frac{1}{4\pi} \int_{-\infty}^{+\infty} \left\{ E(x') \left[\frac{\partial G_0}{\partial z'} - D'(x') \frac{\partial G_0}{\partial x'} \right] - G_0 F(x') \right\} dx' \quad (5-48)$$

$$0 = -\frac{1}{4\pi} \int_{-\infty}^{+\infty} \left\{ E(x') \left[\frac{\partial G}{\partial z'} - D'(x') \frac{\partial G}{\partial x'} \right] - GF(x') \right\} dx' \quad (5-49)$$

where G_0 and G are Green functions in the two media expressed by the outgoing cylindrical wave,

$$G_0(\vec{r}, \vec{r}') = \pi H_0^1(nk|\vec{r} - \vec{r}'|) \quad (5-50)$$

$$G(\vec{r}, \vec{r}') = \pi H_0^1(k|\vec{r} - \vec{r}'|) \quad (5-51)$$

in which H_0^1 is the first kind and zero order [190]. According to the boundary conditions, the source functions should obey the equations below,

$$E(x) = E^{out}(x, D(x)) = E^{in}(x, D(x)) \quad (5-52)$$

$$F(x) = \gamma \left(\frac{\partial E^{out}(\vec{r})}{\partial n} \right)_{z=D^+(x)} = \gamma \left(\frac{\partial E^{out}(\vec{r})}{\partial n} \right)_{z=D^-(x)} \quad (5-53)$$

The superscript *out* and *in* represent the two different media with refractive index of n and 1, respectively, while the + and - stand for the limit approaching the interface from dense medium ($z > D(x)$) and from rare medium ($z < D(x)$). These two

Figure 5-20 Insertion loss due to the surface roughness

equations indicate the continuity of the tangential and normal components of the field

and γ is defined as $\gamma = \sqrt{1 + (D'(x))^2}$.

The insertion loss due to the rough surface is calculated by substituting these equations into the reflectivity Eq. (5-46). Combining the definition of the loss, it has

$$IL_{\text{roughsurface}} = -10 \log R \quad (5-54)$$

The simulation of this kind of loss is shown in Figure 5-20 as a function of the surface roughness. For a perfect surface, the scattering loss is 0. At 80 nm RMS roughness, the loss is increased to about 2.0 dB. Further increase of the roughness results in larger loss. At 300 nm, the loss becomes 25.0 dB.

5.3.1.5 Loss of F-P cavity effect

At the TIR state, the optical beam impinges at the first interface normally and reflected by the second TIR surface, and lastly, the signal is transmitted out of the prism from the third boundary. The optical path is illustrated in Figure 5-21 (a) with

the equivalent schematic as shown in Figure 5-21 (b). Thus, a Fabry-Perot (F-P) cavity is formed. Due to the filtering property of the F-P cavity, the transmitted power is a function of the cavity length (or equivalently, the wavelength).

The transmittance and reflectance as the function of the incident angle, thickness of the prism, surface reflectivity are expressed as

$$T = \frac{I_t}{I_{in}} = \frac{(1 - R_1)(1 - R_2)}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cos \delta} \quad (5-55)$$

$$R = \frac{I_r}{I_{in}} = \frac{R_1 + R_2 - 2\sqrt{R_1 R_2} \cos \delta}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cos \delta}$$

where δ is the phase difference of adjacent reflections and expressed as

$$\delta = \frac{4\pi L n}{\lambda_0} \quad (5-56)$$

in which R_1 and R_2 are reflectivity of the two cavity surfaces, L is the cavity length, n is refractive index of the prism, and λ_0 is the wavelength in free space.

Figure 5-21 Schematic view of F-P cavity for the reflected output: (a) optical beam path, (b) equivalent model of F-P cavity.

The reflectivity of the two surfaces of the cavity is about 0.3 as a result of the Fresnel reflection. The cavity length is about 60.0 μm and the refractive index of the silicon prism is 3.42 for wavelength of 1.55 μm at room temperature. By substituting these constants into Eq. (5-55) and (5-56), the transmittance of the equivalent cavity versus the different incident wavelengths is plotted in Figure 5-22. It is clearly shown that for a different wavelength, the transmitted power is different.

Figure 5-22 Transmittance of the F-P cavity at different wavelengths.

Figure 5-23 Insertion loss due to the cavity effect.

Hence, the loss due to the cavity effect is expressed as

$$IL_{cavity} = -10 * \log T \quad (5-57)$$

The relationship between loss due to F-P cavity effect and the incident wavelength is simulated and plotted in Figure 5-24. The insertion loss for 1550 nm is about 5.33 dB. However, this loss can be suppressed by adjusting the cavity length or increasing the reflectivity of the surface by using anti-reflection coatings onto the interfaces.

5.3.1.6 Loss of mirror scattering

Total reflection is the ideal case for a perfect mirror surface with its ideal smooth surface without any absorption or scattering. However, the micromirror is obtained by deep etching and metal coating. Scattering must occur that induces the loss of power and the quantity relies on the surface roughness, incident wavelength and incident angle. The total integrated scatter is employed to measure the fractional scattered power from an ideally smooth, clean, and conducting surface. The scattered power due to the surface roughness is expressed as

$$\eta = 1 - \exp \left[- \left(\frac{4\pi\sigma \cos \theta_i}{\lambda} \right)^2 \right] \quad (5-58)$$

where η is the scattering percentage, σ is the RMS roughness of the mirror surface, θ_i is the incident angle, and λ is the light wavelength. The scattering power percentage due to the mirror surface roughness for different wavelength from 1540 nm to 1620 nm is plotted in Figure 5-24 where the incident angle is fixed at 45°.

It is observed that the roughness of the mirror should be less than 56.60 nm for the 1550 nm wavelength in order to realize a less than 10% scattering loss (or 0.46 dB

loss). It also proves that the effect of the wavelength on the scattering power is almost negligible compared to the effect of the roughness.

Figure 5-24 Scattered power due to surface roughness for various wavelengths.

Figure 5-25 Scattered power percentage due to the different incident angles.

Another variable that affects the loss is the incident angle. Though the designed value is close to 45° , any fabrication tolerance leads to extra loss. The effect is illustrated by Figure 5-25 with the assumption of the RMS roughness and the wavelength being 60 nm and 1550 nm, respectively. It indicates that the smaller the incident angle, the higher is the scattered power. At an incident angle of 45° , about 11.16% of the power is scattered, corresponding to a loss of 0.51 dB, while at 0° , it is 21.3 % (about 1.0 dB). Therefore, the surface roughness after the fabrication is a key concern for the realization of a low loss switch.

5.3.2 Polarization dependent loss (PDL)

The polarization dependent loss (PDL) is the power difference among various polarization states. For the thermo-optic effect based optical switch, the various interfaces of free space and prism will lead to different PDL.

For the output 1, the incident light impinges onto the first interface and the two s and p polarized components will be transmitted into the prism with different percentage. As expressed by Eq. (5-41b) and (5-42b), the transmissivity is a function of the incident angle and the refractive indices of the two media. Fortunately, the distinction between parallel and perpendicular components disappears for normal incidence, which is the case in this study. Their transmissivity is equal to

$$T = \frac{4n}{(n+1)^2} = 0.70 \quad (5-59)$$

For the second interface, a large PDL is introduced as shown in Figure 5-18 where the maximum PDL of 5.95 dB occurs at the incident angle of 16.5° . The PDL for the incident angle of 16.96° (the design value of this switch) is

$$PDL = -10(\log T_s - \log T_p)_{\theta_i=16.96^\circ} = 8.95 \text{ dB} \quad (5-60)$$

However, for the alternative state of the switch, the PDL is different. The first and third interfaces do not give any contribution as the incident angles at the two interfaces are 90° , while total internal reflection occurs at the second interface. The reflectivities for the s and p components are

$$\begin{aligned} R_s &= \left(\frac{A_{rs}}{A_{is}} \right) = \frac{n^2 \cos \theta_i - i\sqrt{\sin^2 \theta_i - n^2}}{n^2 \cos \theta_i + i\sqrt{\sin^2 \theta_i - n^2}} \\ R_p &= \left(\frac{A_{rp}}{A_{ip}} \right) = \frac{\cos \theta_i - i\sqrt{\sin^2 \theta_i - n^2}}{\cos \theta_i + i\sqrt{\sin^2 \theta_i - n^2}} \end{aligned} \quad (5-61)$$

As the light is totally reflected, the reflected intensity is equal to the incident light. Therefore, the PDL is 0.0 dB.

5.3.3 Cross-talk of the optical switch

The cross-talk from output 2 to output 1 is negligible as the power at the second interface is totally reflected into the output 2 and the power transmitted into the output 1 is so small so that it can be neglected (see Figures (5-6) and (5-7)). However, when output 1 is selected, a portion of the incident light is reflected at the second interface and flows across the third interface into the output 2 and, therefore, the cross-talk takes place. This cross-talk depends on the polarization state of the incident light. According to Eqs. (5-29a) and (5-30a), the two different components have different reflectivities as illustrated in Figure 5-26. When the incident angle is 16° , the reflectivity is 66.5% and 0.7% for the s and p polarized components, respectively. Therefore, for the parallel component, the cross-talk can be ignored. However, for perpendicular component, the cross-talk is as large as 1.77 dB.

Figure 5-26 Reflectivity of p and s polarized beam vs. incident angle.

Figure 5-27 SEM micrograph of the silicon prism.

5.4 Experimental results and discussions

The SEM micrograph of the fabricated prism is shown in Figure 5-27. To investigate the performances, the optical switch is experimentally investigated. A near-infrared single-wavelength laser light source provides the signal with a wavelength of 1550 nm and a power of 2.54 mW. This optical beam is shined at a normal angle onto the first interface of the prism from the free space after passing

through the polarization controller. Two sensitive photodetectors (PDs) are employed to detect the powers at the two outputs for measuring the insertion loss and the cross-talk. Two current sources are used to inject current to the thermal actuator to fine tune the initial orientation of the prism to meet the total internal reflection criteria. To heat and cool the switch, a thermal electric cooler (TEC) with dimension of $3 \times 3 \times 1$ mm is stuck beneath the optical switch by a thermal conductive tape to prove the concept of the switch though the localized heating can be realized by the switch itself. The power consumption of the temperature adjustment is less than 3.6 W. Because the thermal actuator is one element of the switch for accurately adjust the incident angle of the prism, it can be used to inject current through the prism in order to tailor the local temperature of the prism as well. Two imaging methods are employed in the setup. One is a visible-light CCD to precisely align the switch and the input and output fibers. Another camera is a sensitive infrared (IR) camera to visualize the infrared power distribution and the switching function.

5.4.1 Measurement results and discussions

5.4.1.1 Switching through changing the incident angle

Firstly, the performance of the prism was investigated without fiber grooves so that a wider range of incident angle is available to characterize the prism. The incident signal at the first interface of the prism is shown in Figure 5-28. As the incident angle was much smaller than the critical angle, the beam transmitted through the prism with only a small portion of Fresnel reflection. Hence, there was no signal at the two outputs at all. When the incident angle was tuned close to 16.96° , incident light was transmitted into output 1 as shown in Figure 5-29 (a). Then the light was redirected

into output 2 as the incident angle exceeded the critical angle (see Figure 5-29 (b)). This switching was obtained by tuning the incident angle. In this way, the idea of total internal reflection prism was investigated and proved. However this switching was realized by changing the incident angle in order to satisfy the switching conditions. The thermo-optic effect based TIR optical switch was next to be then investigated.

Figure 5-28 Incident light onto the prism taken by the infrared camera.

Figure 5-29 Switching between the two outputs: (a) Transmission, (b) TIR.

5.4.1.2 Thermal actuator characterization

The thermal actuator was experimentally investigated with the maximum rotation angle of 0.254° when the injected current is 20mA, which meets the requirement as analytical simulation required value of 0.25° . What is more important is the high accuracy of the rotation angle. As precise as 0.008° resolution was demonstrated as shown in Figure 5- 30.

Figure 5- 30 Rotation angle of the thermal actuator.

5.4.1.3 Switching through thermal-optic effect

When the input linearly polarized beam with a power of 2.54 mW was incident onto the first interface of the prism and the incident angle was set to be just over the critical value, the light was directed to output 2 by the total internal reflection at the second interface. The received power was $1.71\ \mu\text{W}$. Then the prism was cooled down to 10°C from the room temperature. The received power from the output 2 decreased dramatically to only $50.0\ \text{nW}$ while the power at the output 1 rose from 0 to $32.0\ \mu\text{W}$. The switching from the output 2 to the output 1 has thus been achieved.

Figure 5-31 Reflection power cycle as a function of sample temperature.

When the temperature recovered to room temperature for 20 minutes, the power at output 2 increased to 500 nW only. Further heating up to 78.6°C made the coupling power rise to 1.70 μ W. This power remained unchanged even though the temperature of the sample is later returned to room temperature. The reverse switching was obtained by increasing the device temperature. The whole sequence is plotted in Figure 5-31.

Therefore, the insertion loss of output 2 is $IL_2 = 31.72$ dB. The cross-talk from output 2 to output 1 $CT_{1,2}$ is negligible when the switch selected output 2. The insertion loss of output 1 is $IL_1 = 19.0$ dB and the cross-talk of the alternative state is $CT_{2,1} = -28.06$ dB. These properties are summarized in Table 5-3.

5.4.2 Insertion losses discussions

The insertion loss comes from the numerous contributors as discussed in section 5.3. For output channel 1, the input light, flowing across the interface of optic fiber

and free space, meets the prism at the first interface after propagating for a distance of about 60 μm in free space. Then it propagates in the prism with the divergence caused by a 30.0 μm transition distance in silicon, after which, the signal bounces to the second interface between the prism and free space before it is reflected by the fixed metal coated mirror to the output fiber 1, as schematically shown in Figure 5-32. Hence the loss comes from Fresnel reflection at the interfaces between different media, the Gaussian beam divergence after the long transmission distance, partial transmission at the second side of the prism and scattering loss as a consequence of the rough surface of the metal-coated fixed mirror.

Table 5-3 Optical properties of the optical switch

Specifications	Output1	Output 2
Insertion loss (dB)	19.0	31.72
Cross-talk (dB)	-	-28.06

Figure 5-32 Beam path from input to output 1.

There are two interfaces between free space and fiber (silica), whose refractive index is 1.4681 [192] at the fiber facets, and two interfaces between free space and the silicon prism in the beam path. According to Eq. (5-28), the Fresnel's loss is

$$IL_{Fresnel} = 2 \times (-10) \times \left\{ \log \left[1 - \left(\frac{3.42 - 1}{3.42 + 1} \right)^2 \right] + \log \left[1 - \left(\frac{1.4681 - 1}{1.4681 + 1} \right)^2 \right] \right\} = 3.41 \text{ dB}$$

The Gaussian beam along the entire optical path is schematically shown in Figure 5-33. When the incident signal comes out of the input single mode fiber, it diverges according to Eq. (5-30) to a beam waist of w_1 and a radius of the curvature of R_1 at the first boundary of the prism. After it enters the silicon prism, the beam spot expands to w_2 and R_2 at the exit surface of the prism. The beam waist at the facet of the receiving fiber is spread to w_3 after propagating in the free space by a distance of z_3 . Since the optical properties of the prism are different from those of free space, the divergence and propagation cannot be simulated using the same method. However, its effect can be equivalent to the free space because the higher refractive index n makes the optical path in silicon equal to $1/n$ of the spreading distance in silicon, as shown in Figure 5-34. The beam waist (w_1) and radius of the curvature (R_1) at the entrance and the corresponding parameters at the exit surface (w_2 and R_2) are equal for the free space and prism. Hence, a $30.0 \text{ } \mu\text{m}$ z_2 is equivalent to a length of $8.98 \text{ } \mu\text{m}$ in free space considering that the numeric apertures are the same. Therefore, the coupling loss induced by the longitudinal gap $IL_{divergence}$ is calculated according to Eq. (5-32) to be 7.60 dB. The misalignments in the lateral and angular directions also contribute to some losses.

The partial transmission gives a large loss $IL_{transmission}$, which is 10.93 dB for the s polarized beam and 1.98 dB for the p polarized beam, respectively. Another source of

loss is the reflective mirror, which contributes a loss $IL_{mirror} = 0.34$ dB. Therefore, the total insertion loss is the sum of all these factors,

$$\begin{aligned}
 IL_1 &= IL_{Fresnel} + IL_{divergence} + IL_{transmission} + IL_{mirror} \\
 &= \begin{cases} 22.28 \text{ dB} & \text{for } s \text{ polarized wave} \\ 13.33 \text{ dB} & \text{for } p \text{ polarized wave} \end{cases}
 \end{aligned}$$

For the alternative output, TIR output 2, the sources of insertion loss are different from the above discussion. Besides the same Fresnel loss and similar Gaussian beam divergent loss with different propagation distance, a large portion of the optical losses results from the roughness at the second total internal reflection surface and the F-P cavity effect. The optical path is schematically shown in Figure 5-35, where the optical longitudinal distance is $60 + 60 + (30.0 + 30.0 + 0.775)/3.42 = 137.77$ μm , leading to the loss of 4.12 dB according to Eq. (5-32).

Figure 5-33 Gaussian beam divergence in the beam path.

Figure 5-34 Equivalent optical path.

Figure 5-35 Optical path of the alternative state.

Though the root mean square (RMS) roughness of the second interface is only about 60 nm, especially for the middle part is as smooth as 20 nm after the deep RIE etching, the localized etching scallops and vertical etching lines make the total insertion loss condition fail. Thus, the insertion loss $IL_{roughness}$ is about 10.10 dB as discussed in section 5.3.1.3. The last major loss is the cavity effect of 5.33 dB for 1550 nm incident light. Therefore, the total insertion loss is

$$IL_2 = IL_{Fresnel} + IL_{divergence} + IL_{roughness} + IL_{cavity} = 22.96 \text{ dB}$$

These estimated insertion losses are slightly smaller than the experimental results listed in Table 5-3. The discrepancy may come from the rough surfaces of the prism and the lateral and angular misalignment between the input and output fibers.

5.4.3 Cross-talk Discussion

When output 1 is selected, the incident light transmits through the prism. However, at the second interface of the prism, a portion of the incident power is reflected back to the prism, which is especially significant for the *s* polarized wave as discussed in 5.3.3. Only about 70% of the reflected beam can pass through the third interface of the prism because of the Fresnel reflection. Hence, the cross-talk is dependent not only on the polarization state of the incident light but also on the incident angle, as shown in Figure 5-36. It is observed that the cross-talk is positive for the *s* polarized component when the incident angle is greater than 15.26°. This is the natural result of a reflection larger than the transmission. However, for the parallel component, the cross-talk is always negative, implying that the transmitted power always remains larger than the reflected power. In this study, the theoretical cross-talk

Figure 5-36 Cross-talk as a function of incident angle and polarization state.

is -28.20 dB for the p polarized wave when the incident angle is about 16.15° for the 1550 nm wavelength, which is consistent with the measurement result of -28.06 dB.

The cross-talk of the other state is negligible because almost the entire input is reflected to output 2 despite of its the rough surface. The scattered local light is either reflected back into the prism or transmitted into the free space through the prism, while the scattering angle is broad and random. Therefore, the power coupled into the output 1 is very small and the cross-talk from output 2 to output 1 is negligible.

5.5 Summary

This chapter has presented the physical study, architecture design and experimental results of a novel thermo-optic switch that utilizes total internal reflection. The optical switch consists of a silicon prism finely tuned by two MEMS thermal actuators, and the input and output optical fibers. There are two alternative states of the switch. One is the transmission state, in which the incident light passes through the prism from the first interface to the second one with a very large refractive angle. The other state is the reflection state, in which the incident beam is totally reflected by the second interface of the prism as a consequence of the increased refractive index of the prism. The refractive index of the prism is changed through the thermo-optic effect of silicon by tailoring the temperature of the prism. This optical switch is fabricated using DRIE process. It demonstrates the switching function with insertion losses of 19.0 dB and 31.72 dB for the transmission and reflection outputs, respectively. The cross-talks are -28.06 dB from the transmission to the reflection and negligibly small from the reflection to the transmission. The measurement results are consistent with the theoretical simulation results within the experimental tolerance.

Although the insertion loss, polarization dependence loss and the cross-talk are relatively large in the current work, this optical switch demonstrates special advantages over the conventional micromechanical switches as mechanical movement and is not required and is hence more reliable. The actuators make it convenient to finely adjust the position and angle of the prism.

CHAPTER SIX

CONCLUDING REMARKS

6.1 Conclusions

Three main aspects of a MEMS optical switch have been developed in this study. First, a stable actuator with large displacement has been theoretically analyzed and experimentally measured. Second, a DRIE fabrication technology with special reference to SOI substrate has been carefully investigated. Third, a total internal reflection (TIR) thermo-optic (TO) switch has been explored and experimentally proved. The major conclusions from this study are summarized as follows:

In the *actuator* study, a *compliant microstructure* that incorporates with comb-drive has been designed, modeled, fabricated and measured. This compliant structure provides a large ratio of output to input displacement. The simulation showed that the ratio can be as high as 100 and the output motion direction can be altered by the

design. The microbeam bifurcation effect was numerically simulated and used for self-limitation. The concept has been proven by optimizing the configuration that was fabricated using the DRIE process developed in this study. The experiments verified that the effective displacement amplification of 54.2 times was obtained when the input displacement was only $0.96\text{ }\mu\text{m}$ while the output displacement reached $52.0\text{ }\mu\text{m}$ and was stabilized by the bifurcation effect. The resonant frequency of this actuator was 2.395 kHz.

In the study on the *actuator*, the influence of the *fabrication tolerances* including sloped profile of the comb fingers and compliant microbeams, uneven depth of different portions of individual comb fingers, and undercuts for the microbeams have been analyzed. These models show that outwards comb fingers combined with inwards compliant beams gave a larger displacement ratio because a greater electrostatic force was generated and a softer suspension was provided. The electrostatic force increased by 1.716 times when the comb finger had an angle of $+1.0^\circ$ and the output displacement deviated by 56% from the designed value when the beams had a tapered angle of -1.0° . The uneven depth comb finger led to a jitter when the displacement of the input equaled the original overlap length. The driving force decreased with the rise in the undercut of comb fingers because of the reduced capacitance. When the undercut was $0.1\text{ }\mu\text{m}$, the force generated was only 92.6% of the corresponding designed value, while the undercut of the compliant beams increased the effective amplification due to the softer system. These models are an important guide for designing a predictable device by compensating the fabrication tolerances at the design stage.

In the *deep reactive ion etching fabrication* study, the principle of DRIE ICP process was explained followed by a discussion on the effects of numerous fabrication parameters on the process in terms of etch rate, etch profile and etch selectivity that have been proven by the experimental results. Then the loading effect in terms of local trench width, overall trench distribution and exposal area has been studied. Additionally, the relationship between the beam profile and the feature design has also been experimentally demonstrated. All these provide good guidance in designing a reliable and predictable device and system.

The important – and even applicability – of the *notching effect* is emphasized from the fabrication point of view. The mechanisms of the lateral etching were explained and different factors that affected the notching were analyzed, especially in terms of over-etch time and trench width. Based on this study, a novel spacer oxide thin film technique has been developed to eliminate the commonly observed notching problem in an SOI substrate-based fabrication. More importantly, the lateral etching could be tailored for a reliable and adjustable dry release in order to prevent the stiction issue caused by wet release and rinse. This process is a universal approach which is not only suitable for optical devices fabrication, but also applicable for other types of MEMS devices.

In the study on total internal reflection (TIR) *thermo-optic (TO) switch*, the physics of the thermo-optic effect of silicon and the total internal reflection have both been thoroughly investigated. Based on these principles, the architecture of the switch

including key optical component of silicon prism, thermal actuator and optical fiber grooves have been designed. This robust thermo-optic switch has the advantage of fine tuning and batch precise fabrication in MEMS technology. The optical performances of the switch were theoretically investigated by employing electromagnetic wave theory and Maxwell's equations. The optical insertion losses caused by various mechanisms, such as Fresnel reflection, beam divergence, partial transmission at the TIR surface, F-P cavity effect, and loss due to surface roughness, have been analyzed. The polarization dependent loss (PDL) was simulated as a function of incident angle at two different states. At the reflection state, PDL was 0 dB while it was about 8.95 dB at the transmission state when the incident angle was 16.96° . The refractive index dispersion of silicon vs. wavelength has been compensated by using MEMS thermal actuators. The optical cross-talk between the two alternative outputs was studied by separately analyzing the *s* and *p* polarization components.

This *TIA thermo-optic switch* has been fabricated by using a DRIE process and the concept was proven for the first time. The insertion loss at the transmission state was 19.0 dB while it was 31.72 dB at the alternative TIR state. These insertion losses are explained by the theoretical simulation of various sources of loss. The optical cross-talk from TIR to transmission output was negligible, but the leakage from the transmission to the TIR output was -28.06 dB due to partial transmission where the complementary portion was directed to the TIR channel.

6.2 Recommendations

Based on this study, recommendations for future research are summarized as follows.

The TIR prism optical switch based on the TO effect is significant because it utilizes the merits of different technologies and physics. However, there is still room to improve the performances by making use of different physical principles. Since the prism material is also photonic activated, it can be triggered directly by a high power density laser. Optic nonlinear effect, such as single-photon absorption, two-photon absorption (TPA), multi-photon absorption, and/or Kerr effect can be explored to change the refractive index of the prism because the effective area is small which makes local refractive index tuning possible. In this way, the switching can be speeded up from milli-second to pico-second.

It may be meaningful to introduce new technologies into the MEMS optical systems to address the existing problems. Coupling is always a concern for the free space optical systems as it constraints the expansion of the optical switch matrix, deteriorates the coupling efficiency between the light source, and limits the tuning range and output power of a MEMS tunable laser. A possible solution is to introduce photonic crystal technology which can confine the optical beam in two dimensions and allow the signal to propagate along other targeted directions. However, the nano-feature fabrication is still a challenge even though new techniques are being developed. Additionally, the problem of how to efficiently couple the power from a single mode fiber to the photonic crystal structures is also not addressed successfully.

Another exploration is to integrate silicon or organic waveguides with the MEMS optical devices.

The fabrication process that has been developed in this study plays a crucial role in providing a universal platform to fabricate various types of optical devices. It can be used to obtain optical switches, variable optical attenuators, tunable lasers, tunable filters and controllable couplers. Therefore, the next phase is to investigate into the possible process techniques that satisfy the particular requirements of various components and to realize photonic integrated circuits (PIC) by integrating MEMS technology with other techniques. In this way, all devices can be self-aligned with high precision without the need for manual assembly.

The package for the MEMS devices and system is always a bottleneck that hinders the usage of this technique. Therefore, it is urgent to address the packaging issues. Utilizing the advantage of both integrated electric circuit and MEMS with a reliable and compatible process is interesting and challenging. Also, there is plenty of room in the theoretical study and new applications of the optical MEMS devices, such as display, IR imagers, spectrometers, bar code readers, maskless lithography, adaptive optics and automotive head up display and bioimaging systems.

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APPENDIX I LINEAR AMPLIFICATION

As Eqs. (4-2) to (4-4) expressed, the internal forces and moments are the function of the configuration of the compliant structure and the external applied force,

$$N_1 = F_1 \sin \alpha - \frac{F}{2} \cos \alpha \quad (4-2a)$$

$$M_1 = M_a + F_1 \cos \alpha \cdot x + \frac{F}{2} \sin \alpha \cdot x \quad (4-2b)$$

$$\frac{\partial N_1}{\partial F_1} = \sin \alpha, \quad \frac{\partial N_1}{\partial F} = -\frac{1}{2} \cos \alpha \quad (4-2c)$$

$$\frac{\partial M_1}{\partial M_a} = 1, \quad \frac{\partial M_1}{\partial F} = \frac{1}{2} \sin \alpha \cdot x, \quad \frac{\partial M_1}{\partial F_1} = \cos \alpha \cdot x \quad (4-2d)$$

$$N_2 = F_2 \sin \beta \quad (4-3a)$$

$$M_2 = M_b - F_2 \cos \beta \cdot x \quad (4-3b)$$

$$\frac{\partial N_2}{\partial F_2} = \sin \beta \quad (4-3c)$$

$$\frac{\partial M_2}{\partial M_b} = 1, \quad \frac{\partial M_2}{\partial F_2} = -\cos \beta \cdot x \quad (4-3d)$$

$$N_3 = \frac{F}{2} \cos \gamma - F_1 \sin \gamma - F_2 \sin \gamma \quad (4-4a)$$

$$\begin{aligned} M_3 = & M_a + M_b + \frac{F}{2} l_1 \sin \alpha - F_2 l_2 \cos \beta \\ & + F_1 l_1 \cos \alpha - \frac{F}{2} \sin \gamma \cdot x - (F_1 + F_2) \cos \gamma \cdot x \end{aligned} \quad (4-4b)$$

$$\frac{\partial N_3}{\partial F} = \frac{1}{2} \cos \gamma, \quad \frac{\partial N_3}{\partial F_1} = -\sin \gamma, \quad \frac{\partial N_3}{\partial F_2} = -\sin \gamma \quad (4-4c)$$

Appendix I

$$\begin{aligned}
\frac{\partial M_3}{\partial F_1} &= l_1 \cos \alpha - \cos \gamma \cdot x \\
\frac{\partial M_3}{\partial F_2} &= -l_2 \cos \beta - \cos \gamma \cdot x \\
\frac{\partial M_3}{\partial F} &= \frac{1}{2} l_1 \sin \alpha - \frac{1}{2} \sin \gamma \cdot x
\end{aligned} \tag{4-4d}$$

The relationship between the generalized reaction force and the external force is expressed by Eq. (4-8).

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ F_2 \\ M_a \\ M_b \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \end{bmatrix} \tag{4-8}$$

To obtain the elements of the coefficient matrix $[C]$ that are the functions of the geometric configurations and the structure stiffness of the beam system and the column matrix $\{D\}$ which depends on the external loading force F , the boundary conditions are employed

$$\frac{\partial U}{\partial F_m} = 0 \text{ and } \frac{\partial U}{\partial M_n} = 0 \tag{4-7}$$

Therefore,

$$\begin{aligned}
\frac{\partial U}{\partial F_1} &= \frac{1}{EA_1} \int_0^{l_1} \left(F_1 \sin \alpha - \frac{F}{2} \cos \alpha \right) \sin \alpha \cdot dx \\
&+ \frac{1}{EI_1} \int_0^{l_1} \left(M_a + F_1 \cos \alpha \cdot x + \frac{F}{2} \sin \alpha \cdot x \right) \cdot x \cdot \cos \alpha \cdot dx \\
&+ \frac{1}{EA_2} \int_0^{l_1} 0 \cdot dx + \frac{1}{EI_2} \int_0^{l_2} M_2 \frac{\partial M_2}{\partial F_1} dx \\
&+ \frac{1}{EA_3} \int_0^{l_3} \left(\frac{F}{2} \cos \gamma - F_1 \sin \gamma - F_2 \sin \gamma \right) (-\sin \gamma) dx \\
&+ \frac{1}{EI_3} \int_0^{l_3} \left(M_a + M_b + \frac{F}{2} l_1 \sin \alpha - F_2 l_2 \cos \beta + F_1 l_1 \cos \alpha - \frac{F}{2} x \cdot \sin \gamma \right. \\
&\quad \left. - F_1 x \cos \gamma - F_2 x \cos \gamma \right) \cdot (l_1 \cos \alpha - x \cos \gamma) \cdot dx
\end{aligned} \tag{A1-1}$$

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$$\begin{aligned}
&= \frac{1}{EA_1} \left[F_1 \sin^2 \alpha l_1 - \frac{F}{2} l_1 \cos \alpha \sin \alpha \right] \\
&+ \frac{1}{EI_1} \left[\frac{l_1^2}{2} M_a \cos \alpha + \frac{l_1^3}{3} F_1 \cos^2 \alpha + \frac{l_1^3}{6} F \sin \alpha \cos \alpha \right] \\
&+ \frac{1}{EA_3} \left[-\frac{F}{2} l_3 \cos \gamma \sin \gamma + F_1 l_3 \sin^2 \gamma + F_2 l_3 \sin^2 \gamma \right] \\
&+ \frac{1}{EI_3} \left[l_1 l_3 M_a \cos \alpha + l_1 l_3 M_b \cos \alpha + \frac{F}{2} l_1^2 l_3 \sin \alpha \cos \alpha - F_2 l_1 l_2 l_3 \cos \alpha \cos \beta \right. \\
&+ F_1 l_1^2 l_3 \cos^2 \alpha - \frac{F}{4} l_1 l_3^2 \sin \gamma \cos \alpha - \frac{l_1 l_3^2}{2} F_1 \cos \gamma \cos \alpha - \frac{l_1 l_3^2}{2} F_2 \cos \gamma \cos \alpha \\
&- \frac{l_3^2}{2} M_a \cos \gamma - \frac{l_3^2}{2} M_b \cos \gamma - \frac{F}{4} l_1 l_3^2 \sin \alpha \cos \gamma + \frac{1}{2} F_2 l_2 l_3^2 \cos \gamma \cos \beta \\
&- \left. \frac{1}{2} F_1 l_3^2 l_1 \cos \alpha \cos \gamma + \frac{F}{6} l_3^3 \sin \gamma \cos \gamma + \frac{1}{3} F_1 l_3^3 \cos^2 \gamma + \frac{F_2}{3} l_3^3 \cos^2 \gamma \right] \\
&= 0
\end{aligned}$$

Thus,

$$\begin{aligned}
C_{11} &= \frac{L_1}{A_1} \sin^2 \alpha + \frac{L_3}{A_3} \sin^2 \gamma + \frac{L_1^3}{3I_1} \cos^2 \alpha + \frac{L_1^2 L_3}{I_3} \cos^2 \alpha \\
&- \frac{L_1 L_3^2}{I_3} \cos \alpha \cos \gamma + \frac{L_3^3}{3I_3} \cos^2 \gamma
\end{aligned} \tag{A1-2}$$

$$\begin{aligned}
C_{12} &= \frac{L_3}{A_3} \sin^2 \gamma - \frac{L_1 L_2 L_3}{I_3} \cos \alpha \cos \beta - \frac{L_1 L_3^2}{2I_3} \cos \alpha \cos \gamma \\
&+ \frac{L_2 L_3^2}{2I_3} \cos \beta \cos \gamma + \frac{L_3^3}{3I_3} \cos^2 \gamma
\end{aligned} \tag{A1-3}$$

$$C_{13} = \frac{L_1^2}{2I_1} \cos \alpha + \frac{L_1 L_3}{I_3} \cos \alpha - \frac{L_3^2}{2I_3} \cos \gamma \tag{A1-4}$$

$$C_{14} = \frac{L_1 L_3}{I_3} \cos \alpha - \frac{L_3^2}{2I_3} \cos \gamma \tag{A1-5}$$

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$$D_1 = \left(\frac{L_1}{2A_1} \sin \alpha \cos \alpha + \frac{L_3}{2A_3} \sin \gamma \cos \gamma - \frac{L_1^3}{6I_1} \sin \alpha \cos \alpha - \frac{L_1^2 L_3}{2I_3} \sin \alpha \cos \alpha \right. \\ \left. + \frac{L_1 L_3^2}{4I_3} \cos \alpha \sin \gamma + \frac{L_1 L_3^2}{4I_3} \cos \gamma \sin \alpha - \frac{L_3^3}{6I_3} \cos \gamma \sin \gamma \right) F \quad (A1-6)$$

$$\begin{aligned} \frac{\partial U}{\partial F_2} &= 0 \\ &= \frac{1}{EA_2} \int_0^{l_2} F_2 \sin^2 \beta \cdot dx + \frac{-1}{EI_2} \int_0^{l_2} (M_b - F_2 \cos \beta \cdot x) \cdot x \cdot \cos \beta \cdot dx \\ &\quad + \frac{1}{EA_3} \int_0^{l_3} \left(\frac{F}{2} \cos \gamma - F_1 \sin \gamma - F_2 \sin \gamma \right) \cdot (-\sin \gamma) \cdot dx \\ &\quad + \frac{1}{EI_3} \int_0^{l_3} \left(M_a + M_b + \frac{F}{2} l_1 \sin \alpha - F_2 l_2 \cos \beta + F_1 l_1 \cos \alpha - \frac{F}{2} x \cdot \sin \gamma \right. \\ &\quad \left. - F_1 x \cos \gamma - F_2 x \cos \gamma \right) (-l_2 \cos \beta - x \cos \gamma) \cdot dx \\ &= \frac{1}{EA_2} [F_2 \sin^2 \beta \cdot l_2] + \frac{1}{EI_2} \left[-\frac{1}{2} M_b l_2^2 \cos^2 \beta + \frac{1}{3} l_2^3 F_2 \cos^2 \beta \right] \\ &\quad + \frac{1}{EA_3} \left[-\frac{F}{2} l_3 \sin \gamma \cos \gamma + F_1 l_3 \sin^2 \gamma + F_2 l_3 \sin^2 \gamma \right] \\ &\quad + \frac{1}{EI_3} \left[-l_2 l_3 M_a \cos \beta - l_2 l_3 M_b \cos \beta - \frac{F}{2} l_1 l_2 l_3 \sin \alpha \cos \beta + F_2 l_2^2 l_3 \cos^2 \beta \right. \\ &\quad \left. - F_1 l_1 l_2 l_3 \cos \alpha \cos \beta + \frac{F}{4} l_2 l_3^2 \sin \gamma \cos \beta + \frac{l_2 l_3^2}{2} F_1 \cos \gamma \cos \beta + \frac{l_2 l_3^2}{2} F_2 \right. \\ &\quad \left. \cos \gamma \cos \beta - \frac{l_3^2}{2} M_a \cos \gamma - \frac{l_3^2}{2} M_b \cos \gamma - \frac{F}{4} l_1 l_3^2 \sin \alpha \cos \gamma + \frac{1}{2} F_2 l_2 l_3^2 \cos \gamma \cos \beta \right. \\ &\quad \left. - \frac{1}{2} F_1 l_3^2 l_1 \cos \alpha \cos \gamma + \frac{F}{6} l_3^3 \sin \gamma \cos \gamma + \frac{1}{3} F_1 l_3^3 \cos^2 \gamma + \frac{F_2}{3} l_3^3 \cos^2 \gamma \right] \\ &= 0 \end{aligned} \quad (A1-7)$$

Thus,

$$C_{21} = \frac{L_3}{A_3} \sin^2 \gamma - \frac{L_1 L_2 L_3}{I_3} \cos \alpha \cos \beta - \frac{L_1 L_3^2}{2I_3} \cos \alpha \cos \gamma \\ + \frac{L_2 L_3^2}{2I_3} \cos \beta \cos \gamma + \frac{L_3^3}{3I_3} \cos^2 \gamma \quad (A1-8)$$

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$$C_{22} = \frac{L_2}{A_2} \sin^2 \beta + \frac{L_3}{A_3} \sin^2 \gamma + \frac{L_2^3}{3I_2} \cos^2 \beta + \frac{L_2^2 L_3}{I_3} \cos^2 \beta$$
(A1-9)

$$+ \frac{L_2 L_3^2}{I_3} \cos \beta \cos \gamma + \frac{L_3^3}{3I_3} \cos^2 \gamma$$

$$C_{23} = -\frac{L_2 L_3}{I_3} \cos \beta - \frac{L_3^2}{2I_3} \cos \gamma$$
(A1-10)

$$C_{24} = -\frac{L_2 L_3}{I_3} \cos \beta - \frac{L_2^2}{2I_2} \cos \beta - \frac{L_3^2}{2I_3} \cos \gamma$$
(A1-11)

$$D_2 = \left(\frac{L_3}{2A_3} \sin \gamma \cos \gamma + \frac{L_1 L_2 L_3}{2I_3} \sin \alpha \cos \beta + \frac{L_1 L_3^2}{4I_3} \sin \alpha \cos \gamma \right. \\ \left. - \frac{L_2 L_3^2}{4I_3} \cos \beta \sin \gamma - \frac{L_3^3}{6I_3} \cos \gamma \sin \gamma \right) F$$
(A1-12)

$$\frac{\partial U}{\partial M_a} = 0$$

$$= \frac{1}{EI_1} \int_0^{l_1} \left(M_a + F_1 \cos \alpha \cdot x + \frac{F}{2} \sin \alpha \cdot x \right) dx \\ + \frac{1}{EI_3} \int_0^{l_3} \left(M_a + M_b + \frac{F}{2} l_1 \sin \alpha - F_2 l_2 \cos \beta \right.$$
(A1-13)

$$\left. + F_1 l_1 \cos \alpha - \frac{F}{2} x \cdot \sin \gamma - F_1 x \cos \gamma - F_2 x \cos \gamma \right) dx$$

$$= \frac{1}{EI_1} \left[M_a l_1 + \frac{1}{2} F_1 l_1^2 \cos \alpha + \frac{F}{4} \sin \alpha \cdot l_1^2 \right] + \frac{1}{EI_3} [M_a l_3 + M_b l_3 + \frac{F}{2} l_1 l_3 \sin \alpha \\ - F_2 l_2 l_3 \cos \beta + F_1 l_1 l_3 \cos \alpha - \frac{F}{4} l_3^2 \cdot \sin \gamma - \frac{1}{2} F_1 l_3^2 \cos \gamma - \frac{1}{2} F_2 l_3^2 \cos \gamma]$$

Thus,

$$C_{31} = \frac{L_1^2}{2I_1} \cos \alpha + \frac{L_1 L_3}{I_3} \cos \alpha - \frac{L_3^2}{2I_3} \cos \gamma$$
(A1-14)

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$$C_{32} = -\frac{L_2 L_3}{I_3} \cos \beta - \frac{L_3^2}{2I_3} \cos \gamma \quad (\text{A1-15})$$

$$C_{33} = \frac{L_1}{I_1} + \frac{L_3}{I_3} \quad (\text{A1-16})$$

$$C_{34} = \frac{L_3}{I_3} \quad (\text{A1-17})$$

$$D_3 = -\left(\frac{L_1^2}{4I_1} \sin \alpha + \frac{L_1 L_3}{2I_3} \sin \alpha - \frac{L_3^2}{4I_3} \sin \gamma\right) F \quad (\text{A1-18})$$

$$\frac{\partial U}{\partial M_b} = 0$$

$$\begin{aligned} &= \frac{1}{EI_2} \int_0^{l_2} (M_b - F_2 \cos \beta \cdot x) dx + \frac{1}{EI_3} \int_0^{l_3} (M_a + M_b + \frac{F}{2} l_1 \sin \alpha \\ &\quad - F_2 l_2 \cos \beta + F_1 l_1 \cos \alpha - \frac{F}{2} x \cdot \sin \gamma - F_1 x \cos \gamma - F_2 x \cos \gamma) dx \\ &= \frac{1}{EI_2} \left[M_b l_2 - \frac{1}{2} F_2 l_2^2 \cos \beta \right] + \frac{1}{EI_3} [M_a l_3 + M_b l_3 + \frac{F}{2} l_1 l_3 \sin \alpha \\ &\quad - F_2 l_2 l_3 \cos \beta + F_1 l_1 l_3 \cos \alpha - \frac{F}{4} l_3^2 \cdot \sin \gamma - \frac{1}{2} F_1 l_3^2 \cos \gamma - \frac{1}{2} F_2 l_3^2 \cos \gamma] \end{aligned} \quad (\text{A1-19})$$

Thus,

$$C_{41} = \frac{L_1 L_3}{I_3} \cos \alpha - \frac{L_3^2}{2I_3} \cos \gamma \quad (\text{A1-20})$$

$$C_{42} = -\frac{L_2 L_3}{I_3} \cos \beta - \frac{L_2^2}{2I_2} \cos \beta - \frac{L_3^2}{2I_3} \cos \gamma \quad (\text{A1-21})$$

$$C_{43} = \frac{L_3}{I_3} \quad (\text{A1-22})$$

$$C_{44} = \frac{L_2}{I_2} + \frac{L_3}{I_3} \quad (\text{A1-23})$$

$$D_4 = \left(\frac{L_3^2}{4I_3} \sin \gamma - \frac{L_1 L_3}{2I_3} \sin \alpha\right) F \quad (\text{A1-24})$$

APPENDIX II COMB-DRIVE

The comb-drive is using the mechanism of the plate capacitor consisting of two parallel plates, A and B , with an overlapping area of S (product of plate depth b and length y_0) and the gap of d which is d_0 at the initial position as shown in Figure A-1. Thus the capacitance is expressed as $C = A\epsilon\epsilon_0/d$. The electric energy stored in the capacitor is $E_e = A\epsilon\epsilon_0 V^2/2d$.

Figure A-1 Parallel plate capacitor

If there is an external force, the position and energy of the system will change. Two orthogonal forces, normal or tangential are possible [89].

(a) Normal force (F_n) is applied

The energy conservation equation is $F_n \Delta x + \frac{dE_e}{dx} \Delta x + \frac{dE_s}{dx} \Delta x = 0$, where E_s is the internal source energy and E_e is the electrical energy. Therefore the normal force is

$$F_n = -\frac{dE_e}{dx} - \frac{dE_s}{dx} = -\frac{A\epsilon\epsilon_0}{2x^2} V^2 \quad (\text{A2-1})$$

The negative sign indicates that the force applied to move the plate is an attractive force from the stationary electrode.

(b) Tangential force (F_t) is applied

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When a tangential force is applied, the function $F_t \Delta y + \frac{dE_e}{dy} \Delta y + \frac{dE_s}{dy} \Delta y = 0$ should be satisfied. Hence, the tangential force is

$$F_t = -\frac{b\epsilon\epsilon_0}{2d_0} V^2 \quad (\text{A2-2})$$

Therefore the ratio of the two forces at initial position is expressed as

$$\frac{F_n}{F_t} = \left(\frac{A\epsilon\epsilon_0}{2d_0^2} V^2 \right) / \left(\frac{b\epsilon\epsilon_0}{2d_0} V^2 \right) = \frac{y_0}{d_0} \quad (\text{A2-3})$$

Obviously the ratio is often much greater than 1.0 because the overlapping length y_0 is usually much larger than the gap d_0 between the two plates, thus the normal force is dominant. However, when either of the two plates is movable in the normal direction, the normal force F_n varies with the motion while the tangential force F_t is independent of the tangential movement of the plate.

The comb-drive actuator makes use of the tangential force for driving, which is independent on the tangential displacement. Though the normal force is much larger than the tangential force as discussed above, it is balanced by arranging the fixed fingers symmetrically on both sides of the each movable finger so that the normal forces from both sides cancel out by pairs. However, to get the accurate force generated by the comb-drive actuator, it is more complicated than the plate capacitor case due to the fringe effect.

When a voltage is applied to the comb fingers, the electrical field has a distribution as shown in Figure A-2 (a). All dielectric/air interfaces are modeled as equivalent magnetic walls as it is usually done in the partial capacitance technique and the electric walls are assumed at the planes of symmetry of the electric field distribution, where the field lines are normal to the electric wall. The capacitance, C of the comb structure may be approximated as the sum of the contribution of the field

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capacitance, C_u on the vertical sides of the comb fingers (see Figure A-2 (b)) and the contribution of the fringe field capacitance, C_f due to the top and bottom sides of the comb fingers (see Figure A-2 (c)).

Figure A-2 Electrical field of the comb-drive (a) Electrical field distribution of comb-drive, (b) Field distribution on the vertical sides, (c) Fringe field due to the top and bottom sides of the comb fingers

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The height of the comb fingers obtained by DRIE is so large that the field capacitance, C_u on the vertical sides of the comb fingers is the dominant part of the total capacitance, which is similar to the parallel plate capacitor except the extra capacitor between the finger tip and the comb finger. The total capacitance of the comb-drive is expressed as

$$C = \frac{2n\epsilon_0 Hx}{g} + \frac{(1 + \frac{\pi}{2})[(2n-1)b + 2w]\epsilon_0 H}{L-x} \quad (\text{A2-4})$$

where n is the number of movable comb fingers. Accordingly the number of fixed comb fingers is $n+1$, and b is the width of the comb fingers except the two utmost side fixed comb fingers whose width is w . L is the total length of the finger and x is the overlap length. The first term comes from the overlapping finger parts and the second term is the contribution of the capacitor between the tip of the comb fingers and the beam.

The electrostatic force is derived by taking differentiation of the potential energy with respect to any direction of the axis. From Eq. (A2-3), the lateral electrostatic force is determined as

$$F_x = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \left\{ \frac{n\epsilon_0 H}{g} + \frac{(1 + \frac{\pi}{2})[(2n-1)b + 2w]\epsilon_0 H}{2(L-x)^2} \right\} V^2 \quad (\text{A2-5})$$

The relationship between the electrostatic force and the overlapping distance of the comb-drive is plotted in

Figure A-3. It clearly shows that a non-linear relationship exists at the initial and final overlapping distance of the comb-drive due to the fringing electric field effect and the dominant parasitic capacitor. The driving force is constant and independent on the

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lateral displacement at the range of $0.3L < x < 0.7L$, where the tip contribution is ignorable compared to the vertical fingers and the expression of the electrostatic force is simplified as

$$F_x = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{n \epsilon_0 H}{g} V^2 \tag{A2-6}$$

Figure A-3 Relation of lateral force with overlap of the comb-driver