DESIGN AND ANALYSIS OF WAFER-LEVEL VACUUM-ENCAPSULATED DISK
RESONATOR GYROSCOPE USING A COMMERCIAL MEMS PROCESS

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ABSTRACT

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In this Thesis, the design and analysis of a mode-matched Disk Resonator Gyroscope (DRG) characterized by high Quality factor exceeding 1 million is presented. The resonator is designed using Micro Electro Mechanical Systems (MEMS) Integrated Design for Inertial Sensors (MIDIS) process offered by Teledyne DALSA Semiconductor Incorporated (TDSI). The MIDIS process offers wafer-level vacuum encapsulation at 10 mTorr and includes Through Silicon Vias(TSVs) that allows flip chip bonding with an integrated circuit for signal detection and processing. Wafer-level encapsulation with ultra-low leak rate is achieved by using MIDIS process, with leak rate as low as $6.58\text{E-}18$ atm.cm³/s. The DRG design has a circular shape of 600 μm diameter with a single crystal

silicon device layer thickness of 40 μm . The designed DRG has a resonant frequency of 277.54 kHz in drive mode and 278.30 kHz in sense mode. The frequency split between drive and sense modes is 760 Hz. A Quality factor of 1.34 million is achieved for the designed DRG.

Dedicated to my parents

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LIST OF ABBREVIATIONS

AC	Alternating Current
ARW	Angular Random Walk
CMP	Chemical Mechanical Planarization
DC	Direct Current
DOF	Degrees-of-Freedom
DRG	Disc Resonator Gyroscope
DRIE	Deep Reactive Ion Etching
FEM	Finite Element Modeling
HRG	Hemispherical Resonant Gyroscope
IMU	Inertial Measurement Unit
ISDP	In-Situ Doped Polysilicon
M ² TFG	Mode Matched Tuning Fork Gyroscope
MEMS	Micro Electro Mechanical Systems
MIDIS	MEMS Integrated Design for Inertial Sensors
PECVD	Plasma Enhanced Chemical Vapor Deposition
QMG	Quadruple Mass Gyroscope
RIE	Reactive Ion Etching
RSG	Resonator Star Gyroscope
SCS	Single Crystal Silicon
SIRU	Scalable Inertial Reference Unit
TDSI	Teledyne DALSA Semiconductor Inc.
TED	Thermoelastic Dissipation
TSVs	Through Silicon Vias

LIST OF NOTATIONS

$\vec{F}_{Coriolis}$	Coriolis force
H_2O	Water
$\vec{V}$	Velocity
$\vec{\Omega}$	Rotation rate
Ω_z	Magnitude of rotation rate along z axis
Q_{anchor}	Quality factor by considering anchor losses
Q_{gas}	Quality factor by considering air damping
$Q_{surface}$	Quality factor by considering surface losses
Q_{TED}	Quality factor by considering thermoelastic dissipation
Q_{total}	Total quality factor
f_0	Resonant frequency
f_{drive}	Drive mode frequency
f_{sense}	Sense mode frequency
k_b	Boltzmann constant
x'	Pitch axis in inertial frame of reference
y'	Roll axis in inertial frame of reference
z'	Yaw axis in inertial frame of reference
KOH	Potassium Hydroxide
Si	Silicon
SiO_2	Silicon dioxide
Δf	Bandwidth
L	Inductance
P	Pressure

Q	Quality factor
T	Temperature
V	Voltage
i	Current
m	Mass of the moving particle
n	Mode number
q	Charge of electron
x	Pitch axis in non-inertial frame of reference
y	Roll axis in non-inertial frame of reference
z	Yaw axis in non-inertial frame of reference

CHAPTER 1

INTRODUCTION

1.1 Background

Gyroscopes are sensors that detect and measure angular motion of an object relative to an inertial frame of reference. Ideally, without any influence of environmental factors like magnetism or gravity, gyroscopes can measure the complex motion and track the rate of rotation and position of a moving object. Gyroscopes are typically classified into two types depending on whether the angular velocity or angular orientation is being measured. The gyroscope output can help to determine the roll, pitch and yaw of the moving object. Thus, the two types of gyroscopes are:

- i. Rate gyroscopes: Gyroscopes that measure rate of rotation of the object or angular velocity.
- ii. Rate integrating gyroscopes: Gyroscopes that measures angular position or angular orientation of an object directly.

Gyroscopes have number of applications in consumer, aerospace and automotive markets, for example in vehicle stability control, navigation assist, roll over detection, guidance and navigation and many more applications. MEMS gyroscopes with their feature size in hundreds of micrometers have many advantages over conventional optical gyroscopes that are much larger, exceeding several centimeters. Typically, MEMS gyroscopes are rate

measuring type and are utilized for motion detection. MEMS gyroscopes are smaller in size, consume less power, and are available for lower cost. In today's market, micromachined inertial sensors are becoming popular. MEMS accelerometers and MEMS gyroscopes are commonly used to build inertial sensors. For more comprehensive measurement of motion and position of an object in space, a ten degrees-of-freedom (10-DOF) sensing microsystem comprising a three-axes accelerometer, three-axes gyroscope, three-axis magnetometer and a barometer are utilized. Here, the accelerometer measures linear motion along x , y , and z axes, while the gyroscope measures rate of rotation around these axes.

An Inertial Measurement Unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, sometimes magnetometers. Today, MEMS based 6-DOF inertial measurement units consisting of tri-axial accelerometer and tri-axial gyroscope are widely available as single-package and single-chip form. These devices can integrate both sensors and interface electronic components. These 6-DOF IMUs are used in many consumer applications like human physical activity monitoring, active stabilization in cameras, head-mounted virtual reality displays as well as industrial applications such as robotics and vibration monitoring, tracking and monitoring of mechanical shock and vibration during transportation and handling of variety of equipment. [1-4]. High performance IMUs are essential components for self-contained navigation and guidance systems in various aerospace applications. However, 6-DOF MEMS IMUs are yet to break into these high-precision navigation applications. The

limiting factor is due to lack of high accuracy MEMS gyroscopes. MEMS gyroscopes are prone to noise and bias drift when utilized for long periods of navigation.

High precision inertial sensors need an ultra-clean high vacuum environment to reduce air damping and to improve their performance. The encapsulation of gyroscopes with pressure below atmospheric pressure influences its quality factor (Q), response time, stiction, damping and humidity exposure. Quality factor indicates the ability of the mechanical resonator to retain energy during oscillation. Specifically, considering the case of high performance gyroscope to reach navigation grade performance, the Q which is directly related to the sensor sensitivity, plays a critical role. Here, mode matched gyroscopes can provide a high Q [5].

1.2 MEMS Gyroscopes

At a micro scale combining electrical and mechanical systems, MEMS led to a revolution in the development of inertial sensors. Draper laboratory in the year 1991 introduced first micromachined gyroscope shown in Figure 1.1[7]. Various micromachined gyroscope designs fabricated using techniques like surface micromachining, bulk micromachining, and hybrid surface-bulk micromachining technologies have been reported [6]. Extensive research efforts towards commercial micromachined gyroscopes led to several innovative gyroscope topologies, detection techniques, fabrication, integration approaches. Even though there are several micromachined gyroscope designs and operation principles, most of the reported micromachined gyroscopes use vibrating mechanical elements to sense angular rate based on sensing the motion due to the coriolis force. The use of vibrating elements exhibits many advantages over utilizing spinning parts. Vibrating devices have no rotating parts and therefore, eliminates the need for

bearings and other complex parts not amenable for miniaturization. That is the primary reason for miniaturizing vibratory gyroscopes using MEMS fabrication technologies which are becoming attractive compared to their macro-scale counterparts.

Micromachined vibratory gyroscopes operating principle is typically based on Coriolis effect [6] on a mass spring damping system. A proof mass is a known quantity of mass used in a measuring instrument as a reference to measure unknown quantity. Proof mass is driven by a sinusoidal electrostatic force called drive mode. The proof mass is suspended above the substrate with the help of a suspension system made with flexible beams. When an external angular velocity is applied, the Coriolis force affects the proof mass moving in a direction normal to both the driving direction and the rotation axis (sense mode). Rotation rate or angular velocity is measured by sensing the motion in sense direction. Overall, the system provides two degrees of freedom (2-DOF).

Figure 1.1: Comb drive tuning fork gyroscope by Draper lab [7]

Coriolis effect is responsible for the energy transfer from drive mode to sense mode proportional to the external angular rate applied. To attain maximum possible gain and

sensitivity it is desirable to utilize resonance in both the drive and sense modes. This can be achieved by matching the drive and sense resonant frequencies. As an alternate, the sense mode is slightly shifted from drive mode to improve robustness and thermal stability, while this design has low gain and less sensitivity. The impact of variations in oscillatory system parameters that shift the natural frequencies and damping values can be reduced by increasing spacing between drive and sense mode. Advanced control and signal processing architectures are necessary to compensate the resulting errors [8].

1.3 Operating Principle of Vibratory Gyroscopes

MEMS vibratory gyroscope operating principle relies on Coriolis effect with an energy transfer between two vibration modes [9]. A vibratory MEMS gyroscope is a resonator with drive-mode and sense-mode. Improving the performance specifications of MEMS gyroscopes such as resolution, sensitivity, and bandwidth all require a high quality factor [10-14]. Different structural designs are used depending on the target application and processing technology [15].

Figure 1.2: Coriolis force visualization with respect to inertial frame coordinates

Coriolis force is an inertial force that acts on objects that are in motion relative to a rotating reference frame. The fictitious force caused by the rotational movement in a system is the Coriolis force. Consider an object moving in x -direction as shown in Figure 1.2. When the object moving along x -direction is subjected to rotation about z -axis, the Coriolis force is exerted on the moving object along the y -direction. The exerted force direction is orthogonal to the direction of movement of the object and the rotation axis, and its amplitude is directly proportional to the velocity of the movement and rotation rate (Ω). Equation (1.1) gives the analytical representation of coriolis force,

$$\vec{F}_{Coriolis} = -2m\vec{\Omega} \times \vec{V} \quad 1.1$$

where m is mass of the moving particle, Ω and V are the rotation rate and velocity of the object, respectively.

Figure 1.3: View of vibratory gyroscope

Figure 1.3 shows theoretical model of a single z axis vibratory gyroscope consisting of a proof mass, m suspended in xy plane. The xyz non-inertial frame of reference associated with the sensor is moving relative to the inertial frame of reference $x'y'z'$ with an angular velocity, $\Omega = (0, 0, \Omega_z)$. Coriolis force between the x, y axis causes the energy exchange which is used to detect the input angular rate Ω_z .

MEMS vibratory gyroscopes have three suspended frames, drive frame, proof mass, and sense frame, that are mechanically connected through springs. The simplified view of vibratory gyroscope is shown in Figure 1.3. During gyroscope operation, the drive frame is continuously vibrated by the means of either electromagnetic, piezoelectric or electrostatic actuation mechanisms, among others [16]. To ensure proper operation of gyroscope, if the velocity of drive frame becomes zero, the coriolis force induced by rotation becomes zero. The proof mass frame vibrates along the drive and sense frame

direction to transfer the energy induced by the angular rotation rate to the sense mode. The transferred energy is proportional to the amplitude of rotation rate or angular velocity which leads to displacement at sense axis. By using different sensing mechanisms, such as piezoelectric, optical detecting, piezoresistive or capacitive [17], the displacement is detected as a rotation rate or angular velocity in the sense mode of gyroscope.

To achieve a high gain which corresponds to a high sensitivity for the gyroscope sensor, the drive and sense modes of vibratory gyroscopes are excited into resonance using sinusoidal signals. By adjusting the difference between resonance frequencies of drive and sense modes, vibratory gyroscopes are operated in mode-matched or mode-mismatched conditions. The rotation caused by coriolis energy is transferred to sense mode by vibrating the proof mass frame at drive mode resonance frequency. It is desired to operate the gyroscope in matched-mode condition where the frequency split between the resonance modes of gyroscope is 0 Hz.

Rate gyroscopes are used to measure the rate of rotation or angular velocity applied along the z axis of the sensor. The sense-mode of a rate gyroscope can be operated either in an open-loop or in a force-to-rebalance closed loop, where a feedback force is generated to suppress the sense-mode vibrations and is simultaneously used as the measure of the input rate. In our design, the electrodes sense Coriolis acceleration due to change in capacitance between the rings.

The structure of MEMS gyroscopes can be classified into two categories: degenerate mode gyroscopes and non-degenerate mode gyroscopes [9]. Degenerate mode gyroscopes are usually axis symmetrical with fundamental modes as drive and sense modes. The drive mode corresponds to sense mode and are of same order but orthogonal to each other, a

node's drive mode locate at the anti-node of sense mode and vice versa. Therefore, they are inherently matched if there are no fabrication imperfections. Non-degenerate mode gyroscopes usually contain one or more proof masses which are supported by designed tethers to allow multiple degrees of freedom. Since the tethers at drive and sense directions are different, they are not degenerate modes.

1.4 Wine Glass Modes

Typically, axis symmetric gyroscopes such as ring or disk gyroscopes utilizes wine glass modes for gyroscope operation [18]. In these modes, there are sinusoidal deformations along the radius of the structure and these deformations are characterized by mode number n depending on period of sinusoid. For axis symmetric applications, such as ring or disk gyroscopes the most commonly used resonance modes are first two wine glass modes, or so called $n = 2$ (4-node) and $n = 3$ (6-node) wineglass modes. This is done as lower order wineglass modes have higher angular gain factors and lower resonance frequencies. Each wineglass mode has two degenerate modes that are spaced at 45° for $n = 2$ wineglass modes and 30° for $n = 3$ wineglass mode. Due to standing wave pattern, the degenerate mode pair of very low fundamental frequency splits becomes indistinguishable. The coriolis input to the resonator causes the standing wave pattern to rotate at an angle proportional to the angle of rotation.

1.5 Mode Matching

Rate gyroscopes can operate either in mode matched condition [19] or mode mismatched condition [20]. In mode mismatched condition, the sense mode is at a different frequency from the drive mode operation frequency, resulting in partial energy transfer between two modes. When both drive and sense modes are matched, the coriolis signal is

amplified by both sense and drive mode quality factor and results in a higher sensitivity. Due to fabrication imperfections, the two modes can rarely match after fabrication. Hence, a tuning mechanism is required to match the two modes post-fabrication. Some mode matched MEMS gyroscopes are intentionally designed with a split between drive and sense modes, and use electrostatic spring softening for fine tuning and mode matching [10]. Rate integrating gyroscopes need mode matched condition, means the peak of one the mode needs to be within the 3 dB bandwidth of other mode. Since rate integrating gyroscopes are usually with high Q at low frequency, the bandwidth is small. Figure 1.4 shows matched mode and mismatched mode operation.

Figure 1.4: Matched mode and Mismatched mode operation

1.6 Performance Specifications

The quality of gyroscope sensors is measured by performance characters which are as follows,

- **Scale factor:** The measure of rate output voltage variation in response to an angular input rotation. Scale factor is measured in $V/(^{\circ}/S)$. The scale factor can

be measured by fitting a straight line to the input and output data using method of least squares [17].

- **Dynamic Range:** The maximum applicable input range that gyroscope responds to a rotation without losing its performance. It is measured in $\pm ^\circ/\text{S}$.
- **Resolution:** The minimum change in input that will result in a change in output. The resolution can be determined by measuring the standard deviation of white noise. It is measured in $^\circ/\text{S}/\sqrt{\text{Hz}}$.
- **Drift Rate:** The output of a gyroscope is subject to a slowly changing random function that is independent of input angular rate. The drift rate is the peak to peak value of this function and is measured in $^\circ/\text{S}$.
- **Bandwidth:** The bandwidth of the gyroscope is range of frequencies where the displacement of proof mass is equal to half of resonant peak value. The bandwidth can be calculated using this formula $\Delta f = f_0/Q$.
 f_0 is the natural frequency and Δf is the range of frequencies and Q is quality factor.
- **Bias instability:** The minimum detectable rate input within the gyroscope and is measured by units $^\circ/\text{h}$.
- **Angular Random Walk (ARW):** ARW is due to white thermo-mechanical and thermo-electrical noise within the gyroscope. It is measured in $^\circ/\sqrt{\text{h}}$.

According to performance specifications, MEMS gyroscopes are classified into 5 categories, commercial grade, rate grade, tactical grade, inertial grade gyroscopes, and strategic grade [21]. There are only military applications for strategic grade devices and their discussion will not be included in this Thesis. Table 1.1 shows the classification of gyroscopes according to the performance specifications suitable for consumer applications.

Table 1. 1: Classification of gyroscopes according to performance specifications

Parameter, Unit	Commercial Grade	Rate Grade	Tactical Grade	Inertial Grade
Angular Random Walk, $^{\circ}/\sqrt{h}$	>0.5	< 0.5	< 0.05	< 0.001
Bias instability, $^{\circ}/h$	30	30	6	0.06
Scale factor, %	0.1-1	0.1-1	0.01-0.1	< 0.001
Dynamic Range, $^{\circ}/S$	50-1000	50-1000	>500	>400

1.7 Motivation

Disk Resonator Gyroscopes provides several advantages such as excellent mode matching, high resolution and long-term stability [10]. As mentioned earlier, even in mode matched rate gyroscopes due to fabrication imperfections there will be a mode mismatch between drive and sense mode frequencies. Different techniques are available to reduce the frequency split between the two degenerate modes. Some of the techniques such as mass loading and electrostatic tuning etc. are employed after fabricating the gyroscope [12]. In this thesis, a geometric compensation technique is used to reduce the frequency mismatch. This technique is used during the design process of the DRG. Therefore, this technique has the advantage of avoiding post fabrication tuning techniques.

1.8 Main Objectives of the Thesis

The objective of this Thesis is to design and analyze a mode-matched Disk Resonator Gyroscope (DRG) characterized by high Quality factor exceeding 1 million using a commercially available MIDIS process.

1.9 Technical Approach

Apart from achieving high Quality factor exceeding 1 million, to reduce the mode mismatch between the drive and sense modes, a geometric compensation technique is used in the design of proposed DRG. In the geometric compensation technique, the geometric parameters of the DRG such as ring width, spoke width and spoke angle are varied [15]. By varying each of these individual parameters separately keeping the other two variables unchanged, different DRGs are designed and simulated. The DRG is designed using a commercially available MEMS fabrication process known as MIDIS process. For the design and simulation purposes CoventorWare software is used. Simulations are performed to obtain the Quality factor and resonant frequencies of the drive and sense modes. Based on the simulation results, the geometric parameters for a DRG characterized with highest Quality factor will be obtained.

1.10 Thesis Outline

In Chapter II, literature review of MEMS Gyroscopes and the wafer level vacuum encapsulation process that is MIDIS process from TDSI that is utilized for our MEMS DRG will be discussed in detail.

In Chapter III, the design of the DRG will be discussed in detail.

In Chapter IV the Results and Analysis of the designed DRG are discussed in detail.

Chapter V concludes with discussion of Thesis summary and the future scope of this work.

CHAPTER 2

MIDIS FABRICATION PROCESS

2.1 Different Types of MEMS Gyroscopes

In recent years, symmetrical MEMS gyroscopes such as ring [22,23], disk [24-27], and microscale 3D wineglass gyroscopes [28,29] have received great attention, due to the degenerate wineglass mode shape. The mode-matching operation of degenerate wineglass mode gives good performance with large scale factor and low noise. Different techniques are used to reduce the split between two degenerate modes. For instance, Dennis et al. [30] demonstrated a mass loading technique instead of modifying the resonator's stiffness where the mass of resonator is perturbed to reduce the frequency mismatch. Resonator mass loading technique eliminates the need for electrostatic tuning and therefore only single bias voltage for resonator is needed to operate the rate sensor. In contrast to electrostatic and mass tuning technique there are automatic closed loop control systems used to match the drive and sense mode frequencies [31]. In this thesis, a geometric compensation technique is used to reduce the frequency mismatch between drive and sense modes. By varying the geometric parameters of DRG such as ring width, spoke width and spoke angle the frequency mismatch can be reduced. Using a similar technique of geometric compensation, Ahn et al. [27,32] demonstrated a DRG fabricated using wafer-level epitaxial silicon encapsulation process known as Epi-SealTM process. The frequency

split of 250 kHz DRG wineglass modes thus fabricated using epi-seal process was reduced from > 10 kHz to 96 Hz without any electrostatic tuning. MEMS gyroscopes require an ultra-clean vacuum encapsulation with low leakage to achieve high Q and maintain stability of the Q for long term by reducing the air damping and surface losses [33]. Therefore, an ultra-clean vacuum encapsulation is one of the most important factors for the development of a high performance MEMS gyroscopes such as tactical grade and inertial navigation grade gyroscopes.

At macro-scale, Hemispherical Resonator Gyroscope (HRG) functioning in the wineglass mode achieved a Q of 26 million [34]. The Scalable Inertial Reference Unit for space (SIRU) from Northrop Grumman is composed of 3 HRGs and is the one of the most advanced inertial grade IMUs with $ARW = 0.00015^\circ/\sqrt{\text{Hr}}$. [34]. However, at micro scale it is difficult to apply these fabrication methods. At micro scale, many designs of high Q gyroscopes are proposed to date. For example, the Quadruple Mass Gyroscope(QMG) developed by Prihodko et al. [35] obtained Q reaching 1.1 million (highest Q demonstrated to date), Micro Birdbath Resonator Gyroscope developed by Cho et al. [28] exceeded a Q of 252,000, Disk Resonator Gyroscope (DRG) developed by Taheri-Teharani et al. [36] exceeded a Q of 100,000, Resonator Star Gyroscope (RSG) by Zaman et al. [37] has achieved a Q of 60,000, and Mode-Matched Tuning Fork Gyroscope (M²-TFG) by Sharma et al. [38] has achieved a Q of 36,000, but with using automatic electronic mode-matching, the system obtained an outstanding $ARW = 0.003^\circ/\sqrt{\text{Hr}}$. It is important to note that most of the above gyroscopes laboratory demonstrations examined either by using large vacuum chamber test equipment or short-term hermetic sealed ceramic packages to obtain high Q , which otherwise would not be possible to obtain at the chip-

level. From the above list of gyroscopes, only DRG is microfabricated using getter-free ultra-clean wafer-level vacuum packaging process, called Epi-Seal process, as described in Candler et al. [39]. The Epi-Seal process has a total equivalent leak rate of approximately 1×10^{-15} atm cm³. The leak rate is not sufficient to maintain the stability of the Q for long-term.

2.2 MIDIS Fabrication Process

MIDIS process is a high aspect ratio bulk micromachining of a Single Crystal Silicon (SCS) device layer that is sandwiched between two other silicon wafers, namely the interconnect layer at the top and handle wafer at the bottom. Deep Reactive Ion Etching (DRIE) is performed on the bottom handle and top interconnect wafers to pattern cavities of 30 μm and 20 μm , respectively. The device structure is suspended over these top and bottom cavities. The device structure is also patterned using DRIE with a minimum structural feature size of 1.5 μm . The MIDIS process is explained in detail in several previous publications [40-42] and is briefly explained below.

A SCS wafer that ultimately forms the device layer is fusion bonded on top of the handle wafer at a temperature of 1100°C. Chemical-Mechanical Planarization (CMP) is then used to thin it down to 40 μm . The top interconnect wafer undergoes several processing steps after the initial 20 μm deep etched cavity. Through Silicon Vias (TSVs) are then formed by etching trenches and filling them with In-Situ Doped Polysilicon (ISDP) and silicon dioxide. Finally, this wafer is flipped, and fusion bonded to the handle and device wafers under high vacuum of 10 mTorr at a temperature of 1100°C. Due to the low leak rate offered by the MIDIS process, the encapsulated MEMS device's Q degradation with time

slows down and device can operate with the designed specifications over a longer lifetime.

Figure 2.1 shows the cross-section of a device designed in the MIDIS process.

Figure 2.1: Cross sectional view of MIDIS process with different structural layers

The MIDIS process has thirteen different steps to build the final wafer stack. First step is to perform deep reactive ion etching (DRIE) on the handle wafer to etch the 20 μm depth to form a bottom cavity on the handle wafer. The bottom cavity allows free vibration of the device structure. The pattern on the photoresist is transferred onto the silicon wafer through a physical and chemical etching in the chamber filled with inert gas [43]. Chemical process is responsible for etching silicon material through chemical reaction and on the other hand physical process is responsible for removing the passivation layer which inhibits etching to continue. In second step, a conformal layer of silicon dioxide is formed on the handle wafer for electrical isolation. This layer of silicon dioxide is formed by thermal oxidation technique. In thermal oxidation, high temperatures of (900°C and above) is

applied to quartz tube in which wafers are placed. Silicon wafers placed in this quartz tube react with oxygen atoms to form a layer of silicon dioxide with a thickness about $1.5\ \mu\text{m}$. Usually in MIDIS process, a $1\ \mu\text{m}$ thick layer of silicon dioxide is deposited.

Processed handle wafer and membrane wafer are bonded by utilizing fusion bonding technique. A membrane wafer of about $30\ \mu\text{m}$ to $40\ \mu\text{m}$ thickness is used in MIDIS process. Fusion bonding involves mating of two wafers at room temperature and annealing process at a bonding temperature of over 1000°C [44]. In MIDIS process, bonding temperature is 1100°C and fusion bonding is processed under a high vacuum of 10 mTorr. The high vacuum encapsulation allows the DRG to achieve higher Q and sustain it for longer duration. In fourth step, using DRIE etching technique the membrane wafer is patterned to form the device structure and the required electrodes based on our design. A minimum feature size of $1.5\ \mu\text{m}$ is allowed on the device layer in MIDIS process. With the help of DRIE the interconnect wafer is etched by $20\ \mu\text{m}$ above the bottom surface to form a top cavity. In the next step using anisotropic wet etching another $2\ \mu\text{m}$ thickness is etched from the deep bottom of the wafer to form two inclined side walls ($\{111\} - \text{plane}$) at an angle of 45.74° to the device surface ($\{111\} - \text{plane}$). This step is essential for patterning generic bonding plane to fusion bond interconnect wafer to the wafer assembly. Typically, anisotropic wet etching of silicon is processed at an etching temperature of 80°C when the silicon wafer is drowned in a chemical liquid compound mixed with water (H_2O) and potassium hydroxide (KOH) at a ratio of 2: 1. The average etching rate of a silicon wafer in a plane perpendicular to orientation direction of $\langle 100 \rangle$ is about $1.4\ \mu\text{m}/\text{min}$ for anisotropic wet etching process.

In seventh step Through Silicon Vias (TSVs) are formed on the interconnect wafer. An isolated trench is made through the wafer from the top surface of each electrode using DRIE etching technique and filled with ISDP and silicon dioxide. The main purpose is to provide isolated electrical conductive pathways from contacts to the electrodes of different functions like bias, actuation or sensing can be given to device layer.

To remove the potential cross talk between electrical paths on the surface for TSV wafer, a $1\ \mu\text{m}$ thick silicon dioxide is grown on the TSV wafer in the eighth step. Plasma Enhanced Chemical Vapor Deposition (PECVD) technique is used for this thin film deposition. PECVD process involves chemical reaction between two reactants in gas phase catalyzed by ion energy of plasma in a high-pressured chamber where the silicon wafer is placed. The products of the process are in solid phase and will be absorbed by and diffused into the surface of the wafer to form a layer of thin film. Reactive ion etching is used in ninth step to create space on the oxide layer to extend the electrical conduction pathways to the layer above the contact layer.

A contact layer of $2\ \mu\text{m}$ thick will be deposited using plasma sputtering technique. The thin film will be layered on the silicon wafer in a vacuum chamber, where ions of plasma generated in an inert gas bombards target material and forms atoms of that material to be ejected and deposit on the wafer surface [43]. Contacts are patterned in eleventh step, wires and bond pads on the contact layer are formed by RIE etching technique. A $5\ \mu\text{m}$ thick passivation layer using polymer material is grown for protecting against corrosion atop silicon dioxide layer. Finally, the processed interconnect wafer is fusion bonded with device wafer at high temperature to remove any remaining gas or particles. All thirteen steps are illustrated in the following section from Figure 2.2(a) to Figure 2.2(m).

Figure 2.2(a): Handle wafer

Figure 2.2(b): Etch the bottom cavity

Figure 2.2(c): Deposition of silicon dioxide

Figure 2.2(d): Stack membrane wafer

Figure 2.2(e): Pattern device structure

Figure 2.2(f): Interconnect wafer

Figure 2.2(g): Etch top cavity

Figure 2.2(h): Etch bonding plane

Figure 2.2(i): Etch trenches for TSV

Figure 2.2(j): Fill material in TSV trenches

Figure 2.2(k): Deposit and etch sio2 and contact layer

Figure 2.2(l): Deposit and etch passivation layer

Figure 2.2(m): Fusion bond to form a wafer stack

CHAPTER 3

DESIGN OF DISK RESONATOR GYROSCOPE

Our proposed device is anchored at the center and the location of drive/sense electrodes and spokes are as shown in Figure 3.1. The layout of the DRG is shown in Figure 3.2 (a) and three-dimensional (3D) model of DRG is shown in Figure 3.2 (b). Table 3.1 shows the design parameters. Single Crystal Silicon (SCS) with $\langle 100 \rangle$ crystal orientation is utilized for the design with an area of $700 \mu m \times 700 \mu m$. DRG contains a total of 31 concentric rings connected through alternating spokes which reduces radial stiffness of DRG and enables large in-plane vibration [45].

Figure 3.1: Location of anchor, spokes, and drive/sense electrodes

(a)

(b)

Figure 3.2: Disk Resonator gyroscope (a) Layout (b) Solid model of DRG

Table 3. 1: Design parameters of DRG

Parameter	Value
Number of Rings	31
Number of Spokes	16
Ring width	3 μm
Spoke width	3 μm
Thickness	40 μm
Gap between device and electrodes	1.5 μm
Material and Crystal Orientation	<i>Si</i> < 100 >
Overall Dimensions	700 $\mu m \times$ 700 $\mu m \times$ 40 μm

Figure 3.3: Expanded view of Spoke width and Ring width

The width of each ring is $3\ \mu\text{m}$ and the spacing between each ring is $2\ \mu\text{m}$. The diameter of innermost ring is around $300\ \mu\text{m}$ and outermost ring has a diameter of $600\ \mu\text{m}$. All the 31 concentric rings are interconnected using spokes and the anchor is at the center of the disc. The angle between spokes is a multiple of 22.5° . Figure 3.3 shows expanded view of spoke and ring width. Solid model is extracted from the designed layout using Coventorware software.

Figure 3.4: DRG with drive and sense electrodes

Figure 3.4 shows the solid model of DRG with drive and sense electrodes. The green and red dotted lines are the principle axes for the 0° and 45° modes respectively. To compensate the frequency mismatch geometrically, the width of the spokes of the principle

axes are adjusted to $8\mu m$ and remaining spokes have a width of $3\mu m$. The effective stiffness from both directions can be tuned to compensate the anisotropy of SCS.

CHAPTER 4

ANALYSIS AND RESULTS

The proposed DRG is evaluated by utilizing Finite Element Modeling(FEM). In this chapter simulation and analysis methods and results obtained are discussed.

4.1 MEMS Resonator Evaluation Methods

- I. **Analytical Methods:** This method closely follows the design process. This method involves the solution of high order differential systems and a series of mathematical manipulations. The complexity increases as the effects such as electrostatic spring softening are considered. Typically, analytical approach is used in the initial stages of design.
- II. **Electro-mechanical Analogy:** The electrical to mechanical analogy relies on equations governing the behavior of a mechanical system are like equations governing the electrical system behavior. A detail analysis of a microsystem [46] shows that there is direct correlation between mechanical and electrical parameters. A displacement x corresponds to charge q , velocity v corresponds to current i , a rigid mass m corresponds to an inductance L and a force F is mathematically analogous to a voltage V . MEMS DRG can be transformed into RLC circuit. The main advantage of the electro-mechanical analogy method is

that the mathematical models based on electronic circuit simulation are advanced, which leads to very fast modeling. Due to mechanical effects such as Thermoelastic Dissipation (TED) the accuracy of MEMS resonators is reduced and have less flexibility.

III. Finite Element Modeling (FEM): FEM method is a numerical technique that tries to approximate solutions to partial differential equations and other boundary value problems. The first step in MEMS analysis is to discretize the mechanical structure to large number of finite elements. Nodes are created between elements to connect them. The combination of nodes and finite elements composes mesh of the structure. FEM technique has large overhead during its initialization process. The simulation results obtained from FEM analysis are closer to experimental values when compared with the prior two techniques. Mechanical effects such as electrostatic spring softening and TED can be included very easily in the model. FEM method is utilized for the evaluation of MEMS DRG in this work. The simulations are performed using Coventorware finite element modeling suite.

4.2 Quality Factor and Energy Loss

A resonating system can be defined by two parameters, the resonant frequency (f_0) and the Quality factor (Q). The frequency at which the device exhibits higher amplitudes of vibration is a resonance frequency. Quality factor is defined by Equation (4.1) as,

$$Q = 2\pi \frac{\text{Energy Stored}}{\text{Energy dissipated per cycle}} \quad 4.1$$

The information about efficiency can be obtained from Q . The relation between resonator's bandwidth and center frequency can be obtained from Q . A high Q indicates that the oscillations will die slowly and there is small energy loss in periodic operation. Q has no unit dimensions. Equation (4.1) can be rewritten as Equation (4.2),

$$Q = \frac{f_0}{\Delta f} \quad 4.2$$

where, f_0 is resonant frequency and Δf is half-power bandwidth. Q is depends on the frequency of operation. At very high frequencies, it is difficult to achieve a high- Q because anchor damping, thermoelastic dissipation and material non-linearities are harder to overcome. A MEMS resonator device slowly loses energy to the surrounding environment, like a physical resonator device. The macroscopic energy loss mechanisms such as air damping and anchor damping are present. At micro dimensions, the energy loss mechanisms such thermoelastic dissipation and surface losses are to be considered. The final Q of the device can be found adding individual contributions of each factor as given by Equation (4.3),

$$\frac{1}{Q_{total}} = \frac{1}{Q_{anchor}} + \frac{1}{Q_{gas}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{surface}} \quad 4.3$$

4.2.1 Anchor Damping

The transfer of kinetic energy from resonator device to its support structure is called as anchor damping. Mechanical vibrations travel at a speed of sound called as elastic waves. When these waves hit the resonator or anchor interface the waves either get reflected or they transverse through to the substrate. The transverse elastic waves to the substrate are completely lost along with the energy in them. Anchor damping imposes considerable losses in MEMS resonator devices. As the resonant frequency increases, the

losses increase exponentially and reduces the Q [47]. Impedance mismatch techniques are developed to address this form of energy loss [48,49].

4.2.2 Gas Damping

The transfer of kinetic energy from the resonator device to surrounding air is called gas damping. When the resonator device is operated at atmospheric pressure levels, air damping is one of the dominant energy loss mechanisms in electrostatic transduction resonator devices. After anchor damping, the gas damping is more dominant. The resonator gap, the small gap between input-output electrodes, at high vibration speeds introduces considerable Couette flow damping [50]. There is further drop in the Q of resonator device due to squeeze film damping. Hence, electrostatic MEMS resonator devices are operated in vacuum or at very low-pressure environments. Under these conditions, air behaves as kinetic particles rather than continuous medium.

The air damping is easier to calculate as there is only a single energy loss mechanism. There is collision of air molecules with the vibrating structure. The resulting Q of from air damping can be expressed as Equation (4.4),

$$Q_{gas} = C \sqrt{\frac{k_b T}{P}} \quad 4.4$$

where, P is pressure, k_b is Boltzmann constant, T is operating temperature and C is a constant that depends on design parameters such as mode of vibration and shape of resonator [47]. When the operating pressure is reduced, there is decrease in energy losses and as the temperature rises there is increase in energy losses. Here, the air collisions are directly proportional to the temperature and inversely proportional to pressure.

4.2.3 Thermoelastic Dissipation (TED)

The transfer of energy from the resonator device to thermal energy due to temperature non-uniformities is described as Thermoelastic Dissipation (TED). During operation, the resonator constantly changes its shape based on the mode of vibration. As the device moves some parts of the structure are compressed while other parts are tensile stressed. According to thermodynamics, the compressed region has a higher temperature, while the tensile stressed region has a lower temperature. As a result, there is temperature difference across the structure. To balance it a heat flow between hot and cold part of the resonator is created. All the energy that is converted to heat energy is completely lost. This phenomenon was analyzed by Zener Clarence in the year 1938 [51].

4.2.4 Surface Losses

Surface losses are due to the defects found at surface level of most of the materials. Lattice defects, discontinuities, impurities and contamination due to hydrogen and oxygen introduces non-linearities that leads to dissipation of energy. At microscale, the magnitude of energy loss is not considerable. However, it is important at sub-micron levels where the surface to volume ratio is high [52].

By considering anchor loss and TED, a Q of 1.34 million is estimated through simulations.

4.3 Modal Analysis

A 3D model of the DRG is generated from the designed layout. A mesh is created on the 3D model. Modal analysis is performed to identify the natural frequencies of vibration of a mechanical structure under equilibrium. Natural frequencies with corresponding modal shapes are utilized to understand response of MEMS DRG. They show maximum response of the mechanical system and the system's deformation during the oscillation. A

study of mode shapes can show the desired behavior of the DRG. In Coventorware, modal analysis can be performed by using MemMech module. The DRG is undamped because the modal analysis on mechanical structures need to be performed under equilibrium condition. The amplitudes obtained in the modal shapes are normalized to $1\ \mu m$. The modal shapes of drive and sense mode are shown in Figure 4.1 and Figure 4.2, respectively.

The blue color in the figures indicate the point that is fixed. In our design, central anchor is fixed. The green color indicates large displacement and red color indicates maximum displacement. DRG is desired to operate at $n = 2$ wineglass modes that is fundamental vibration modes. These wineglass modes are chosen because higher order wineglass modes have smaller effective modal mass and smaller angular gain. Thus, higher order vibration modes provide low sensitivity.

Figure 4.1: Wine glass mode at 0°

Figure 4.2: Wine glass mode at 45°

The resonant frequency at 0° wine glass is 277.54 kHz and the resonant frequency at 45° wineglass modes is 278.30 kHz. These modes are drive and sense modes, respectively. To achieve a higher Q, drive and sense modes must be matched [53]. Initially, the frequency split between drive and sense mode was > 10 kHz, by geometrical compensation technique the frequency split between the drive and sense modes is reduced to 760 Hz. By electrostatic tuning method the remaining split can be reduced to match the drive and sense modes.

4.4 Parametric Study of Spoke Width

To compensate > 10 kHz frequency split between the drive (0°) and sense (45°) modes using the geometrical compensation technique, the spoke width of the 45° mode principle axes is varied from $3 \mu m$ to $10 \mu m$ in the steps of $1 \mu m$. At a spoke width of $8 \mu m$ the frequency split between the drive and sense modes is minimal. Table

4.1 illustrates the values of different spoke widths and the associated frequency split values. Figure 4.3 shows the variation of split frequency at different spoke widths.

Table 4. 1: Table showing different frequency split values for different spoke widths

Spoke width	Split frequency
$3 \mu m$	12.28 kHz
$4 \mu m$	7.45 kHz
$5 \mu m$	4.67 kHz
$6 \mu m$	2.72 kHz
$7 \mu m$	846.4 Hz
$8 \mu m$	760 Hz
$9 \mu m$	2.65 kHz
$10 \mu m$	4.47 kHz

Figure 4.3: Variation of frequency split at different spoke widths

4.5 Harmonic Electromechanical Analysis

To evaluate the performance of DRG, its frequency response is studied. The frequency domain harmonic electromechanical analysis is utilized to study the frequency response characteristics of our designed DRG. HarmonicEM module from Coventorware is used to perform the harmonic electromechanical analysis. A 1 V AC signal is applied to actuating electrodes, a DC voltage of 10 V is applied to the structure of DRG. The frequency of the AC signal is swept in increments of 500 Hz, from “ $-2000 + f_0$ ” to “ $+2000 + f_0$ ” where, f_0 is the resonant frequency calculated from modal analysis. The simulations are performed at an atmospheric pressure of 0.103 MPa with viscosity of air set at $1.86e^{-11}$ Kg/ μ m S [54].

Figure 4.4: Frequency response of DRG

The frequency responses at 277.54 kHz and 278.30 kHz are shown in Figures 4.4 to 4.6 respectively. The results confirm the resonant frequency values obtained by modal analysis, and the unwanted modes are not present at the operating frequencies. The frequency response plots are also used to extract Quality factor Q of the DRG at drive and sense modes.

Figure 4.5: Frequency response at 277.54 kHz

Figure 4.6: Frequency response at 278.30 kHz

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this work, the design and analysis of a mode-matched disk resonator gyroscope is presented. The gyroscope is designed using MEMS Integrated Design for Inertial Sensors (MIDIS) process. The disk resonator gyroscope has a circular shape of $600\ \mu\text{m}$ diameter with a SCS device layer thickness of $40\ \mu\text{m}$. The DRG operates at $277.54\ \text{kHz}$ and $278.30\ \text{kHz}$ in drive and sense modes respectively. To reduce the frequency split between drive and sense modes a geometric compensation technique is used. Using this technique, the spoke width of the 45° mode principle axes is varied from $3\ \mu\text{m}$ to $10\ \mu\text{m}$ in the steps of $1\ \mu\text{m}$. It has been observed that at a spoke width of $8\ \mu\text{m}$ a minimal frequency split of $760\ \text{Hz}$ is observed between the drive and sense modes. From the simulation results it has been observed that a Q of 1.34 million is achieved for the proposed geometry.

5.2 Future Work

In a future work, the designed gyroscope could be submitted to Teledyne DALSA Semiconductor Incorporated (TDSI) for fabrication. Once the device is fabricated the split frequency will be measured and if necessary external electrostatic tuning techniques can be deployed to reduce the mode mismatch further. Then, all the device parameters such as ARW, bias instability, drift rate, bandwidth etc. will be measured experimentally.

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