Processing and characterization of high permeability thin-film for micro rotating gyroscope development

Tjeung, Ricky Theodore

2005

Tjeung, R. T. (2005). Processing and characterization of high permeability thin-film for micro rotating gyroscope development. Master' s thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/6329>

<https://doi.org/10.32657/10356/6329>

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PROCESSING AND CHARACTERIZATION OF HIGH PERMEABILITY THIN-FILM FOR MICRO ROTATING GYROSCOPE DEVELOPMENT

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2005

Processing and Characterization of High Permeability Thin-Film for Micro Rotating Gyroscope Development

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A thesis submitted to the Nanyang Technological University in
fulfillment of the requirement for the degree of Master of Engineering

2005

Abstract

Current advancement in micro motor area is not encouraging. The devices generally suffer from limited lifetime issue. For this reason, most micro gyroscopes are designed to be of a vibrating type. Unfortunately, these designs have a major problem called “drift”. Drift arises due to intrinsic instability, which is related to number of mechanical coupling associated with its design. Reliable operation of these gyros would require severe stability of all its parameters.

A micro levitation gyroscope design would be the preferred solution to address these problems. This design had two advantages in both addressing the lifetime and drift problem. Since there is no mechanical contact, common micro motor problem of wear and limited lifetime could be solved. This design also will remove drift problem suffered by micro vibrating gyroscopes due to its non-contact design.

In spite of these benefits, the development of such a design is still in its infancy. Many limitations associated with this design prevent it from commercialization. The main problem relating to this design is its high power consumption.

The micro-rotating gyroscope utilizes electromagnetic principle for its operation. The device draws large amount of current in order to produce a levitation force to act as magnetic bearing. This problem can be addressed by adding an extra magnetic material as a backing plane to enhance the magnetic flux produce and hence the force. This enhancement would reduce the high current consumption currently suffered by the device.

The main intention of this project is to explore *magnetic material to be used as backing plane for micro gyroscope development*. Four objectives were set in achieving the main intentions, namely:

1. To develop high permeability magnetic film
2. To establish infrastructure for the growth of magnetic thin films.
3. To set up a reliable magnetometer for rapid, non-invasive and magnetic anisotropy testing
4. To assess magnetic material performance at high frequency application.

Infrastructure establishment was accomplished successfully. Utilizing the facilities established, high permeability magnetic thin film was deposited; thick film up to few μm thickness is achieved.

The MOKE magnetometer had been set up to achieve high sensitivity and stability. The ***intensity stability*** of **0.1%** was achieved to enable the MOKE magnetometer to obtain hysteresis loops from thin films with ***signal to noise ratio*** of **40:1** for a data collection of 20 seconds.

High frequency performance testing was performed by inductance testing of micro transformer structures. The result suggested that use of FeNi as magnetic backing plane would indeed improve efficiency of the gyroscope. Substantial amount of improvement in operating speed and current consumption would be expected with inclusion of FeNi as magnetic backing plane

Acknowledgement

The author would like to express his gratitude towards these following people for all their assistance in regard to his research project and writing this report. The author has had an enriching experience doing a MEMS project on micro gyroscopic sensor. First of all, he would like to thank his supervisor, Associate Professor Christopher Shearwood for all his patience and support in supervising the project. The author especially would like to express his gratitude for the constructive advise, determined effort and guidance in various areas to the author during his research.

The author would also like to thank these following people:

- Ho Wei Hong, who worked in collaboration with the author to set up the electroplating equipment and high frequency performance testing
- Oh Yuin Chang, who was giving valuable contribution in MOKE experiments
- Dr. Fu Yongqing for his help on sample preparation and essential advice
- All the research staffs and technicians in the MMC for their guidance and explanation about their respective equipments expertise in the Micro Machines Centre, which help the author a lot during his research.
- Fellow students who are doing their FYP and Postgraduate studies in the MEMS lab for their valuable help and advice.

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Processing and Characterization of High Permeability Thin-Film for Micro Rotating Gyroscope Development

Introduction

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INTRODUCTION

1.1 Background

Micro Electro-Mechanical System is a technology, which manipulates IC micro fabrication technology to suitable micromachining techniques in order to produce micro size mechanical elements. MEMS devices generally consist of sensors and actuators. It is a promising technology, as it can greatly reduce cost due to its batch fabrication techniques. MEMS technology is also very efficient in utilizing raw material due to size miniaturization. Not only that, it offers more reliable as a sensor or actuator than conventional technologies, yet, the price of these MEMS devices is generally lower. [1-7]

Minimizing the size of conventional machine will also reduce the power consumption greatly. In miniaturizing these machines, the functional requirement of the machine is conserved but the reliability and usage is expected to improve significantly. [1-4]

One of the most successful commercialized MEMS products is the micro size accelerometer. It is now normally used in navigation replacing the conventional accelerometer. In automotives industry it is usually used as an air bag deployment sensor and suspension system.

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A complete inertial sensor would require a set of accelerometer and gyroscope. Both are utilized to sense linear acceleration and rotational speed respectively. Therefore after successful micro size accelerometer commercialization, micro size gyroscope should be the next highly demanded MEMS device. [8]

In order to reproduce a rotating structure in the micro domain, a micro size motor is required. Current advancement in micro motor areas has not been promising. Most micro motor does not produce satisfactory performance. The main problem is its limited lifetime. Therefore most micro gyroscope created are vibrating gyroscope instead.

This vibrating structure however has limitation, which make rotating gyroscope still a preferable choice. The main problem associated with this system is *short* and *long term drift*. This problem is due to its intrinsic instability, which is related to numbers of mechanical coupling associated with its design. Reliable operation of these gyros would require severe stability of all its parameters. Any thermal mismatch, change in mechanical properties of any of the parts would cause this drift problem. More discussion is presented in subsequent chapter. [9]

Micro levitation gyroscope design would be the preferred solution to address these problems. [10] This design had two advantages in addressing lifetime and drift problem. Since there is no mechanical contact, common micro motor problem of wear and limited lifetime could be solved. This design also will remove drift problem

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suffered by micro vibrating gyroscopes due to its non-contact design. The design consisted of a micro stator attached to a fixed platform and a levitating rotor with magnetic bearing. [10]

In spite of these benefits, the development of such design is still in its extreme infancy. Many limitations associated with this design prevent it to become a commercialized device. Main problem relating to this preliminary design is high power consumption.

After examining the limitations associated with this preliminary design, it was concluded that some modification can be applied to this design to overcome its main problem.

The micro rotating gyroscope utilizes electromagnetic principle for its operation. The device draws large amount of current in order to produce levitation force as magnetic bearing. This problem could be addressed by adding an extra magnetic material as backing plane to enhance the magnetic flux produce and hence the force. This enhancement would reduce the high current consumption currently suffered by the device.

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1.2 Objectives

The main intention of this project is to explore *magnetic material to be used as backing plane for micro gyroscope development*. Four objectives were set in achieving the main intentions, namely:

1. To develop high permeability magnetic film
2. To establish infrastructure for growing magnetic film
3. To set up reliable magnetometer for rapid, non-invasive and magnetic anisotropy testing
4. To assess magnetic material performance at high frequency application.

1.3 Scope

This research project focuses on investigation of magnetic material required for micro rotating gyroscope development. The project shall exclude fabrication of the rotor since it has been well established. This research project interest is on assessment on magnetic material suitability for usage as backing plane. However, suitable equipments to serve the objectives were not available.

For this reason, the project includes:

1. Establishment of facilities to accommodate sample preparation

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2. Establishment of MOKE equipment as equipment to determine qualitative result of magnetic material permeability.
3. Establishment of process for high frequency performance testing, i.e. fabricating micro structures for inductance testing in high frequency operation.

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2.1 Inertial Sensors

A moving body in the spatial environment is characterized by its translation and rotational motion. For this reason, any control or measurement system must include measurement of the linear and rotational motion. [11]

An accelerometer is the device to measure the linear acceleration. A gyroscope is usually utilized as rotational measuring device. Characterization of motion using accelerometers and gyroscopes is called *inertial navigation*. Both the gyroscope and accelerometer are called inertial sensors, because these instruments use inertial properties of matter for their operation.

Accelerometer has been developed for years as speed measurement system. Conventional accelerometer consists of a proof mass suspended by compliant beams anchored to a fixed frame. It can be modeled using second order spring mass system. The system has mass, stiffness, and damping. External acceleration displaces the support frame relative to the proof mass, which changes the internal stress in the suspension spring. External acceleration is then measure either by the relative displacement or the beam stress.

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Micro machined accelerometer is one of the most successful commercialized MEMS applications. A lot of successful fabrication and improvement on different types / operating principles of accelerometers have been reported. [12-25]

Accelerometers would not be discussed further in this review since the focus of the thesis was on gyroscope.

2.2 Conventional Gyroscope

2.2.1 Discussion on conventional Gyroscope

By definition, a gyroscope is a symmetrical mass usually a wheel, mounted to gimbals so that it can spin about an axis in any direction. Figure 2.2 shows a gyroscope, its working principle and the law governing it. A gyroscope has a special interesting property, whenever it is subjected to a torque in its spin axis; the axis will turn perpendicular to the torque direction. This motion is called *precession*. This motion is based on *conservation of angular momentum principle*. [26, 27]

Law of Gyroscopic:

$$T = H \times \Omega$$

{2.2}

T = input torque

Ω = precession rate

H = angular momentum = $I\omega$

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Figure 2.1 Law of Gyroscopic Motion

Large gyroscopes are used in ship stabilizers to counteract rolling. The gyroscope is the main part of most automatic steering systems. It is also used in the gyrocompass, a directional instrument used on ships. [26, 28]

However, currently the word gyroscope refers to any device, which detects rotation of a body with respect to inertial space. [10] Hence, the application of gyroscopes have been widen to diverse areas, such as: anti-jitter in camera, toys, free space pointer, etc. [28]

Yazdi, et al (1998) [29] stated some important factors which determine performance of a gyroscope. They are:

1. Resolution

The resolution is set by the white noise and is expressed in terms of the standard deviation of equivalent rotation rate per square root of bandwidth of detection

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$[(^{\circ}/s)/\sqrt{\text{Hz}}$ or $(^{\circ}/h)/\sqrt{\text{Hz}}$]. Sometime the term “angle random walk” in $^{\circ}/\sqrt{h}$ may also be used.

2. *Drift*

Short and long terms varying function. It is usually expressed in $^{\circ}/s$ or $^{\circ}/h$.

3. *Zero Rate Output(ZRO)*

The output of the device in the absence of a rotation rate.

4. *Scale Factor*

The amount of change in the output signal per unit change of the rotation rate. It is expressed in $V/(^{\circ}/s)$.

Yazdi, et al (1998) [29] also classified gyroscopes based on performance requirement.

They are:

1. Rate Grade
2. Tactical Grade
3. Inertial Grade

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The table below shows the performance requirement for each grade gyroscope. [11]

Parameter	Rate Grade	Tactical Grade	Inertial Grade
Angle Random walk, $^{\circ}/\sqrt{\text{h}}$	>0.5	0.5-0.05	<0.001
Bias Drift, $^{\circ}/\text{h}$	10-1000	1.0-10	<0.01
Scale Factor accuracy, %	0.1-1	0.001-0.1	<0.001
Full Scale range, $^{\circ}/\text{sec}$	50-1000	>500	>400
Max.Shock in 1 msec, g's	10^3	10^3 - 10^4	10^3
Bandwidth, Hz	>70	-100	-100

Table 2.1 Performance Requirements for gyroscopes

However, standard gimbals supported gyroscopes do not have suitable sensitivity for usage in recent applications. A very accurate measurement system is required. Optical gyroscope has been developed for years to attend the need for accurate measurement system.

Generally, optical gyroscopes consist of ring laser gyroscope and fiber optic gyroscope. Both types utilize Sagnac Effect in their operating principles. Brief review of the two types of optical gyroscopes is presented.

2.2.2 Ring Laser Gyroscope

The system consists of laser source and ring laser cavity. The cavity is usually in the form of equilateral triangle. The laser source produces two antiphase circulating beams inside the cavity. External rotation will turn the cavity, which induce a difference in path length and hence frequency of the two counter propagating beams.

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This frequency difference is then measured, as it is proportional to the rate of external rotation. This frequency difference / shift is termed Sagnac effect. [30]

$$f = \frac{4\Omega A}{\lambda S} \quad (2.3)$$

f = frequency shift (Hz)

Ω = angular velocity (rad/s)

A = area of the triangular cavity

λ = wavelength

S = perimeter

2.2.3 Fiber Optic Gyroscope

This device also utilizes Sagnac effect. Light is splitted by a beam splitter and launched into both ends of a coil of single-mode optical fiber. The two light travel in opposite direction to each other in a coiled fiber. When the coil is rotated, the light traveling parallel to the rotation remains inside the fiber a while longer. Consequently, the two output beams have phase difference between each other. The phase difference is then measured as proportional to the rate of rotation. [10, 30]

$$\Delta\phi = \frac{8\pi A\Omega N}{c\lambda} \quad (2.4)$$

$\Delta\phi$ = phase shift

A = area of the coil

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Ω = angular velocity

N = numbers of coil turns

c = speed of the light

λ = wavelength

Optical gyroscopes are very accurate measuring devices. A Ring Laser Gyroscope has around 2×10^{-6} °/s ZRO and 10^{-4} % scale factor accuracy. A fiber Optic Gyroscope has around 0.1 °/s ZRO and 1% scale factor accuracy. However, their high price and large sizes made them unfavorable for practical usage. A Ring laser gyroscope costs approximately three times standard gimbals (spinning wheel) gyroscope, while a fiber optic gyroscope costs approximately two times. [11, 30, 31]

2.3 Micro Gyroscope

2.3.1 Discussion

Clearly both ring laser and fiber optic gyroscope are not ideal choice for most applications due to their size and price. The requirement for smaller and cheaper gyroscope called for micro sizes gyroscopes. It is shown in the next table how wide the market for small rotational sensors is. The next table also shows performance requirement for diverse areas of application. [32]

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Area	Example of Application	Range	Accuracy
Automotive Safety reliable, inexpensive, lifetime, rough environment			
	improved control of airbag	50 g, 200 °/s	500 mg, 10 °/s
	anti-collision system	100 °/s	1 °/s
	active suspension	50 °/s	2 °/s
	anti-skid	100 °/s	1 °/s
Consumer inexpensive, small, lifetime, low-power			
	free-space pointer (small computer)	100 °/s	1 °/s
	remote control devices (TV-controls)	100 °/s	2 °/s
	video camera (anti jitter compensation)	50 °/s	0.5 °/s
	navigation (complement to GPS)	50 °/s	0.5 °/s
	toys and sports equipment	varies	varies
Industrial reliable, small, rough environment			
	machine control	10 °/s	0.01 °/s
	angular vibration measurements	varies	varies
	attitude control of flying objects	20 °/s	0.02 °/s
	automatic guided vehicles	50 °/s	0.2 °/s
	stabilised platforms	20 °/s	0.2 °/s
	robotics	10 °/s	0.01 °/s
Medical reliable, small, low-power			
	monitoring of body-movement	10 g, 100 °/s	100 mg, 1 °/s
	vibration diagnostics	0.1 g, 50 °/s	1 mg, 0.5 °/s
	controls for paralysed patients	2 g, 100 °/s	20 mg, 2 °/s
	surgical instruments	20 °/s	0.1 °/s
	wheel-chairs	2 g, 50 °/s	20 mg, 0.2 °/s
Military reliable, small, rough environment			
	new weapon systems		
	smart ammunition		

Table 2.2 Application that required small and inexpensive gyroscope

Micro machining technology is an advancing technology, which is able to produce reasonably complicated device with small size and low cost. With current advancement in MEMS technology, it is possible to manufacture micro size gyroscope, which satisfy performance requirement. Micro machined gyroscope should be the most attractive solution for small and cheap measuring device. Therefore lot of research and commercialization has been done in this field.

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It is interesting to note that almost all reported micro machined gyroscopes are vibrating type. Most micro machined gyroscopes do not follow macro size gyroscope in operating principle. They do not rely on the conservation of angular momentum of a rotating structure. This is partly because vibrating structures are generally easier to micro fabricated and mainly because bearing friction of rotating structure will restrict lifetime. Therefore conservation of linear momentum of a vibrating structure is chosen instead. [32,33]

2.3.2 Vibrating gyroscope operating principle

The gyroscope is modeled as a three-dimensional spring-mass system. The mass is vibrated at resonant at one axis by external excitation. The excitation is controlled such that constant amplitude is achieved during the vibration. This vibration motion is termed primary motion. Any rotation of the whole system will induce Coriolis force, the magnitude of this force is proportional to the rate of rotation, but its direction is perpendicular to the primary motion. This Coriolis force induced perpendicular motion is termed secondary motion. The amplitude of this secondary motion is measured. From this information, the rate of rotation is determined. [29, 34]

Burdess et al (1994) classified vibrating gyroscopes based on their general form of sensing element. They are:

1. Beams

A Beam is used as the sensing element. It is excited into flexural vibration by piezoelectric elements (primary motion), which are bonded in its sides. Any

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external rotation will cause it to vibrate in perpendicular direction (secondary mode). This secondary motion causes voltages of opposite phase generated by the piezoelectric elements. The electronics subtraction is measured and taken as a measure of the applied rotation. [34]

2. Tuning Forks

Two tines of fork shape device are arranged to vibrate in antiphase to each other. It can be shown that this primary motion is dynamically balanced. It is important to have zero force resultant in this design for ZRO. Again, the actuation is caused by piezoelectric elements attached to the device. External rotation will induce Coriolis force, which causes the two tines to move in direction perpendicular to the plane of the device and opposite against each other. The voltage generated by piezoelectric elements due to this secondary motion is taken as measure of the applied rotation. [34]

3. Cylinders

When a cylinder is rotated about its central axis, positions of its circumferential nodes do not remain stationary with respect to the cylinder. They move by an amount proportional to the total turn. If the locations of the nodes points are held stationary during rotation then the control action used to maintain this situation can be taken as a measure of the applied rate. [34]

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The principles of operation of this gyroscope are usually electrostatic force. Electrostatic input acts as the source of vibration of the element. Generally, sensing element used for these gyroscopes is either piezoresistive or capacitive sensing. Piezoresistive sensing element is generally more accurate than capacitive sensing, but it is temperature and package induced stress dependent. While capacitive sensing element is simpler to fabricate and is not temperature-dependent. Capacitive sensing is not affected by package-induced stress. However, capacitive sensing required high-resolution electric circuit to detect small change in capacitance. [35]

2.3.3 Successfully Fabricated Micro Gyroscopes

Employing vibrating principle, a large number of successfully fabricated micro machined gyroscopes have been reported in the last decade. [34-47]

Söderkvist (1994) has fabricated micro machined tuning fork gyroscope. Piezoelectric mechanism was utilized as sensing mechanism. The gyroscope can be driven with small power; only 10 μ W power is required to excite vibration of the system. The device also has $< 0.1^{\circ}/s$ resolution, $< 0.3^{\circ}/s$ noise level, virtually no cross-axis sensitivity and better than $0.5 (^{\circ}/s)/h$ ZRO stability. [32, 33] The tuning fork gyroscope is shown in the figure 2.3

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Figure 2.2 Tuning Fork Micro Vibrating Gyroscope

Cylinders type of vibrating gyroscope was successfully developed by Anders et al (1994) from GEC-Marconi Avionics Ltd. The device is called START (Solid-State Angular Rate Transducer) vibratory gyroscope. It has $< 0.03^\circ/\text{s}$ resolution, $< 2^\circ/\text{s}$ ZRO, 0 - 40 HZ bandwidth and $> 100,000$ hr lifetime. The device requires 375 mW power at 12 DC for operation. [11] Almost an order of resolution improvement were made compared to previous tuning fork gyroscope. The schematic representation of the gyroscope and working principle could be observed in the figure2.4. [34]

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Figure 2.3 Schematic Representation of Cylinder Type Gyroscope

Current MEMS fabrication technology improvement has enabled high aspect ratio structure fabrication. Ayazi, et al (1998) from University of Michigan has fabricated polysilicon vibrating ring gyroscope using a high aspect ratio polysilicon trench refill fabrication was employed to fabricate 30-40 μ m thick polysilicon rings with 0.9 μ gap spacing. Two different materials was utilized for the devices, the materials used was Nickel and poly silicon. The devices had 0.5 $^{\circ}$ /s and 0.0025 $^{\circ}$ /s sensitivity at 10 Hz bandwidth and 30 kHz and 33 kHz resonance for the nickel and polysilicon gyroscope respectively. This polysilicon vibrating ring gyroscope could be referred to the figure 2.4. [36-38]

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Figure 2.4 High Aspect Ratio Polysilicon Vibrating Ring Gyroscope

Electromagnetic planar vibrating gyroscope was proposed by Lee et al. (1998) in their design; a vibrating structure is put on top of driving and sensing multiple turn coils. The vibration of the gyroscope was made by electromagnetic force and sensing is done by inductive method. Sensitivity obtained varies from 4.2 to 26 mV/ $^{\circ}$ C depending on change of voltage and air gap of the sensing part. Range of the sensor was -51.6 to 51.6 $^{\circ}$ Sensitivity could be controlled by changing number of turn of driving and sensing coils, voltage and air gap. This method gives significant improvement over electrostatic detection, which generally gives μ V/ $^{\circ}$ C sensitivity. [35]

During the last few years, most vibrating gyroscopes use comb drive structure as their driving mechanism. This trend could be due to the efficient force produces compared to input voltage.

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Park et al (1998) utilized comb drive structure as vibrating mechanism for their gyroscope design. Additional force balance electrode enabled closed loop operation. The rate gyroscope had force balance electrode to improve linearity and dynamic range. The rate gyroscope was also supported by fish hooked shape springs for stiffer system, which gave more resistance to cross-axis input and shocks. Equivalent noise level was $0.1 \text{ }^{\circ}/\text{s}$ at a bandwidth of 100 Hz, and dynamic range of $90 \text{ }^{\circ}/\text{s}$. Although large bandwidth and dynamic range could be an attractive choice, resolution of the device is an order better compared to previous designs. On the contrary, the fish hooked shape spring was an attractive method for increasing cross axis stiffness. [39]

Figure 2.5 Micro Vibrating Gyroscope using comb drives structure enhanced with fishhook shape spring

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Tsuchiya et al (2000) utilized three layer of polysilicon surface micromachining in their design. The middle layer was the comb drive structure for vibration mechanism. The middle layer is vibrated laterally with input turn rate also in other lateral axis. Vertical displacement oscillation was then measured by differential capacitive sensing utilizing the upper and bottom electrodes. The device had $1^{\circ}/s$ resolution, $202 \text{ mV}/(^{\circ}/s)$ voltage sensitivity and $\pm 20^{\circ}/s$ dynamic range. Figure 2.7 shows the three layer polysilicon gyroscope. [40, 41]

Figure 2.6 Three Layer Polysilicon Micro Vibrating Gyroscope

Electromagnetic sensing, instead of capacitance sensing was used by Kim et al (2000). This detecting method benefits in voltage output, hence simpler readout circuit is required. Higher sensitivity and linearity could also be achieved by this

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method. Electrostatic comb drive structure is again used as driving mechanism. The design used field coil attached to the static structure and sensing coil on the moving structure. A comb actuator was made to vibrate in lateral x direction. Input turn rate was sensed in the lateral y-axis, resulting in z-axis coriolis oscillation. The vertical oscillation distance was then detected by measuring induced voltage of the sensing coil. The device was expected to have $0.15^\circ/\text{s}$ resolution, $30 \text{ mV}/(^\circ/\text{s})$ sensitivity, $\pm 500^\circ/\text{s}$ dynamic range with less than 0.8% full-scale output nonlinearity.

Figure 2.7 Schematic Representation of the Electromagnetic Sensing Gyroscope

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Comb drive driving mechanism seemed to be a very attractive, however, comb drive structure generally suffers mechanical and electromechanical coupling, which cause non-linear behavior. Comb drives gyroscope structure consists of primary and secondary motion, which refers to electrostatic vibrating motion and coriolis oscillation respectively. The mechanical coupling occurs if the comb drives are not decoupled from secondary oscillation, [42, 43]

In order to address this problem, Geiger et al (1999) has fabricated a new comb drive gyroscope design. From the next figure it can be shown that the design consisted of static base, which is used as capacitive sensing, and vibrating part suspended above the base by center anchorage. The vibrating structure consisted of comb drives inside an inner wheel and outer rectangular structure. The inner wheel was decoupled from the base, leaving only the rectangular structure coupled to the base. The turn rate was detected by measuring lateral oscillation of the outer rectangle against the base using capacitive sensing. The comb drives inner wheel acted as primary motion and vertical oscillation of the rectangular as the secondary motion. By separating these two motions, the mechanical coupling problem should be addressed. The device had 0.14 $^{\circ}/s$ with 8mV/ ($^{\circ}/s$) on a bandwidth of 50 Hz. It had $\pm 300^{\circ}/s$ dynamic range and less than 0.3% linearity. [42, 43]

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Figure 2.8 Vibrating Gyroscope design to remove mechanical coupling

As explained earlier, mechanical coupling occurs if secondary and primary motion is not separated. However, it is sensible to design gyroscope with similar resonance frequency between the primary and secondary motion for better gain and resolution, compromise must be done in satisfying this requirement. Geiger et al (1999) has addressed mechanical coupling problem by separating this two motion at the expense of resolution.

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Alper et al (2001) tried to address this problem and satisfying both requirements. They have designed a system to have both lateral primary and secondary motion for similar resonance frequency. The system consisted of symmetric comb drive structure with 4-point anchorage. By this design, similar resonance frequency could be operated and the anchors prevent any mechanical coupling. The resonant frequencies were 28,535 Hz and 30,306 Hz for driving and sensing motion respectively. The mismatch was due to manufacturing constraints. The design was expected to have 0.37 $^{\circ}$ /s resolution in a 30 Hz bandwidth. [44]

Figure 2.9 Comb Drives Gyroscope with four Anchor Points

While it seems attractive to use micro machined vibrating gyroscope for angular rate sensor, there are still few rooms for improvement. Careful examination of the vibrating gyroscope discussed shows problems associated with them. The main problem associated with this system is *short and long term drift*. This problem is due to its intrinsic instability, which is related to numbers of mechanical coupling associated with its design. Reliable operation of these gyros would require severe

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stability of all its parameters. Any thermal mismatch, change in mechanical properties of any of the parts would cause this drift problem. [10]

Resonant frequency is also very sensitive to minor changes, which could also contribute to problem resulting in manufacturing limitations. Moreover, the device is required to measure very small change in vibration amplitude; any discrepancy would alter its sensitivity greatly. For this reason, most vibrating gyroscope would have changes in the sensitivity, scale factor and ZRO with time. Much design cares and consideration must be made in designing this vibrating gyroscope. [44]

Compared to a vibrating structure, a rotating structure is a much simpler concept. It has less mechanical coupling, hence is intrinsically more stable. However at present time, development of rotating device in the micro domain (i.e. micro motor) is still in its infancy. Any conventional rotating systems need bearing suspension, which induced mechanical friction due to surface contact. Due to high surface to volume ratio in the micro domain, the friction causes extreme wear and restrict lifetime. This is the main reason why most research works are still done in improving micro vibrating design instead. [23]

Previous works on micro sized motor are analyzed in order to design suitable micro rotating device in the micro domain.[49-56]

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2.4 Micro Motor

A motor works by changing electrical energy to mechanical energy. Its main part consists of at least a stator and a rotor. The stator usually a metal coil wrapped with a conductor wires. The stator is just a lump mass, usually disk shape that may or may not be a permanent magnet. Electrical current, I flow through the wire and induced magnetic induction, B . The coupling magnetic induction and current will induce magnetic force, F , which causes rotation of the rotor. [50]

General mechanical device requires input power for motion manipulation. This source of input usually in form of a motor. Therefore, to run miniaturize mechanical structure would require similar source of power. It is then sensible to manufacture micro motor for running MEMS devices.

However most micro motor does not give satisfactory performance. Most micro motor suffers from stiction during fabrication, especially during rotor release step. The main problem in micro motor is its lifetime. Lifetime is limited by frictional wear during operation. The surface force on the motor bearing usually damage the material limiting lifetime into few hours or even minutes.

Tavrow et al (1992) had fabricated a micro motor with six stator and 4 rotor poles. The device was able to rotate up to 2000 rpm. But frictional wear of the bearing rotor

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limited its lifetime up to approximately 30 minutes. Bearing frictional wear is a significant problem, which must be addressed. [51]

In 1993, Wagner, et al has demonstrated few types of conceptual micro motor on silicon base material. They managed to fabricate sliding, rolling, rotating types. In all of these types, they put a permanent magnet onto a path (made by etching the silicon). The path is in the middle of few planar coils. The planar coils acted as the stator, current is put into it. The permanent magnet (rotor) is shown to be able to slide, roll, or rotate depending on the type. Maximum operating speed of 2000 rpm was achieved for the rotating type. The experiment was not yet optimized for certain application; it can only be viewed as demonstration. [52]

Figure 2.10 Silicon Based Micro Motor

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Ahn, et al (1993) has successfully fabricated a fully functional electrically excited planar variable reluctance magnetic motor on a silicon substrate. Magnetic cores wrapped around with current carrying planar meander shape conductors are used as the stators. This arrangement shall produce more efficient device due to large flux density production. The rotor was a hollow disk shape with salient structures. Electroplating was utilized to fabricate the rotor and the stators structure inclusive of the platform and pin for rotor bearing suspension. The stator shape was utilized for minimizing magnetic core reluctance. Iron (19 %) –Nickel (81%) were utilized as the stator and the rotor material. Maximum rotation of this motor was 500 rpm. [53]

Fujita from Institute of Industrial Science, The University of Tokyo has successfully fabricated a high speed electrostatic micro motor. The speed achieved was 10,000 RPM. The rotor size was 100 μm in diameter and 7 μm in thickness. The micro motor picture is shown in figure 2.12. [54, 55]

Figure 2.11 High Speed Electrostatic Micro Motor

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Although a successful rotor rotation, rotor suspension by pin in the middle of its hole will generate mechanical friction due to surface contact. This friction could cause wear, limit most structure lifetime and speed. It is not a suitable system to be implemented to the rotating gyroscope. Other type of rotor support should be implemented.

Komori, et al (2001) has an ingenious way of supporting the rotor without mechanical contact. Two pairs of electromagnet were used as the stator. They used a pair of electromagnet to levitate the rotor and another pair for rotation. Since no surface contact, mechanical friction was diminished. The rotor was a permanent magnet, therefore when the electromagnet was activated; the rotor would rotate to align itself with respect to the magnetic field. Two shapes of electromagnets were used as the stator, horseshoe shape and cylinder shape. The horseshoe shape was able to rotate until 30,000 rpm with stability, it required however almost 0.4 A input current. The cylinder shape was able to rotate until 3000 rpm; it only required approximately 0.6 mA input current. Consequently, in perspective of speed the horseshoe shape's performance was better, in perspective of power consumption, the cylinder was better. The arrangement of the micro motor could be viewed in the figure 2.13. [56]

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(a)

Figure 2.12 Non-Mechanical Contact Micro Motor

Another more attractive solution is suspension of diamagnetic materials. Diamagnetism is observed in almost every material; hence it is a more suitable material to use instead of permanent magnet.

2.5 Micro Rotating Gyroscope

Combining the idea of micro size gyroscope and motor, previous work on micro rotating gyroscope were done. [10] The gyroscope was fabricated using the concept of electromagnetic suspension of a diamagnetic body, and electromagnetic rotation.

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Moreover, due to absent of any mechanical contact, the problem of wear and low lifetime was overcome. Due to the same reason, problem of drift was addressed.

The figure below showed this electromagnetic suspension micro rotating gyroscope.

[5, 6]

Figure 2.13 SEM Pictures of the magnetically levitated gyroscope

Nevertheless, the development of this magnetically levitated gyroscope is still in its preliminary stage. Main problem preventing it to be commercialized is power consumption, which is very high. The working principle of this gyroscope shall be explained in detail in next chapter. After analyzing its working principle, it was concluded that an elegant way to reduce power consumption was to implement magnetic layer. This research project main purpose is to investigate magnetic material performance for improving the levitated gyroscope. Further explanations shall be presented in subsequent chapters.

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Micro Rotating Gyroscope Principle

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Micro Rotating Gyroscope Principle

This chapter would present explanation on the working principles of the micro-rotating gyroscope. In addition, the chapter would also highlight the performance and limitations of the device. Careful analysis of the working principle is essential for finding means to improve the micro-rotating gyroscope.

The multiphase rotating micro gyroscope works as a micro motor with magnetic bearing. The rotor rotates and levitates above the stator with magnetic suspension force. No mechanical contact is required to work as bearing for this system. This arrangement would remove all problems associated with frictional wear, which has been the main limiting factor for most micro size motor. For this reason, problem of short lifetime suffered by most micro motor could be addressed.

3.1 Initial Design of Micro Rotating Gyroscope

3.1.1 Discussion

Preliminary stage of developing the micro-rotating gyroscope had been finished with some limitations to be addressed. This subsequent project aimed to find new ways in improving the device to be able to achieve the required performance. Working principle of the micro rotating gyroscope was extracted from reference [10] as preliminary work was done as explained on this reference.

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Micro Rotating Gyroscope Principle

The micro-rotating gyroscope works by utilizing conservation of angular momentum principle for detecting rotation rate.

When a force is applied on rotating structure on a perpendicular direction with rotational axis, the structure shall move on direction perpendicular to the plane of force and rotation axis. This motion is called precession. Ability to *precess* is a special property of rotating structure, which will be used as principle of gyroscope.

[57]

3.1.2 Micro gyroscope rotating principle

The working principle of the rotating gyro could be referred by figure 3.1.

Figure 3.1 Rotating disk structure with reference axis

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Micro Rotating Gyroscope Principle

Any rotating structure have an angular momentum resulted from its motion. For rotation about z-axis, angular momentum of the disk about its z-axis is:

$$H_z = I_z \dot{\theta}_z \quad (3.1)$$

I_z is the moment of inertia of rotor about Z-axis.

When external torque T_x and T_y is applied,

$$\begin{aligned} T_x &= I_x \ddot{\theta}_x + H_z \dot{\theta}_y \\ T_y &= I_y \ddot{\theta}_y - H_z \dot{\theta}_x \end{aligned} \quad (3.2)$$

The micro-rotating gyroscope consists of a multiphase stator and a levitating rotor.

The disk shape rotor is designed to be rotationally symmetric about z-axis, hence its moment of inertia about x and y axis are equivalent, i.e.: $I_x = I_y = I_n$

The equation then becomes [10]:

$$\begin{aligned} T_x &= I_n \ddot{\theta}_x + H_z \dot{\theta}_y \\ T_y &= I_n \ddot{\theta}_y - H_z \dot{\theta}_x \end{aligned} \quad (3.3)$$

The rotor is designed to be a thin disk shape, which means that

$$I_x = I_y = I_n \ll I_z$$

The gyroscope would be operated under very high rotational speed

$$\dot{\theta}_z^* \geq 10,000 \text{ RPM} = 1050 \text{ rad/s.}$$

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Therefore,

$$\begin{aligned} I_n \ddot{\theta}_x &<< H_z \dot{\theta}_y \\ I_n \ddot{\theta}_y &<< -H_z \dot{\theta}_x \end{aligned}$$

Equation (3.3) then becomes [10]:

$$\begin{aligned} T_x &\approx H_z \dot{\theta}_y \\ T_y &\approx -H_z \dot{\theta}_x \end{aligned} \quad (3.4)$$

3.1.3 Constrained rotation

The gyro working principle can be modeled as a constrained rotation between its rotor and stator. When an external torque is applied, precession occurs for the rotating structure and result in a rotor tilt.

Figure 3.2 Precession of the rotor upon turn rate input

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Micro Rotating Gyroscope Principle

For a constrained rotation, relative angle between rotor and stator about x and y are

$$\begin{aligned} e_x &= \theta_x - \theta'_x \\ e_y &= \theta_y - \theta'_y \end{aligned} \quad (3.5)$$

Total torque of the rotor can be represented by using Newton's 2nd law:

$$\begin{aligned} T_x &= H_z \dot{\theta}_y + d \dot{e}_x + k e_x \\ T_y &= -H_z \dot{\theta}_x + d \dot{e}_y + k e_y \end{aligned} \quad (3.6)$$

Total torque of the rotor (in Laplace Transform)

$$\begin{aligned} T_x &= H_z s \theta_y + e_x (ds + k) \\ T_y &= -H_z s \theta_x + e_y (ds + k) \end{aligned} \quad (3.7)$$

Where

d = damping

k = stiffness

s = Laplace operator

Transfer function for the open loop operation

$$\begin{aligned} e_x &= \frac{-[H_z^2 s^2] \theta'_x - [d H_z s^2 + k H_z s] \theta'_y}{(H_z^2 + d^2) s^2 + 2kds + k^2} \\ e_y &= \frac{-[H_z^2 s^2] \theta'_y + [d H_z s^2 + k H_z s] \theta'_x}{(H_z^2 + d^2) s^2 + 2kds + k^2} \end{aligned} \quad (3.8)$$

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Steady state response

$$\begin{aligned} e_x &= 0 \text{ for } t \rightarrow \infty \\ e_y &= \frac{H_z}{k} \theta'_x \text{ for } t \rightarrow \infty \end{aligned} \quad \left. \begin{array}{l} \\ \end{array} \right\} \begin{array}{l} \text{For external} \\ \text{input } \theta'_x \end{array} \quad (3.9)$$

$$\begin{aligned} e_y &= 0 \text{ for } t \rightarrow \infty \\ e_x &= \frac{H_z}{k} \theta'_y \text{ for } t \rightarrow \infty \end{aligned} \quad \left. \begin{array}{l} \\ \end{array} \right\} \begin{array}{l} \text{For external} \\ \text{input } \theta'_y \end{array} \quad (3.10)$$

These equations show that with force applied proportional to its rotating axis the rotor move in direction perpendicular of the plane of force and rotation axis, which is to *precess*. [10]

External angular rotation to be measured is proportional to the relative angle of the stator and rotor. Hence angular rotation can be measured by observing the relative angle. It is also shown that angular rotation in y-axis would produce relative angle in x-axis and the inverse happens for x-axis angular rotation.

In the two equations above, $\frac{H_z}{k}$ is the *effective gain* of the sensor.

These two equations also show that high value of gain is essential for a high resolution sensor.

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Minimum range of the sensor is then limited by the gain of the sensor, while maximum range is limited by the rotor-stator separation. I.e.: rotor levitation height. This height limits the distance of tilt of the rotor without touching the stator.

3.1.4 Operational Bandwidth

From the transfer function, resonance frequency could be calculated as:

$$\omega_n = \frac{k}{\sqrt{H_z^2 + d^2}} \quad (3.11)$$

The gyroscope is designed to work under closed-loop operation utilizing electromagnetic force balance. The bandwidth of a closed loop operating inertial sensor is usually quoted as high as 40 % of the resonance frequency, regardless of the damping coefficient. [10]

$$B = \frac{0.4}{2\pi} \left(\frac{k}{\sqrt{H_z^2 + d^2}} \right) \quad (3.12)$$

Where:

ω_n = resonance frequency in rad/s

k = stiffness

H_z = rotor moment of inertia about Z-axis

d = damping

B = Bandwidth in Hz

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This equation shows that:

- B is inversely proportional to H_z , and
- B is proportional to k

Accordingly there is a *trade-off* between *bandwidth* and its *sensitivity*. This is the reason for many high sensitivity micro gyroscopes can only operate in small range of bandwidth.

The way of improving resolution, of course is to *increase gain (speed)*, for 500 μm diameter, and 10 μm thick aluminum rotor, and with rotor speed of 10,000 rpm, the gain ($\frac{H_z}{k}$) is 2.5×10^{-3} s with around $0.04^\circ/\text{s}$ resolution at a bandwidth of 1 Hz for a 100 ppm capacitance measurement resolution. or $0.24^\circ/\text{s}$ for max bandwidth of 35 Hz.

3.1.5 Simplified electromagnetic induction force for levitation

The levitating rotor requires vertical force to maintain its levitation. An upward force is required to balance the weight of the rotor. This force is provided by electromagnetic induction force. The levitation force is the product of current and flux density.

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The force per unit length is:

$$\vec{F} = \vec{I} \times \vec{B} \quad (3.13)$$

The stator and rotor is modeled as two circular coils with current flowing in opposite direction. The wire has certain amount of resistivity. To provide the force, input AC current is supplied in the stator. The input current will induce flux around its coil. The flux (resulted from mutual inductance from stator) then affects the rotor resulting eddy current flowing around it. The eddy current in turn also induces a small amount of flux onto the stator. Both the stator and rotor would produce a force due to its own current flow and flux from the respective component. [10] The net force of these two forces is then the force to levitate the rotor by balancing its gravity force, i.e.: *weight*.

In next few equations, stator will be referred as primary coil and rotor as secondary coil.

Figure 3.3 Stator and Rotor Model for Simple Calculation

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Input AC current at primary coil:

$$i_1 = I_1 e^{j\omega t} \quad (3.13)$$

This input current will result e.m.f. at secondary coil:

$$e_2 = M_{12} \frac{di_1}{dt} = j\omega M_{12} i_1 \quad (3.14)$$

Where

M_{12} is the mutual inductance between the primary and secondary coil.

As a result of e_2 , a current i_2 flows in secondary coil:

$$i_2 = \frac{e_2}{Z_2} = j\omega \frac{M_{12}}{Z_2} i_1 \quad (3.15)$$

Z_2 = electrical impedance of the rotor.

The interaction of the magnetic fields due to the primary and secondary current results in force between the conductors. This force will have nett component acting along the axial $\hat{z}$ direction due to axial symmetry of the model. Using principal of virtual work, the force ($\bar{F}$) required to move the secondary coil by an infinitesimal distance dz along the axis resulting in infinitesimal change energy dW is:

$$\bar{F} = -\frac{dW}{dz} \hat{z} \quad (3.16)$$

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Total energy input to the secondary coil is:

$$W = \int i_2 e_2^* dt = \int j\omega \frac{M_{12}}{Z_2} i_1 \bullet M_{12} \frac{di_1^*}{dt} dt = \frac{j\omega M_{12}^2}{2Z_2} i_1 i_1^* \quad (3.17)$$

The symbol * denotes the complex conjugate

Hence

$$\bar{F} = -\frac{dW}{dz} = -\frac{j\omega i_1 i_1^*}{2Z_2} \frac{d(M_{12}^2)}{dz} \hat{Z} \quad (3.18)$$

Dropping higher order terms, mutual inductance between the two coils is approximately:

$$M_{12} = \mu r \left[\ln\left(\frac{8r}{z}\right) - 2 \right]$$

$$\frac{d[M_{12}^2]}{dz} = -\frac{2\mu r}{z} M_{12} \quad (3.19)$$

The Impedance into coils 2 can be broken into resistive and inductive terms

$$Z_2 = R_2 + j\omega L_2$$

hence

$$\bar{F} = \frac{\mu r M_{12}}{z} \bullet \frac{j\omega}{R_2 + j\omega L} i_1 i_1^* \hat{Z} \quad (3.20)$$

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The DC force is obtained by substituting M_{12} and taking the real part[10]

$$\bar{F}_{DC} = \frac{\mu^2 r^2 [\ln\{(8r/z)\} - 2]}{z} \bullet \frac{\omega^2 L_2}{R_2^2 + \omega^2 L_2^2} I_1^2 \hat{Z} \quad (3.21)$$

From above equation, it could be observed that force is proportional to the square of current, frequency and permeability. It is inversely proportional to square of resistance. [10]

Therefore, levitation force maximization would require:

- High input current density
- High flux density production (high permeability material)
- High input frequency
- Low resistivity material

3.1.6 Rotation Principle of the rotor

Rotation is made possible by separating the single stator winding into multi planar coils, and exciting each coil with sinusoidal currents with relative temporal phase displacements. This multiphase stator would then produce a rotating magnetic field, which creates torque in the rotor.

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3.2 Initial model of the gyroscope

Previous fabrication on rotating gyro has been reported in reference. [10] The gyroscope was fabricated using single layer of metal. This was done to simplify fabrication process. This process limits the stator topology into single turn coil.

The levitation force is provided by interaction between current and magnetic flux density.

3.2.1 Initial Rotor Design

A single turn coil would produce moderately small amount of magnetic flux. Consequently, high current density is required to provide levitation force. All the coils experience high amount of current density. This will result in large amount of ohmic heating. For this reason, the coils themselves must be made from material with high melting temperature. The coils material should also have low resistivity to minimize power loss and to have better efficiency.

The material for rotor should have low resistivity and low density. High melting temperature should not be a significant factor since only eddy current, which usually is an order of magnitude smaller than the input current, will flow inside the rotor.

Ohmic heating is proportional to resistivity of the material; hence material with low resistivity is an important factor. Low density material will minimize the force required to levitate the rotor. After considering the factors above, Aluminium was

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chosen as the material to fabricate rotor. Aluminum rotor was fabricated using thermal deposition technique.

Maximum thickness limitation is *weight* and *skin effect*. Current density inside a conductor decays exponentially from its surface. Skin effect is the measure of depth of the conductor in which current density can still be considered constant.

Skin depth has relation with permeability, conductivity and frequency. [58]

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}}$$
(3.22)

And current flow inside the conductor would decrease according to:

$$\hat{J} = \hat{J}_0 \exp[-(1+j)\sqrt{\frac{\mu\sigma\omega}{2}}x]$$
(3.23)

Where:

$\hat{J}$ = current density

$\hat{J}_0$ = current density at surface

μ = permeability

σ = conductivity

ω = frequency in rad/s

x = distance from surface

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From above equation, when $x = \delta$, the current density would have decreased to about 37% of its surface value. Therefore the rotor was designed to have skin depth more than its thickness.

Minimum thickness limitation is *bending*. If the rotor material is too thin, the residual thermal stress would cause the rotor to bend into parabolic shape

3.2.2 Initial Stator Design

The stator conversely has to be made from material with high melting temperature due to high current density inside the stator. Low resistivity is also an important factor, while low density is not a factor in choosing stator material. The material chosen was gold. Gold has very high melting point and low resistivity. Gold coil stator was also fabricated using thermal deposition technique.

Maximum limitation of gold thickness is again residual thermal stress due to its fabrication technique. Minimum thickness limitation for gold is current density required. The stator should have sufficient thickness to maintain high current density without melting.

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Next figure show schematic representation of the micro-rotating gyroscope.

Figure 3.4 Schematic representation of the micro-rotating gyroscope (not to scale)

Levitation coil

The levitation system requires two coils with opposite flow of current. Current density is adjusted by the coil width. The net force (amount and direction) required is generated by two coils carrying current in opposite direction. The two coils should be far enough in order not to prevent any field cancellation. The two coils also served as current return path in multiphase stator to generate rotation.

Stability coil

The levitation system is intrinsically unstable. Certain amount of force is required to hold the rotor in position, i.e. not shear off. For this reason, another coil was added concentric and outside of the two levitation coils. This stability coil experienced

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current flow in opposite direction with the outer levitation coil. This outer circumferential stability coil generated net force to push the rotor inward to the center.

Nevertheless, this stability force reduced the levitation force due to its current that works in opposite direction with the levitation coil. For this reason, higher current density flow is required to maintain levitation. Thus power consumption increases with lateral stiffness. [5,6 10]

3.3 Performance and Limitation of initial design

The operation of the system consists of two components, namely radial and circumferential component. The radial component generates torque and levitation force, while the circumferential component provides levitation force and lateral stability.

Previous experimental result showed that the torque produced is proportional to the square of the input current, permeability and conductivity of the material. Rotor speed also is proportional to the square of the input current. However, due to aerodynamic drag, The rotor runs with very high slip. The speed of rotor is much less than the frequency of the input current.. Maximum speed reached (output speed) was 1050 RPM with a 10 MHz maximum frequency input, 1A peak input current at a phase angle of approximately 90° . Maximum current density in the stator was limited to approximately 10^{10} Am^{-2} . [10]

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However, this design has a few limitations associated with:

1. Power consumption
2. Fabrication limitation
3. Speed

3.3.1 Power consumption limitation

Power consumption of the stator was very high. The system needed high input current density with high frequency to maintain levitation and rotation. Furthermore, with high input current, ohmic heating is increased and there is more possibility for the stator to melt. High frequency input also reduces the skin depth, which resulted in less eddy current flow inside the rotor.

3.3.2 Fabrication limitation

Due to fabrication limitation, the stator was made by single layer of metalization. This drawback resulted in inefficiency in running the system. Single layer of coil would only produce low mutual inductance. Other macro design of coil could give more efficient inductance.

3.3.3 Speed limitation

The rotor speed influences the sensitivity of the gyroscope as explained. The rotor speed is proportional to the square of the current density and permeability. Air drag also influences the speed, which might be improved by operating it on certain condition. With limitation on maximum current that can be withstand by the stator

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coil, the system was limited to certain speed. Rotor speed was also limited by lateral vibration, hence lateral stiffness would have to be increased to achieve required speed and hence sensitivity.

3.4 Addressing the Limitations of Initial Design

All of these limitations would be addressed. For overcoming the power consumption and speed limitations stated above, few optimization works were carried out. As stated earlier the magnetic bearing force is dependent on the input current, operation frequency, and permeability. Therefore to achieve low power consumption and high-speed operation, increase in the two factors, namely operation frequency and permeability would be highly desirable. This would eliminate high input current problem by reducing ohmic heating effect.

As stated in the end of previous chapter, *inclusion of magnetic material* as an extra magnetic flux producer would address these issues. It would be an elegant way of producing *more force and reducing power consumption*.

Hence, this research project main objective was to investigate suitability of magnetic material to be used as magnetic backing pane in the micro rotating gyroscope.

Four related works were done in order to satisfy the main objective, namely:

1. Develop Infrastructure for reliable thick film deposition process.
2. Feasibility of fabrication of micro stator utilizing multi layer of metal.

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3. Setting up a reliable measuring device for magnetic layer characterization.
4. Investigation of magnetic material in high frequency operation.

Next chapter shall explain work on establishing infrastructure for sample fabrication. The fabrication process would utilize available micro fabrication facilities available in the Micro Machines Centre, NTU. Electroplating facility available was not suitable for our purpose, consequently it was established.

Reliable measuring device was essential as it always important to know the properties of material used in the project. The measurement done using the measuring device must be reliable and repeatable. Magneto Optics Kerr Effect equipment was being set up for this purpose. Calibration and validation were also done prior to the equipment set up. This work would be presented in chapter 5.

The micro-rotating gyroscope will be operating in high frequency operation due to its required speed to be highly sensitive sensor. The high operation frequency would also reduce power consumption, as explained earlier. Therefore, investigation of the magnetic layer in this range of high frequency is essential. Micro test structures were fabricated making use of micro fabrication technology and subjected to high frequency input. Readings on permeability value against frequency were recorded and presented in chapter 6.

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The figure below showed the initial design of magnetically levitated micro rotating gyroscope. [10]

Figure 4.1 Schematic representation of the micro-rotating gyroscope (not to scale)

As explained in section 3.2, this design still has few limitations. An elegant way to address it was by implementing magnetic material layer. The design is shown in the next figure.

Figure 4.2 Schematic representation of stator (not to scale)

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The rotor was not included in above figure because it was not looked into. Development of the rotor was well established, for this reason, the main focus of the project was the stator. The project excludes fabrication of rotor. The main concern of this project is performance of the magnetic material in the stator. This project focuses on investigation of the magnetic material performance as a magnetic backing plane.

Deposition of this magnetic material was required for investigation purpose. The properties of the deposited magnetic material shall be assessed using MOKE equipment (would be explained in detail in chapter 5). As the micro gyroscope will operate in very high operating frequency, assessment of the magnetic material in this condition was essential. Micro test structure had to be fabricated for this assessment (chapter 6 was devoted to explain this work).

Satisfying requirement for facilities for deposition and fabrication, infrastructure for these samples preparation was explored. This chapter shall explain this work. It shall begin with listing all the micro fabrication equipments required and briefly explained each. Intensive explanation shall be devoted in the electroplating process. This explanation would include setting up electroplating station and verification for reliability result.

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After the infrastructure has been integrated, fabrication of a micro stator was performed for validation. This fabrication process would also serve as feasibility testing of the infrastructure for further / future micro rotating gyroscope development.

Micro fabrication process required was as listed:

- Thin Film deposition, which include Sputtering and Vacuum Evaporation
- Chemical Vapor Deposition
- Electroplating
- Photolithography
- Etching

Section 4.1 would briefly explain each of the process stated above. Most of the process above was facilitated in Micro Machine Centre, School of MPE, NTU. However, electroplating facility available was unsuitable for our purpose; hence some works was done for its establishment. For this reason, electroplating process would be presented in subsequent separate section.

4.1 Micro Fabrication Process

4.1.1 Vacuum Evaporation

A source material, solid or liquid is heated to a high temperature; subsequently individual atoms acquire enough energy to escape from the surface of the solid / liquid. This means of causing ejection of atoms from a surface, called evaporation.

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Two types of heating:

1. Resistance heating

The source material is put inside a metal container, and then the metal container is heated, which subsequently heat the source material to evaporate, possible contamination of the container.

2. Electron beam bombardment

High-speed electrons bombard the source material to cause evaporation, less contamination between the source and container. [59, 60]

Figure 4.3 Vacuum evaporator chamber

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Figure 4.4 Vacuum Evaporation System

Issues relating to this process are listed below:

- Vacuum pressure
- Contamination
- Thermal stress
- Maximum thickness

Vacuum Pressure

Vacuum pressure is the most essential parameter of any vacuum deposition process.

The evaporation chamber must be in vacuum to reduce chance of collision between

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the source material and atoms from other gases present and to reduce evaporation temperature. Main problem for a vacuum chamber is water vapor, which can adsorb to chamber wall easily. Liquid nitrogen should be introduced to the chamber as it can freeze any gas inside especially the water vapor so they can be pumped out easily.

Contamination

Contamination inside vacuum chamber could be due to bad vacuum pressure and other source material. The first issue could be addressed by pumping the chamber for substantial amount of time, i.e.: overnight and by introducing liquid nitrogen. Second issue would require thorough cleaning before each deposition.

Thermal stress and thickness

High temperature evaporation process would cause residual stress on the thin film. Residual stress causes inconsistency in sensor that uses strain as its operation principle, i.e.: piezoresistive, piezoelectric devices.

Even for other type of micro devices, this residual stress could cause the thin film to strip off from the substrate if it is too high. The stress could be minimized by short period of deposition. Then again, some materials like gold and especially iron nickel have very low deposition rate and need substantial amount of time to deposit them.

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4.1.2 Sputtering

If a solid or liquid at any temperature is subjected to bombardment by suitably high-energy atomic particles (usually ions), it is possible for individual atoms to acquire enough energy via collision processes to escape from the surface. This means of causing ejection of atoms from a surface is called sputtering.

The ions that cause sputtering usually is made inside a vacuum chamber with only argon gas inside. Two electrodes are subjected to high voltage difference (thousands of volts). Being inert gas, argon has no charge carrier. Electrons are then introduced which act as charge carriers, they will be moving away from the cathode towards the anode. These high-energy electrons collide with the argon gas particles. An electron hits a gas particle and losses its energy to the particles. Consequently, orbital electron of the gas particle becomes excited with enough energy to separate from the atom and become free electron, leaving the atom to be a positive ion. This process cause high luminous area called plasma. Another negative charge probe is introduced inside this plasma. The negative probe will create an electric field, which attract positive ions but repel electron as it is negatively charged. This field is called ion sheath.

Hence, the target material is attached into this probe and ions will bombard the surf of the target, which cause it surface atoms to be ejected. Substrate to be coated is then introduced and receives the ejected atoms.

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For non-conducting target RF sputtering is used. The target is bonded with a conductor and then high frequency RF signal is introduced which makes sure the target is always at negative charge.

Figure 4.5 Schematic Diagram of Sputtering Process

The issues relating to this process are surface stress. The issue is similar to thermal evaporation since they are both vacuum deposition process. However, since no thermal energy is used, the surface stress in this process is expected to be much lower.

Vacuum chamber of a sputtering equipment is presented in the figure .4.6 [59, 60]

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Figure 4.6 Sputtering equipment vacuum chamber

4.1.3 Chemical Vapor Deposition

Chemical Vapor deposition is used to deposit layer of silicon nitride onto the wafer substrate. Chemical Vapor deposition is a process based on the principle of initiating a chemical reaction in a vacuum chamber resulting in the deposition of the reacted material on a heated substrate. The fabrication used a Plasma Enhanced Chemical Vapor Deposition, which gas can react and deposited in a low temperature substrate by inducing plasma. [60, 61]

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Figure 4.7 Plasma Enhanced Chemical Vapor Deposition

Next few steps in the fabrication were:

1. Mask design
2. Photolithography
3. Etching

These steps / process are used in MEMS to fabricate various types of Microsystems.

4.1.4 Mask Design

Different topographic shapes in a silicon wafer are achieved by first designing a mask.

The user design mask with the *topographic shapes* or *geometric pattern* he wishes (usually with standard software), the pattern is then *projected* / “copied” to the silicon

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wafer. L-edit software for mask design should be utilized. The mask is made of flat transparent glass is the shape of a plate, where a thin film of an opaque substance has been deposited to form the desired pattern.

4.1.5 Photolithography

Photolithography is the next step in working with silicon wafer. It is defined as a process that uses *light radiation* to expose a coating of photo resist on the surface of a silicon wafer. The light source (usually UV light) and the wafer are separated by the mask. The mask provides the geometric pattern for the wafer; hence only portion of the light source reaches the wafer. The light reaches the wafer and creates the geometric pattern on the wafer.

Before being exposed to light source, the wafer is coated with photo resist. Photo resists are organics polymers that are sensitive to light radiation in a certain wavelength. To a certain chemical, the polymers solubility will increase or decrease as the result of their light sensitivity.

Two types of *photo resist* are available. They are *positive* and *negative* photo resist.

A positive photo resist becomes more soluble in light exposure, while a negative photo resist becomes less soluble. A positive photo resist can give better resolution than negative photo resist. However, negatives resist can give well etch resistance.

[60, 61]

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Figure 4.8 Mask Aligner for Photolithography process

After going through photolithography process, the wafer was next subjected to etching process

4.1.6 Etching

Etching is process of selective removal of materials. Portions of the material that are not coated are removed either by wet chemical etching, dry plasma etching, or sputter etching.

Wet chemical etching, as the name suggests used aqueous solution to etch away materials. Acids usually are the preferred choices for etchant. Different types of

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materials have different etchant to suit their needs. Wet chemical etching reaction is *isotropic*.

Dry plasma etching is etching process using ionized gas as etchant. The ionized gas is used to generate reactive atoms or molecules to chemically etched the target upon contact. Fluorine and chlorine gases are usually used in this process. Advantage over wet chemical etching is *anisotropic* reaction.

Sputter etching is physically bombarding the wafer surface with ionized gas causing the surface to eject atom of the material.

Combined plasma etching and sputter etching is possible; it is called *Reactive Ion Etching (RIE)*. [60, 61]

4.2 Electroplating

Deposition of magnetic material as backing plane would require a thick film process. Films of few microns thickness were required to serve the purpose for power consumption reduction. Vacuum deposition is not a suitable candidate for this requirement. Low deposition rate and surface stress shall limit the thickness. Electroplating process is a suitable candidate to satisfy the requirements. Hence this process was explored. This exploration works was performed along with Mr. Ho Wei Hong. His valuable contribution is highly appreciated.

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4.2.1 Electroplating Principle

Coating of metallic layer onto a surface of substrate material by dipping the substrate to an electrolyte solution containing the metal ion to be deposited. Electric current is introduced to the system, in which the substrate to be deposited is used as the cathode and other metal element must be used as the anode. [48, 18] This work utilized platinum mesh as the anode. As the process requires electrical connection, prior to electroplating process, the surface of the wafer has to be deposited with metal layer. This can be done by vacuum deposition.

Material deposit rate can be calculated using Faraday's second Law. [60]

$$\begin{aligned} m &= \alpha_F It = \rho TA \\ \frac{T}{t} &= \frac{\alpha_F I}{\rho A} \end{aligned} \tag{4.1}$$

Where:

m = deposited mass

α_F = (mole weight/valence)/96,500g/C

ρ = density of the plated material

I = current

t = plating time

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T = plating thickness

m = mass of the deposited material

4.2.2 Equipment and Materials

As stated earlier, the electroplating station inside Micro Machine center was not suitable for our purpose. It has been employed mainly for copper deposition. Therefore suitable electroplating station had to be set up and optimized.

The electroplating setup was consisted of the following equipments:

- Electroplating cell /tank
- Stand alone Heater
- Custom made cathode for 4” wafer
- DC power Supply
- pH Meter
- Platinum anode
- Wafer holder as the cathode
- Nitrogen gas supply

The plating tank and stand alone heater were designed and outsource for manufacturing.

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Specification of the electroplating tank design was as follow:

- PVDF material to withstand heat and chemical solution.
- External N2 hose connection was included, for N2 agitation which expected to produce better plating surface uniformity.
- Overall dimension is 225 mm diameter x 180 mm height
- As the plating solutions are hazardous, plating tank cover and exhaust valve was included for safety reason.

The arrangement would also require a stand alone heater for temperature control. The heater applied was L-shape Teflon Coated Heater with 240 V and 1.5kW input power equip with PID temperature controller. Low surface stress deposit was expected due to temperature control process. For this reason, the process was expected to produce thicker material compare to vacuum evaporation. The electroplating set-up can be referred to figure 4.10.

The cathode wafer holder has few strict requirements, namely:

- Able to hold wafer firmly
- Electrical connection between external source and wafer surface
- Stringent seal for its electrical connectors to ensure no contamination occurs.

The cathode wafer holder available in the Micro machine center was utilized. Figure 4.9 shows the wafer for holder as a cathode for electroplating plating process.

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Figure 4.9 Custom made cathode for plating 4" wafers

Figure 4.10 Electroplating setup

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4.2.3 Procedures

Following its initial set up, preliminary operation of the electroplating equipment was performed. It was utilized to deposit FeNi (Permalloy). The solution used was a mixture of $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$, NaCl, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, diluted NaOH and H_2SO_4 .

Initial operating condition of the electroplating followed the solution manufacturer specifications of: DC current supply of 0.177 Ampere, temperature 60°C and pH 3.

4.2.4 Electroplating Issues

There were two significant issues associated with electroplating process, namely:

- Metallic Contamination
- Peeling Of Deposited Layers

4.2.4.1 Metallic Contamination

Initial plating was done with 50 seconds operation time. Prior to plating, the wafer was coated by chromium seed layer using e-beam evaporation.

The result was a green color of uniform metallic layer with patches of red color metal.

Initial hypothesis base on the color suggested copper contamination. Further investigation of the contaminant material was performed utilizing EDX technique.

Investigation of contaminant material

EDX test was used to investigate the elements present and their composition in the deposited material. The EDX arrangement was made up of two components, the

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Hitachi Scanning Electron Microscope and Oxford EDX Analyzer. The test result could be viewed in the figure 4.11.

Figure 4.11 EDX results for contaminated sample

Examination of the test results (figure 4.11) confirmed that copper was deposited onto the substrate. This examination result verified the initial hypothesis, in which copper was the contaminant. However, the EDX test result showed that chromium, silicon, copper, iron and nickel were also present in the tested sample. This encouraging result verified that the electroplating process was successful, yet some adjustments were needed for contamination prevention.

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Discussion on the source of copper contaminant

Careful examination of the electroplating equipment was performed. It was then discovered that the copper contamination was due to improper sealing of the wafer holder, i.e. the cathode.

As stated earlier, stringent sealing is essential for electroplating process, with improper cathode sealing electrical contact occurs between the solution and the copper wire. Upon contact, the copper wire ionizes to form Cu^{2+} ions,

The presence of Cu^{2+} ions in the electrolyte resulted in the deposition of Copper onto the substrate. The deposition of copper should occur due to its positive Standard Reduction Potentials, E°_{red} of copper (+0.337V). As a comparison, potential of Iron is (-0.44V) and Nickel is (-0.25V).

Thorough inspection of the cathode was performed. Suspected reasons were the improper dimensioning of a cathode's fastening screw and O-ring malfunction. The screw thread of the supplied fastener was too long, which prevents it from exerting adequate pressure to the sealing ring. The O-ring had lost its elasticity; this would cause leakage on the cathode. Next two figures highlighted these two issues.

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Improper sealing
due to improper
dimension of
fastening screws

Figure 4.12 Sealing defects on cathode

Figure 4.13 Rubber sealing rings

The fastening screw of the cathode was shortened by approximately 3mm and tested by submerging the cathode in water for 30 minutes. The O-ring was replaced to ensure satisfactory function. The cathode was dried externally and then disassembled to check for the presence of moisture in the copper conductors. The result of o-ring replacement and re-dimensioning of the fastening screws successfully solved the sealing problem that caused the copper contamination.

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Figure 4.14 Machined fastener compared to original fastener

4.2.4.2 Peeling of Deposited Layers

Exploration of types of base layer for better adhesion was performed. Copper and chromium was commonly used as base layer for FeNi deposition. Hence chromium and copper was explored.

The electroplating of Permalloy on silicon wafer substrate was first investigated using chrome seed layer. Chromium was the preferred over copper as the latter tarnishes easily, while the dual seed layer is less cost effective. The electroplating process suffered from the problem of the flaking of FeNi alloy from the substrate. As shown in next figure, the peeling occurred at the boundary between chrome and FeNi alloy.

This observation suggested that the adhesion between chrome and silicon was strong while that of chrome and FeNi layer was less than satisfactory.

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Figure 4.15 Flaking of deposited Permalloy from Chromium base layer

Next deposition was performed using copper as base layer. Yet again peeling of the FeNi layer occurred. Sample inspection showed that flaking occurred between the silicon wafer and the copper layer. It was observed that the FeNi layer and copper layer had good adhesion. This observation suggested that the adhesive strength between copper and silicon is less than desirable.

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Figure 4.16 Flaking of deposited Permalloy and Copper from Silicon Wafer

The two observations above suggested that chromium has good adhesion to silicon and subsequently copper has good adhesion to FeNi. Further exploration should be on adhesion between chromium and copper.

Consequently, next work done was to deposit chromium and copper layer on top of each other using e-beam evaporation. The result was satisfactory; they have good adhesion to each other. Afterward, the sample was electroplated with FeNi.

FeNi was successfully deposited onto the silicon wafers using the copper and chrome base layers consistently. The electroplated result was without any mechanical deformities should be suitable for the development of the magnetic backing plane.

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Figure 4.17 Successful deposition of FeNi on Chromium and Copper base layers

Following successful deposition, the process was repeated by increasing plating time and the DC current input. The flaking problem of FeNi layer did not reocurred during the deposition process.

Afterwards, the electroplating of FeNi was explored to a thickness of $2\mu\text{m}$ to check for possible flaking problem occurrence. Six separate tests were done with successful deposition of FeNi without any flaking or surface defects.

Electroplating station had successfully been established. The station should be able to be used to deposit metal up to few micron thicknesses as demonstrated.

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4.3 Validation of infrastructure established

After establishing all the micro fabrication equipment required, it was validated by fabricating a micro stator.

Fabrication steps

1. Evaporation of thin layer of chromium as base layer
2. Electroplating of gold layer, The gold plating solution used was *MICROFAB AU-100*, a non-cyanide mild alkaline gold solution with 99.99% purity and deposition rate of 3.2 $\mu\text{m/min}$ for 0.5 A/dm^2 input current density
3. Gold layer was then patterned using photolithography.
4. The stator pattern was then etched to reveal the wanted portion.

The fabrication was performed to validate the establishment of infrastructure required.

It was also performed as feasibility testing for future micro rotating gyroscope development.

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Figure 4.18 SEM View of a Four Phase Device Stator Coils

4.4 Conclusion

The stator fabrication was accomplished successfully. This success validates the infrastructure establishment. This success also proved that it was feasible to fabricate gold stator in the infrastructure / facility established earlier. The end product of stator fabrication would be presented in the next two figures.

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Figure 4.19 Fabricated Micro Stator (shown with coin for comparison)

Figure 4.20 Finished Micro Stator Product

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The two pictures above showed stator for the micro motor attached to standard TO-8 IC header package.

The infrastructure was also utilized to fabricate sample for MOKE experiment and high frequency operation testing. Sputter equipment was utilized to deposit Fe sample used for MOKE experiment (explain in chapter 5). High frequency operation testing required micro coils as samples. These samples were fabricated using all of the equipments explained in this chapter. This work was presented in chapter 6.

CHAPTER FIVE

Processing and Characterization of High Permeability Thin-Film for Micro Rotating Gyroscope Development

MOKE Utilization

Chapter Five

MOKE Utilization

As explained in earlier chapter, improvement on the micro gyroscope stator would require implication of magnetic backing plane. This additional layer was expected to reduce power consumption by producing extra magnetic flux density, B . For this reason, the work explained in this chapter was done. Characterization of the magnetic material deposited is essential to fulfill requirement of high flux density production. Quantitative analysis of the material permeability is important. Magnetic permeability measuring equipment is required for this purpose. MOKE equipment is utilized for this purpose.

MOKE equipment has a minor disadvantage of inability to measure an absolute moment value. However, it is still ideal equipment for measuring relative changes and magnetic isotropy. Some other major advantages also justify use of MOKE equipment, they are:

- Non-destructive testing
- Ability to analyze developments of magnetic material and its properties in real time.

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MOKE Utilization

This chapter shall begin with explanation on Magneto Optical Kerr Effect principle. Then explanation of setting up MOKE equipment and validation of the equipment shall follow. Results on the experiments utilizing this equipment shall be presented at the end of this chapter.

Furthermore, quantitative value of permeability could be measured by inductance test as explained in the next chapter. In this work primary interest was setting up the MOKE equipment for qualitative analysis on quality of the magnetic material.

MOKE acronym for Magneto Optic Kerr Effect is equipment, which uses magneto optical effect of magnetic material. A substrate with thin film of magnetic material is placed under magnetic field, and then a laser beam is fired onto it. The laser beam reflection would have its phase plane of polarization rotated slightly (few minutes of arc). The rotation is proportional to magnetization and the thickness of the material. Using this equipment, magnetic hysteresis curve could be constructed. [24]

Figure 5.1 Schematic Diagram of MOKE Equipment

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It is also worth mentioning that Faraday Effect, a similar phenomenon in magneto optical effect, corresponds to a change in the intensity or polarization state of light transmitted through a magnetic material.

Figure 5.2 Magneto Optical Kerr and Faraday Effect

Nevertheless, the scope of this project is limited to using MOKE to examine magnetic properties.

5.1 Magneto Optical Kerr Effect Principle

Reflection of a beam of a linearly polarized light from a magnetized surface causes the polarization to become elliptical, with the principal axis rotated with respect to the incoming light. Usually the amount of rotation (in radians) and of ellipticity (ratio between the minor and major axis of the ellipse) induced in the reflected beam is of

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the order of $1/1000$, i.e. relatively small. This phenomenon as mention earlier is known the magneto-optic Kerr effect. The technique is sometimes referred to as SMOKE, where S stands for Surface [62]. This technique mainly analyze the atoms on the surface in the case of ultra thin films with total thickness below about 10 nm, the effect is proportional to the film thickness.

MOKE technique analyzes the change in the polarization to determine the material properties. MOKE experimental setup normally involves passing laser light through a polarizing filter and then reflecting the light off the sample. The light then passes through another cross-polarizing filter. As light changes in the plane of polarization will thus cause variations in the detected light intensity after the second filter.

MOKE is mainly used to measure the hysteresis loops of thin magnetic films, by plotting the signal (rotation or ellipticity) as a function of the applied magnetic field MOKE can also be used as scanning microscopy technique, so that magnetic domain imaging with micrometric resolution become possible.

Three basic configurations of MOKE experiments:

- The Polar Orientation
- The Longitudinal Orientation
- The Transverse Orientation

[62]

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The three orientations are defined in terms of the direction of the magnetization vector M with respect to the surface of the material and the plane of incidence of an incident optical beam. These are illustrated in diagrams shown in next three figures. [27]

Figure 5.3 Longitudinal Orientation of MOKE

In the longitudinal configuration, the magnetization vector is in the plane of the surface and parallel to the plane of incidence. The sign and magnitude of these effects are proportional to M and its direction. No effect is observed at normal incidence.

Figure 5.4 Polar Orientation of MOKE

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In the polar case the magnetization vector is perpendicular to the plane of the surface. The sign and magnitude of these effects are proportional to M and its direction. In this case there is an effect observed at normal incidence.

Figure 5.5 Transverse Orientation of MOKE

The transverse case is quite different from the previous two. In this case, the reflected radiation remains linearly polarized and here is only a change in reflected (or transmitted) amplitude such that as M changes sign from $+M$ to $-M$ the reflectivity changes from $R+\Delta R$ to $R-\Delta R$. No effect is observed at normal incidence.

5.2 Magnetism

5.2.1 Easy axis of magnetism

Magnetic material has its own preferred magnetic orientation. This preferred alignment is mainly due to the geometry of the material or the crystallographic

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orientation of the atoms arranged in it. The axis where the preferred alignment lies is termed easy axis of magnetism.

On the other hand, the hard axis is usually in perpendicular direction to the easy axis. When the magnetic moments are forced to align in the hard axis, there is a demagnetization effect as shown in the next figure. [63, 64]

Figure 5.6 Easy Axis of Magnetism

Figure 5.7 Hard Axis of Magnetism

5.2.2 Hysteresis Loop and Magnetic Properties

Magnetic Hysteresis Loop is the result of a MOKE experiment. Study of a material hysteresis loop can produce a great deal of information about its magnetic properties. A hysteresis loop shows the relationship between the induced magnetic flux density B and the magnetizing force H . It is generally referred as B - H curve.

A typical Hysteresis loop is shown in the figure 5.8. [63]

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Figure 5.8 Hysteresis Loop of a magnetic material

The hysteresis loop is generated by measuring the magnetic flux B of a ferromagnetic material while the magnetizing force H is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line from (a) as H is increased. As the line demonstrates, the greater the amount of the applied current ($H+$), the stronger the magnetic field in the component ($B+$).

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At point (b), almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in the magnetic flux. The material has reached the point of magnetic saturation. When H is reduced back down to zero, the curve will move from point (b) to point (c). At this point it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the remanence or level of residual magnetism left in the material. (Some of the magnetic domains remain aligned but some have lost the alignment).

As the magnetizing force is reversed, the curve moves to point (d), where the flux has been reduced to zero. This is called the point of coercivity on the curve. (The reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero). The force required to remove the residual magnetism from the material, is called the coercive force or coercivity of the material.

As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction to point (e). Reducing H to zero brings the curve to point (f). It will have a level of residual magnetism equal to that achieved in the other direction. Increasing H back in the positive direction will return B to zero. Notice that the curve did not return to the origin of the graph because some force is required to remove the residual magnetism. The curve will take a different path from point (g) back to the saturation point where it will complete the loop.

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The H is proportional to the current supplied into the circuit. Suppose if the current source to the magnetic field is sinusoidal, the point plotted onto the current-time graph and mapped to the hysteresis loop is shown in figure 5.9. [63, 64]

Figure 5.9 Path of hysteresis and sinusoidal current input

From the hysteresis loop in figure 5.9, a number of primary magnetic properties of a material can be determined.

1. **Retentivity** or **remanence** – a measure of the residual flux density corresponding to the saturation induction of material. It is a material's ability

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to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation. (The value of B at (c) on the hysteresis curve). The term remanence ratio is the value of B_r/B_s .

2. **Residual Magnetism** or **residual flux**- the magnetic flux density that remains in a material when the magnetizing force is zero. Residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.
3. **Coercive force**- (also known as **coercivity**) the amount of reverse magnetic field which must be applied to a magnet to make the magnetic flux return to zero. (The value of H at point (d) on the hysteresis curve).
4. **Reluctance** – is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit. The area of the hysteresis loop determines the total energy required for a full magnetization-demagnetization cycle.

[64]

In addition, the area of hysteresis loop determines total energy required for a full magnetization-demagnetization cycle. $B-H$ represent a net loss in the system, usually in the form of heat .A “square” (thin and tall) loop is preferable in high-frequency applications. The shape of the hysteresis loop tells a great deal about the material being magnetized. The hysteresis curves of the two curves of two different materials are shown next. [64]

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Figure 5.10 Hysteresis loop comparison of hard and soft magnetic material

Relative to the other material, the materials with wide hysteresis loop (red curve) has:

- Lower permeability
- Higher retentivity
- Higher coercivity
- Higher reluctance
- Higher residual magnetism

The material with the narrow loop (blue curve) has:

- Higher permeability
- Lower retentivity
- Lower coercivity
- Lower reluctance

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- Lower residual magnetism

In magnetic particle testing the level of residual magnetisms important. Residual magnetic fields are affected by the permeability, which can be related to the carbon content and alloying of the material. A component with high carbon content will have low permeability and will retain more magnetic flux than a material with low carbon content. [64]

5.3 MOKE Set Up

MOKE equipment has been set up in the laboratory and it should be able to measure any magnetic material with reliable result. Hysteresis curve could be constructed using this equipment.

5.3.1 Experimental Setup

The MOKE set up employed Helmholtz coil arrangement. A helmholz coil is a pair of specially constructed coils mounted a fixed distance apart on a common base. Current passed through the coils produce an extremely uniform magnetic field in the space between them. Based on this fact, it proves to be very useful in the set up of the MOKE magnetometer. Brief explanation on magnetic flux density produced by Helmholtz coil is presented.

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Figure 5.11 Schematic Representative of Helmholtz Coils

The two identical coils are separated by a distance r , which is the radius of the coil, from each other. The magnetic field produced is in the same direction as shown and the B of the Helmholtz coil can be calculated by [63]

$$B_x = \frac{\mu_0 i}{2r} \left[\frac{1}{\left(\gamma^2 + \gamma + \frac{5}{4} \right)^{3/2}} + \frac{1}{\left(\gamma^2 - \gamma + \frac{5}{4} \right)^{3/2}} \right] \quad (5.1)$$

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Where:

B_x: magnetic field at any point on the axis of the Helmholtz coil. The direction of the field is perpendicular to the plane of the loops in Teslas

R is the radius of the current loops in meters

γ is the ratio of x/r

x is the distance on the axis, with center of the helmholz coil as the reference.

However, the magnetic sample of the MOKE set up will be placed on the axis in the center of the helmholz coil (x=0), hence the simplification of equation is:

$$B_0 = \frac{\mu_0 i}{r \left(\frac{5}{4} \right)^{3/2}} \quad (5.2)$$

The Helmholtz coil was chosen to this experiment due to its extremely uniform field strength. This advantage will greatly reduce the error. Another commonly used simple coil arrangement, namely a solenoid does not have such advantage. The graph below makes a comparison between the two types of coils.

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Figure 5.12 Comparison of normalized axial field strength of Helmholtz coil and solenoid

The longitudinal MOKE equipment was chosen for this work. The schematic representation on the equipment setup can be viewed from the diagram below.

Figure 5.13 Schematic Diagram of MOKE setup

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Equipments to be utilized:

1. Melles Griot He-Ne Plasma Laser (Class 3B 30mW model 3230H-PC-M) and adapter with a wavelength of 632.8nm and an output of 30mW
2. Melles Griot Large Dynamic Range Amplifier
3. ThorLabs Model MC1000 Optical Chopper
4. Polarizer, incident angle was set to 150 from the surface normal of the sample
5. Stanford Research Systems Model SR 850 DSP Lock-In Amplifier
6. HP 33120A 15 MHz Function Waveform generator
7. Helmholtz Coil: 5 Layers, 55 turns, Radius: 15 cm

Figure 5.14 MOKE Equipment Setup

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Arrangement of the equipment.

- Test sample is placed in between Helmholtz Coils.
- DC input current is applied to the coils, which will produce magnetic field across the test sample.
- A polarized laser beam is fired onto the sample surface, the beam will be reflected and sense by a photodiode.
- The rotation angle (Kerr rotation) is then recorded by a lock in amplifier.

Prior to MOKE equipment usage, stability of the equipment must be ensured. Hence next section shall comprise discussion on methods ensuring equipment stability, followed by validation to ensure reliable results. Validation was achieved by using thin film iron sample to facilitate comparison with its theoretical properties.

5.3.2 Stability of the Equipment

The task was to ensure that the magnetometer setup was reliable and fairly sensitive. Various adjustments to the setup were done to improve stability.

The intensity stability of the experiment was measured by its % deviation of the stability:

$$\frac{\text{Maximum_Intensity} - \text{Minimum_Intensity}}{\text{Average_Intensity}} \times 100\%$$

(5.3)

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The stability of the experimentation was very important, as it would contribute to the noise of the experiment. The change in intensity measured when a magnetic film was placed in a varying magnetic field was small. A large % deviation would give then a very *poor signal to noise ratio*. Improving results by *removing* the inherent random variation of the experiment was to repeat as many readings as possible and take average trace out the hysteresis loop. Then again it would be time consuming and inefficient. Thus it was necessary to analyze and improve the intensity stability.

For these reason, few important aspects must be explored in setting up the MOKE equipment. They were:

- Laser stability
- Lighting effect
- Effect on power source on large range amplifier
- Mechanical Chopper optimum operating frequency
- Waveform function generator and power supply stability

In this section, all the factors above, which might affect the stability, were looked into. A maximum of *0.5 % deviation of the stability* and *signal to noise ratio* of *40: 1* was desired.

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Stability of the laser from cold start

In this part of the procedure, the stability of the laser was tested from cold start.

Results were shown in the graph below.

Figure 5.15 Stability comparison for different start up time

The figure above confirmed that the warming up of the laser was necessary before any reliable readings area could be taken. Manufacturer specifications stated that from cold start, the laser needed warming up and was able to reach full power and stability in less than 15 minute. Graph analysis showed that at 15 minutes, reasonable signal to noise ratio could be achieved, however the stability was still unsatisfactory. Further analysis showed that both stability and satisfactory signal to noise ratio was achieved at 25 minutes. Therefore, the laser was given a 30 minutes warming up duration. Experiment readings were completed within 8 hours in each session since the laser was predetermined to be stable in the given time frame.

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The initial experimentation was recorded and a data sample rate of 8 Hz in a time span of 200 sec giving a total of 1601 points. Stability results were taken from reflecting the laser off a clean Si wafer without any deposits or doping of any ferromagnetic atoms. The intensity measured was in arbitrary unit.

Effect of lighting in the lab

In any optical experiment, the first aspect was to examine whether the surrounding lights would affect the accuracy of the results. Therefore, effect of the laboratory fluorescence lights was also investigated. There were three fluorescence lights in the laboratory during the experiment. The lights were kept on for the first 3 runs and the next 3 runs were kept off. Then the lights were switched back on for the last run.

Figure 5.16 Effect of surrounding light on stability

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Next figure would give a better understanding where the % deviation of the stability of each run was calculated using equation (5.3). This would distinguish more clearly the effects of the surrounding lights in the laboratory.

Figure 5.17 Surrounding light effect on % deviation of stability

Analyzing the graph above, it showed that the lighting did have an effect. This was probably due to instability of the fluorescent lights. It was decided then, to keep off the lightings throughout the experiment.

Effects on power source for large range amplifier

The next factor considered that might add to the noise of the experiment was the large range amplifier. The large range amplifier was the one connecting the photodiode to the lock-in-amplifier. It was necessary to investigate the influence of using the

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rechargeable batteries or direct AC power supply for the large range amplifier during the experiment. The actual scan length and the % deviation graphs area were shown in the next two figures.

Figure 5.18 Effect of type of power supply on stability

Figure 5.19 Effect of type of power supply on % deviation of stability

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It was concluded that using the rechargeable batteries in the operation would reduce the noise. This was because when using direct power supply for the large range amplifier, the batteries were also going through the charging process, which subsequently produced noise.

Optimum frequency of the mechanical chopper

Next equipment that was explored was the frequency of the mechanical chopper. This frequency was used as reference source to lock-in-amplifier and isolated it to single out the intensity from the photodiode that was of the same frequency.

Figure 5.20 Mechanical Chopper frequency effect on stability

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Figure 5.21 Mechanical Chopper frequency effect on % deviation of stability

The ideal frequency to be chosen was such that none of the equipment in the laboratory was running at that particular frequency range. Frequencies at 50 Hz and multiples were not included because the power supply runs at that frequency. As seen from figure above, the frequency did play a role in the stability of the collected data. The smallest % deviation occurred at about 160 Hz and again about 310 Hz. The high % deviation at other frequencies was probably due to other equipment operating at those frequencies. Careful analysis determined that at about 160 Hz was the 1st cycle of a low noise ratio. A good frequency to use was decided at 317 Hz.

Stability with the waveform function generator and power supply

With all the necessary adjustments made, the next step was to check if the waveform function generator and the power supply for the helmholz coil produce a lot of noise.

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For previous investigations, these instruments were kept off and there was no magnetic field produced. This portion of the experiment could also be used to validate the principle of MOKE. Since the sample is a clean wafer, there should not be any change in the intensity except for the instability and the noise of the setup.

The test duration was reduced to 100 seconds; the power supply for the helmholz coil generated a total of ± 16 Amps. However the coil configurations were in parallel, thus the total current was divided into 2 loops such that each coil received ± 8 Amps. A triangular-wave at 10 MHz was produced by the function signal generator.

The improved adjustments were made and the data was then recorded. The following figure shows the comparison between initial stability and the new improved stability of the MOKE setup.

Figure 5.22 Stability Optimization

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After considering all the factors, the stability of the MOKE was significantly improved. As seen from figure above, the new improved stability calculated to be about **0.1%** deviation, which was excellent. This showed that the required intensity stability of below 0.5 % was achievable.

The summary of the conditions for good intensity stability of the simple MOKE setup is as follows:

- Laser needs to be warmed up to >1 hours
- Lights in the laboratory to be switched off
- Large range amplifier to be using batteries
- Frequencies of mechanical chopper to be 317 Hz

The rest of the equipment had the following operating conditions:

Incident laser angle = 15^0 normal to the sample

Extinction ratio ≈ 2 to 3 degrees off the extinction angle

Large Dynamic range Amplifier = 2 μ A

The lock-in-amplifier settings were

- Sensitivity = 500 mV
- Reserve = max
- Time constant, $\tau = 100$ ms
- Filter = 18db/oct

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- Synchronous = off
- Sample rate = 32 Hz (sample rate can be increased for a larger number of points)

The helmholz coil were set at 15 cm apart = radius of each coils.

Each coil had 5 layers and 55 turns giving a total of $N = 275$.

Using equations discussed before, thus H is found.

$$H = \frac{0.7155 \times N \times i}{r} \quad (5.4)$$

With the current flowing into each loop of the Helmholtz coil at ± 8 A, thus the H is varied from ± 10.494 kA/m.

5.3.3 Validation of MOKE Experimental Setup

The MOKE setup was then used to test on a thin film of Iron deposited on Si wafer by sputtering. The ability of the MOKE experiment to attain a typical hysteresis was tested by altering the magnetic field strength, H . the magnetic field strength was adjusted by controlling the amount of current going into the helmholz coils via the signal generator.

A typical hysteresis loop obtained from the thin film of Fe on a Si wafer substrate as shown in next figure was similar to those obtained in references [64]. From the figure, the signal obtained for the hysteresis loop was clear and fairly stable.

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Figure 5.23 Hysteresis Loop obtained by MOKE as validation

A signal to noise ratio of about **40:1** was achieved by this MOKE setup. This showed that the experimental stability and signal to noise ratio was satisfactory. This typical hysteresis loop of a ferromagnetic material was achieved. This indicated the success of the MOKE setup. A further analysis of this sample was done and discussed in next chapter.

In further investigations, the sample rate would be increased for a higher number of data to trace out the path of the loop. This was done to enhance the accuracy of the coercivity and remanence obtained from the hysteresis loop. The other settings were kept constant to achieve optimum stability and signal to noise ratio.

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Graphical determination of coercivity and remanence ratio

The following section deals with the procedure of obtaining coercivity and remanence ratio from the hysteresis loop. After the data points were collected, the readings were tabulated and plotted. The hysteresis loops were printed out and the coercivity and remanence ratio were obtained by the graphical method as shown in next figure. Coercivity can be read off directly and the remanence ratio can be calculated easily.

Figure 5.24 Coercivity and Remanence Ratio by graphical method

In this project, the coercivity and the remanence ratio were obtained in this graphical method. As the values were acquired in this manner, errors resulting can be rather high. The errors would be further increased especially if the signal to noise ratio was poor. Errors were also dependent on the resolution and the size of the loop printed. If the printing size of the hysteresis loops were reduced, the error would be increased.

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5.4 MOKE Experimental Result

5.4.1 Hysteresis Loop Analysis

In this sub-chapter the MOKE magnetometer was used to test on a few samples. The hysteresis loops of the samples were obtained. The primary interest in determining magnetic material quality was coercivity and remanence. The magnetic samples tested were Metglas 2605SC and Metglas 2705M, both are amorphous material in ribbon form. Amorphous magnetic materials generally have higher permeability, consequently better performance under high frequency operation. This should be viewed as preliminary experiment for future candidate for magnetic backing plane. It should be noted that the MOKE magnetometer was not designed to measure amorphous ribbons. Hence, the accuracy of the hysteresis was expected to be compromised.

METGLAS 2605SC

Metglas 2605SC is an amorphous iron based magnetic alloy. Available in ribbon form, the composition of the alloy is: 81%Fe, 13.5% B, 3.5% Si, and 2 %C. Benefits of this alloy includes the high saturation induction; extremely low core loss and a high B-H squareness. Next figure shows a typical DC hysteresis loop of the material from Metglas Solutions. [63]

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Figure 5.25 Typical Metglas 2605SC Hysteresis Loop

Analysis of Metglas 2605SC

In the analysis of Metglas 2605SC, there were some changes in the MOKE experimental setup. The material was not perfectly smooth hence the reflected laser was diverged and the photodiode could not detect the entire laser beam. Additional focus lens was included to capture all the light and pass it through the polarizer and into the photodiode.

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Figure 5.26 Experimental hysteresis loop of Metglas 2605SC with different scan length

The shiny side surface of Metglas 2605SC was 1st tested with 3 different scan lengths and the hysteresis loops were shown in the figure. A scan length of 20 seconds meant that the signal generator was operating at a frequency of 50 mHz, peak to peak current remains at $\pm 8\text{A}$ giving $H = \pm 10.494\text{ kA/m}$. It could be noticed that even at 10 seconds scan length, a hysteresis loop was obtained. [63] This demonstrated that the magnetic moments in the material were able to align themselves very quickly.

20 seconds scan length was chosen for the rest of the experiments. An essential point to take note was the signal to noise ration was poor compared to the Fe-Si wafer

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sample. This was probably because that magnetic ribbon and was not rigidly fixed onto the sample holder.

Improvement of the readings could be achieved by repeating each scan length 25 times and the average of the results were plotted. It could be noticed in previous figure that the hysteresis loops were not closed loops. Although the laser was supposed to be stable, there seemed to be a slight *drift* in the intensity. This drift in the plasma laser was *independent* of the magnetic field. The drift was compensated / corrected *statistically* by taking the change intensity at the gap and adding them incrementally to each data point so that the ends will coincide at the same point. The correction should provide adequate approximation as the aim of the experiment was to get *qualitative* result. A closed hysteresis loop of 2 cycles is shown in next figure.

[63]

Figure 5.27 Experimental hysteresis loop of Metglas 2605SC (shiny surface)

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The coercivity was found to be about 0.5 kA/m. Remanence ratio was found to be about 0.67. The high “squareness” of hysteresis loop and small area, (i.e. low core loss) were properties of the Metglas 2605SC.

Next the magnetic ribbon was tested on the dull surface. Similarly an average of the 25 readings was taken. Correction was again done to close the loops.

Figure 5.28 Experimental hysteresis loop of Metglas 2605SC (dull surface)

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From the graph, the dull surface had a smaller hysteresis loop area. The energy required for a magnetization –demagnetization cycle was lower compared to the shiny surface. This was probably because there was more crystallization on the shiny surface. The coercivity was very small, $< 0.3\text{ kA/m}$. The remanence ratio was found to be very low at about 0.15.

The results obtained were not very accurate compared with the manufacturer technical data. The inaccuracy of the results obtained would be discussed together with the next sample investigated since the type of material was similar.

METGLAS 2705M

Another amorphous magnetic material tested was Metglas 2705M. It is Cobalt based magnetic alloy with the composition: 70% Co, 23% Si+B, 5% Mn, 2% Fe+Mo. The main benefits are: it has a near zero magnetostriction, high permeability and square B-H loop and a medium saturation induction. A typical DC hysteresis loop of Metglas 2705M is shown below. [63]

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Figure 5.29 Typical Metglas 2605SC Hysteresis Loop

The Metglas 2705M was tested under the same conditions as the 2605SC. Similarly 25 readings were done. The drift in the stability was again mathematically corrected, thus closed hysteresis loops were obtained. In the same manner, the shiny surface was first tested and then the dull surface.

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Figure 5.30 Experimental hysteresis loop of Metglas 2705M (Shiny surface)

From the hysteresis loop,

Coercivity found was about 0.9 kA/m

Remanence ratio was found to be 0.42.

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Figure 5.31 Experimental hysteresis loop of Metglas 2705M (dull surface)

From the hysteresis loop,

Coercivity found was about 0.8 kA/m

Remanence ratio was found to be 0.37.

Both surfaces the two hysteresis loop did not differ by a lot compared to Metglas 2605SC. However, the two hysteresis loops obtained was not as “square” as compared to the loop given by the metglas solutions.

Discussion

The coercivity obtain in both the 2605SC and 2705M, were much higher than specifications given by the manufacturer. This was probably because the amorphous

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ribbon might have crystallized hence a higher coercivity. Remanence ratios obtained were lower as compared to the technical data except for the shiny surface of 2605SC.

In this measurement of amorphous ribbons, the surface was not perfectly smooth and an extra focus lens had to be inserted in the setup. The divergence of the laser also attribute to the poor results obtained, as the photodiode could not capture the entire laser beam.

Another factor to take note was that the graphical method of obtaining the coercivity might have a very high percentage of error. This was the cause of the low value of coercivity. The scale of the hysteresis loops had to be large to enable the read off of small values of the H directly.

As mentioned, the MOKE magnetometer was not designed to measured ribbons. From the graphs, the signal to noise ratio was rather poor. This was probably attributed by the large noise obtained. The loss of accuracy in the results obtained was partially due to poor adhesion of the ribbon of to the sample holder. In the MOKE magnetometer, it was important that the sample was rigidly fixed. Since the 2 amorphous materials were in the ribbon form, its flexibility may have increased the errors and remove the accuracy of the results.

Nevertheless, amorphous material is a very promising candidate for future utilization. Magnetic backing plane should have significantly higher permeability as it has

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virtually no grain boundary. It is an area of work that worth to be pursued for future improvement.

In spite of that, the experiment showed that the MOKE equipment could be used to test magnetic material properties with reasonable accuracy. As it was designed to measure thin film material, a suitable sample should produce satisfactory results. Moreover, since the micro gyroscope would utilize thin film material, this equipment would be suitable and be able to produce reliable and repeatable results.

5.4.2 Easy and Hard Axis Establishment

The MOKE equipment could also be utilized to determine the orientation of magnetic film. This would greatly affect the gyroscope development. Knowledge of easy axis of magnetization would be an essential advantage. The user would be able to optimize all the desirable properties by setting suitable orientation of the magnetic thin film.

Magnetron sputter was used to deposit Fe onto the SI wafer. The sputtering machine employed had 4 available positions for the substrate as shown in the next figure. The iron target was placed at the center shown by red circle. The clean Si wafer was place at any of the positions with the flat edge perpendicular to the radius of the platform. During the sputtering process, the platform would rotate at a constant speed. In this aspect, all 4 samples sputtered would comprise of the same uniformity this suggested that the uniformity of the sputtered Fe atoms should parallel to the flat edge. The

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wafer was sputtered for about 1½ hour for a sufficiently thin film of Fe to be deposited.

Figure 5.32 Schematic representation of sputtering arrangement

Distribution of the magnetic properties

The thin Fe film deposited onto the Si wafer was tested using MOKE at various positions to determine the uniformity of magnetic properties. The wafer was orientated with the flat edge at the bottom and parallel to the magnetic field (x-axis). At each reading, a hysteresis loop was plotted and the coercivity and the remanence could be established.

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Figure 5.33 Reference for finding properties distribution

The experimental procedure was maintained the same. The magnetic field strength was varied from ± 10.494 kA/m. The spot size of the laser was approximately 1 mm^2 . Since it was not possible to measure the total surface of the sample, the thin film was tested on a grid basis by the laser of the MOKE with 1 cm intervals in the X and Y-axis from the origin at the center of the wafer. After each test spot the sample was repositioned to another test spot. Variations of the coercivity and the remanence were plotted in an X-Y axis as shown in the next two figures. [63]

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Figure 5.35 Distribution of Remanence Ratio

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Analysis of the figures suggested that there was some form of uniformity in the X-axis. This was attributed by the sample platform rotating about the ion target. However, towards the left side of the wafer, it seemed that there was a disruption in the uniformity of the magnetic properties along the X-axis. There were similar implications that the Fe film thickness and the coercivity were related below a critical thickness. MOKE intensity was also higher with increased film thickness.

The coercivity and the remanence of the thin Fe film appeared to have a close relationship. A high value of H_S would also cause a high remanence ratio. Coercivity and remanence were recorded highest at the region near the flat edge especially towards the left. This particular region was probably closest to the iron target during the sputtering process and hence had thicker layer of Fe film. At the central region of the wafer in figure 5.32, there seemed to be a wedge splitting in the center Y-axis. This was probably also due to the distance between the target and the substrate. Additional correlation of the distance between the iron target and the sputtered thin film in this area would need further studying.

Anisotropy of Fe deposition on the Si wafer

It was interesting to examine the anisotropy of the iron sputtered onto the silicon wafer. The flat edge of the wafer when parallel to the magnetic field was set as 0^0 . The MOKE magnetometer was then used to search for any anisotropy in the plane of the deposition of the iron. The range of the magnetic field remained the same, ± 10.494 kA/m. The sample was rotated anti-clockwise about the axis of the surface

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normal to vary the azimuthal angle results of the coercivity of wafer. A series of hysteresis loops were plotted at increasing the angle by steps of 30^0 .

Figure 5.36 showed an example of the various shapes of hysteresis loops obtained in different angles of rotation. The “squareness” of the hysteresis loops was an indication of the magnetic material being magnetized in the easy axis. This would prove to be useful in the analysis of the anisotropy of the magnetic sample.

The results are shown in figure 5.38 and 5.39 for $0^0 \leq \varphi \leq 360^0$, the intensity (y-axis) is in arbitrary unit.

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Figure 5.36 Hysteresis Loop for various angles

Figure 5.37 Illustration of wafer with angle defined for this experiment

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Figure 5.38 Hysteresis Loop for $0^\circ \leq \varphi \leq 180^\circ$

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Figure 5.39 Hysteresis Loop for $180^\circ \leq \phi \leq 360^\circ$

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Thorough analysis from the 2 sets of graphs showed that the hysteresis loops shifted progressively to “squarer” in shape with increasing angle from $\varphi = 0^\circ$. It was almost rectangle at 90° and then it gradually became thinner again. The hysteresis loop of $\varphi = 180^\circ$ was almost identical to that of $\varphi = 0^\circ$. Close examination of the hysteresis loops within $180 \leq \varphi \leq 360^\circ$ showed a repeat of curves similar to those within $0^\circ \leq \varphi \leq 180^\circ$. This was clear evidence showing that the sample had an in-plan uniaxial magnetic anisotropy. The shape of the hysteresis loop at $\varphi = 90^\circ$ and 270° was close to that of a rectangle and seems to only exist in these 2 angles. The magnetization reached saturation at $H_S = 4$ kA/m and remains in saturation even as the external magnetic field decreased to the negative value. At all azimuthal angles, the external magnetic field was sufficient to create saturation in the Fe-Si wafer.

To further comprehend the hysteresis loops, the coercivity and remanence ratio were plotted at different angles as shown in next 2 figures. [63]

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Figure 5.40 Anisotropic distribution of Coercivity

Figure 5.41 Anisotropic distribution of Remanence Ratio

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Comparing all the hysteresis loops, the value of H_S was the smallest the 2 angles, $\varphi = 90^\circ$ and 270° . However the coercivity and the remanence were the largest at these 2 angles. From figures 5.36 – 5.39, it was clearly shown that **$\varphi = 90^\circ$ and 270° were the easy axis of magnetization**. As the rectangle shaped loop changed into a smooth curve from $\varphi = 90^\circ$, the value of H_S increased and was the largest at $\varphi = 180^\circ$, similar to that of $\varphi = 0^\circ$. Correspondingly, the *coercivity* and the *remanence* were reduced to the *lowest value*. Consequently, this also showed that $\varphi = 0^\circ$ was the relative hard axis of magnetization.

5.5 Conclusion

The MOKE magnetometer had been established to achieve high sensitivity and stability. The ***intensity stability*** of **0.1%** was achieved to enable the MOKE magnetometer to obtain hysteresis loops from thin films with ***signal to noise ratio*** of **40:1** for a data collection of 20 seconds.

Preliminary work on assessment of amorphous magnetic materials was performed. True performance of these materials was not able to be determined due to inconducive sample form. The surface roughness would compromise accuracy of any optical methods. Nevertheless it is a promising area to look into in the future.

The MOKE equipment also showed application in determining anisotropy of magnetic material. It was able to deduce the easy and hard axis of thin film iron

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sample. Optimization of magnetic material orientation could be done based on this knowledge. This would greatly benefit the gyroscope development.

Further improvement on the MOKE equipment was PC controlled. Ideally with PC control, the trace scan can be repeated as many times as necessary and all the data points will be recorded automatically. The average can then be taken and hysteresis loops obtained will be more accurate.

The process of the collection of data in the experiment was then automated by using the software, LabVIEW, with the circuits used shown in the diagram below.

Figure 5.42 Circuits controlling the magnetic field using LabVIEW™

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Inductance Test Structure

Chapter Six

Inductance Test Structure

Magnetic property of material especially in our concern, permeability value generally reduces with frequency it is subjected into. Therefore, a high permeability material chosen and tested by MOKE may have its permeability reduced greatly in high frequency operation. For this reason, another important part of the project was to investigate the performance of magnetic material to be used in high frequency operation of the micro gyroscope.

The objective of this work was to assess frequency performance of magnetic material. The work included the investigation of various properties of the selected material to determine its suitability for use as a backing plane.

This work was done in collaboration with Ho Wei Hong who was doing his final year project. The author was having great experience on working together doing the experiments.

As shown in previous chapter, the force required to act as magnetic bearing depend on the value of permeability μ , input current I , and frequency f . Therefore, it was required to employ magnetic material with high permeability and was able to perform well in high frequency operation Soft magnetic material was the preferred choice for

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this application. Alloy of 20% Fe and 80% Ni (Permalloy) was chosen. In this chapter exploration of the magnetic material shall be presented.

In general, permeability of magnetic materials reduces with increase in frequency [58, 64]. Therefore, a trade-off was required in our application. It was then important to know the decrease of permeability value against frequency. For this reason, soft magnetic material with very high initial permeability (at zero hertz) was required.

Optimization of the magnetic material was required to ensure that at high frequency operating condition, it would still have high enough permeability value to satisfy the purpose. As no previous work in the school has been done in this field, it was required to design and develop new test structures. This test structure would also be used to test the performance of the selected material as a high permeability magnetic backing plane. Design and Fabrication of the structure shall be discussed

The test structure required to test for the effectiveness was essentially a micro-transformer with gold wire and magnetic core. Electrical characteristics between different terminals will be tested to determine the inductance, permeability and the performance of the magnetic core.

6.1 Micro-Transformers

For any transformer, made by a process of alternately depositing conductor or magnetic material, it must have at least two steps of conductor deposition or 2 steps of core deposition. This arrangement ensures interlink between the core and the coil,

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which can be considered variations or combinations of the basic constructions in figure.6.1 and figure. 6.2. Two main types of transformer structure could be used for the development of the test structure for the permeability of material of interest. They are the pot-core and toroidal design. [65]

Figure 6.1 Basic Pot-Core design for Micro Transformer

Figure 6.2 Basic Toroidal design for Micro-Transformer

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As both of them should give reasonably similar performance [65], an important parameter for the selection of these two structural designs then was the *ease of fabrication*. For the toroidal-core design, the main difficulty lies in the *connection of the bottom and top layers* of conductors to encircle the core. This requires registration between the layers to be adequate to insure proper connections, requiring low-resistance contacts and connections over a vertical distance equal to the thickness of the backing plane. [65] This would result in cost, material, and process inefficiency.

On the other hand, the pot-core design has less severe interlayer connections. This is because connections to particular wires are not required. Moreover, small gaps of insulator would not be a problem as the area can be made sufficiently large that the gap reluctance is negligible. The planar design of the pot-cored allows for simpler fabrication using photolithography masking together with chemical etching. [65]

For reasons stated above, pot-cored design was chosen for this project, as it was fabrication efficient without suffering from any major performance disadvantage.

Details of Designed Micro Transformer Structure

The test structure was modeled from reference [66] with modification to be appropriate to our purpose. The designed test structure had 4.35 x 3.6mm dimension, which included four contact terminals. The primary and secondary windings configuration of the test structure can be observed in next figure.

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Figure 6.3 Basic spiral coils as test structure

The determination of the magnetic permeability of the FeNi layers was done by calculating the measured inductance between the inductance of the primary winding, L_1 and L_{1A} , with L_1 being the inductance between the primary terminals of the test structure deposited on the material to be tested and L_{1A} the inductance between the primary terminals on an air cored test structure. The values of R_1 and R_{1A} can be similarly found by measuring the resistance on the primary coil. From these data, L_{1M} and R_{1M} can be calculated using the equations shown below: [66]

$$L_{1M} = L_1 - L_{1A}$$

$$R_{1M} = R_1 - R_{1A}$$

(6.1)

Using the equation shown below, μ' which is the specific magnetic permeability in the hard direction measured at the input test signal of the magnetic layer can be calculated. [66]

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$$N_I^2$$

$$L_{1M} = \frac{1}{\frac{4g}{\mu_o \pi (4b^2 - a^2)} + \frac{4g}{\mu_o \pi a^2} + \frac{b}{\mu_o \mu' \pi t a}} \quad (6.2)$$

Where, N_I is the number of primary windings, g the distance between the lower and upper magnetic films, μ_o permeability of free space (1.26×10^{-6} H/m), b the radius of the magnetic film, a the radius of the outermost primary windings and t the thickness of the windings. [66]

$$\mu'' = \mu' \frac{R_{1M}}{2\pi f L_{1M}} \quad (6.3)$$

From the value of μ' , the complex permeability of the magnetic backing plane can then be obtained.

The metallic multiplayer inductance test structure could be viewed in the next figure. As explained earlier it was essentially a micro transformer with gold wire and magnetic core. Few holes would be etched to create contact for external testing device.

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Figure 6.4 Schematic Representation of the inductance test structure

6.2 Fabrication of Inductance Test Structures

6.2.1 Fabrication Steps

Fabrication of these structures was done using micro fabrication techniques. Process flow of the fabrication was showed in figure 6.5.

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Figure 6.5 Fabrication Process Flow for inductance test structure.

The first two layers, chromium, copper were essential as they give good adhesion to FeNi. Both of these layers were deposited using thermal (E-beam) evaporation process. Thin layers of chromium and copper with thickness approximately 50 nm each were deposited. These layers would act as a base layers for FeNi deposition.

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Subsequent process was deposition of FeNi. *Two* methods were explored in this process, namely *thermal evaporation* and *electroplating*. Thermal evaporation was a much simple process yet it might cause high surface stress for thick material. The surface stress would limit the thickness of material to be deposited. On the other hand, negligible thermal stress should be observed with electroplated sample.

6.2.2 Thermal stress and thickness

High temperature evaporation process would cause residual stress on the thin film. The main problem caused by this thermal stress would be flaking of the deposited films. Some of the films deposited by thermal evaporation suffered from this problem.

Figure 6.6 Failure of deposition due to high thermal stress

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Thermal stress could be measured using Stress Measurement system. The equipment measures the curvature of wafer surface. As shown in chapter 4, residual stress either tensile or compressive, then can be calculated using formula stated below:

$$\sigma = \frac{1}{R} \frac{E}{6(1-\nu)} \frac{T^2}{t}$$

(6.4)

Where

σ : Stress

E: Young's modulus

R: Radius of curvature

ν : Poisson ratio

T: Thickness of the substrate

And t: Thickness of the applied film

[61]

Stress measurement was done using TENCOR stress measurement Unit.

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Graph in figure 6.7 shows comparison of thermal stress of the samples produces by the two methods. For comparison, sample from 0.3 μ m to 0.6 μ m range of FeNi deposited was tested.

Surface Stress Analysis (E-Beam Evaporated Sample)

Figure 6.7 Surface stress of FeNi alloy deposited by E-Beam Evaporation method

Analysis of the graph showed that sample by thermal evaporation had approximately two order higher value of surface stress. The evaporation process deposition for FeNi was limited to approximately 0.4 μ m before the film peel off. For this reason, in terms of surface stress, electroplating was the preferred method. However, evaporation

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process has advantage of simpler and less hazardous process. Hence, samples produced by both process were retained and tested for comparison.

Electroplating method successfully deposited FeNi ranging from 0.3 μm to 2 μm thick. Since the thickness required for the device should be around 1 μm , this range should be a sufficient set of data for determining the rate of deposition. The result of FeNi electroplating can be viewed in next few figures.

Time (s)	Initial Mass (g)	Final Mass (g)	FeNi	Thickness deposited (micron)	Thickness per second
300	7.9498	7.9613	0.0115	0.29	0.00099
300	7.9457	7.964	0.0118	0.3	0.00097
600	8.4003	8.4219	0.0216	0.56	0.00093
1200	8.2271	8.2711	0.044	1.13	0.00094
1500	8.1019	8.1542	0.0523	1.34	0.0009
2000	8.2248	8.2939	0.0691	1.77	0.00089

Table 6.1 Data of electroplating of FeNi alloy

i alloy

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Figure 6.8 Rate of deposition of Permalloy against successive number of plating attempts

Six separate tests were done with successful deposition of Permalloy without any exfoliation or surface defects. The results of the test showed a general gradual decline in the rate of deposition of Permalloy onto the substrate. This result was expected as the same electrolyte was used without any replenishment during the test. Having a lower concentration of source ions, a decrease in the rate of deposition is expected

6.2.3 EDX Test on Electroplated Deposit

The deposited Permalloy samples using the electroplating method were tested employing EDX to check for the composition of the deposited Iron nickel alloy.

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The EDX test was performed on three separate samples that had been deposited with FeNi alloy of thickness 1.13, 1.34 and 1.78 microns.

EDX Results

The results of the EDX test spectrum of the tested samples, shown in next figure, recorded the presence of silicon, nickel, iron, copper and chromium elements in the tested substrate.

Figure 6.9 EDX Test Result on the desposited samples

The composition test results from the EDX were summarized in the next table. The composition test yielded an average composition of Ni-83.42 Fe-17.58. The test

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results on the three samples also showed high level of fluctuation approximately 10% of composition of the FeNi alloy.

Composition (%)	Test 1 (1.13 microns)	Test 2 (1.34 microns)	Test 3 (1.78microns)	Average
Nickel	82.34	77.5	87.36	82.42
Iron	17.66	22.5	12.64	17.58

Table 6.2 Composition of electroplated FeNi alloy

The EDX test results showed that the composition of the deposited material has a composition that is closed to that of Permalloy. The average compositions of the samples are recorded at 82.42% nickel and 17.58% Fe.

The exact composition of Permalloy ranges from 78-80 % nickel with the rest being made up by iron. The deviation of the electroplated deposition from the accepted range of composition ratio of Permalloy could be due to the fluctuation of local composition of the alloy.

The slightly lower than expected level of iron in the composition of the FeNi alloy recorded during might also be due to the oxidization of Fe^{2+} ions to Fe^{3+} ions at the elevated temperature the solution was subjected to. Due to the increase in oxidation

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state, the oxidized ions would require greater amount of electrical charge for every atom of Fe^{3+} ions deposited instead of Fe^{2+} ions by Faraday's law. Fe^{3+} ions are also less likely to undergo the electro-reduction process due to its low concentration and "less negative" E_{RED}^0 value, thus reducing the composition of deposited iron element in the alloy. [67]

Deposition of Silicon Nitride

Silicon Nitride was also an important layer, as it is an essential insulation medium to prevent electrical path from the test structure to the conductive iron-nickel layer. The Silicon Nitride layer was deposited using the *Technics Micro PD 900-11 Plasma Enhanced Chemical Deposition (PECVD)*.

Process condition for Si_3N_4 was as follow,

SiH_4 (20 sccm) + NH_3 (50 sccm), power 50 W, $T = 300^\circ\text{C}$

The next layer to be deposited was gold; it was deposited using again thermal evaporation. The gold would later be patterned in spiral shapes for inductance testing as explained earlier. Using the mask designed previously, the gold was patterned using photolithography and etching process.

6.2.4 Photolithography and Lift-Off Process

Tanner L-Edit software was employed to design two layers photolithography mask. Two different sizes test structures were designed. The purpose was for compensation on photolithographic process limitation and theoretical calculation validation.

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The two types of designs had difference in the spacing between the inter coil distance. The dimensions of the first design, Test Structure A, windings were 20 μm in width, 6 μm in thickness and 10 μm in space between conductors with the contact pad dimensioned at 150 x 150 μm . The second test structure, Test Structure B, had the dimension between the coils increase to 20 μm and an increased in the dimension of the contact pad to 200 x 200 μm .

The number of turns for the primary winding of Test Structure A and Test Structure B were 21.4 and 21.9 respectively and the secondary windings 20.8 and 21.2.

The procedures for the design of the mask were as follows.

1. Design structure of both layers using L-Edit
2. Add alignment marking onto the design
3. Checking of design
4. Sent design for fabrication

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Layout of the test structures designs is shown in figure 6.10.

Figure 6.10 Layout of the test structures design

[68]

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The photolithography process was done using AZ9260cp positive photo-resist, The Karl Suss spin coater for the coating of the HDMS primer, the photo-resist and the OAI Contact Aligner for the exposure of the photoresist to UV light.

Figure 6.11 Schematic illustration of process flow for the test structure

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Before next fabrication steps was done, the gold structure was analyzed using SEM, the result was as shown in figure 6.13. Examination of the figure showed that the gold deposition was successfully done.

Figure 6.12 Deposited Test Structure on Silicon Nitride Layer

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Figure 6.13 Deposited Test Structure A

Figure 6.14 Deposited Test Structure B

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Due to time constraint the fabrication process was discontinued after reaching the gold layer. The gold was patterned and subsequently was tested. These test results should give qualitative value of high frequency effect on permeability value. Hence the test structure configuration was as shown in the next figure.

Figure 6.15 Test configuration of High Permeability magnetic backing plane

Two types of magnetic core structure had been developed, namely the electroplated FeNi and evaporated one. For this test, the electroplated samples with deposited FeNi alloy thickness of 1.13 μm and 0.29 μm of FeNi alloy. The latter was chosen to provide a basis to compare the magnetic properties of samples deposited using the E-Beam Evaporation method, which cannot exceed the thickness of 0.4 μm consistently.

For comparison purpose, another set of structure was made using air core, i.e. only gold wire without any FeNi backing plane. The structure of this air cored test structure was illustrated as next figure.

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Figure 6.16 Air cored test structure

6.3 Inductance Test Results

6.3.1 Equipment

Inductance test was done utilizing Hewlett Packard 4284A Precision LCR meter and contact probe. The LCR meter was connected to a microprobe for electrical connection to the electrode of the structures.

Figure 6.17 HP8284A LCR meter

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Figure 6.18 Microprobe connecting device

Figure 6.19 Measurement Contacts setup for HP4284A

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Before any measurement was taken, stability and validity of the equipment must be ensured. Calibrating the equipment compensating the effect of equipment and cable inductance would ensure stability. The Precision LCR meter was successfully calibrated to measure inductance accurately using the cable as a connector. The test was carried out at 1 kHz and repeated five times on each inductor after re-performing the open/short correction.

Validation of the testing equipment was performed using standard inductance, the result was as shown.

Figure 6.20 Standard test inductors used for testing of accuracy of HP4284A

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Figure 6.21 Accuracy test results for HP4284A Precision LCR Meter

The range of results, illustrated in figure above, showed that the LCR meter was capable of measuring small inductance value with very high accuracy.

Only after ensuring that the equipment could produce reliable results, then it was used to measured inductance of the fabricated test structures.

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6.3.2 Inductance Test on the structures

The test structures were subsequently tested using the HP4284A LCR meter. Each test was done on three structures of the same type with the same thickness of deposited material. The final results, presented as figure 6.29 and figure 6.30 are the mean value the yielded raw results. Note that the inductance value is in logarithmic scale.

Figure 6.22 Graph of Inductance against Frequency for Test Structure A

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Figure 6.23 Graph of Inductance against Frequency for Test Structure B

The inductance test results showed that the inductance of the coils with the deposited FeNi backing plane had much higher value compare to the air cored ones. It was also noted that the electroplated samples exhibited slightly higher value of inductance compared to the evaporated ones.

Using the Test Structure B, the inductance test produced similar trend with magnetic core coils exhibiting much higher inductance values compare to the air core ones.

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6.4 Test Results

Analyzing the inductance test results, the relative permeability of the test structure could be estimated using the equation shown earlier. The equation used for the analysis of the magnetic permeability was applicable for a complete system, in which the gold magnetic test structure was deposited between two layers of high permeability alloy. Hence the calculation result should be viewed as qualitative result instead. The calculated results are shown in next two figures. Note that the relative permeability value is in logarithmic scale.

Figure 6.24 Graph of Permeability against Frequency for Test Structure A

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Figure 6.25 Graph of Permeability against Frequency for Test Structure B

The results of the permeability calculation showed that there was a sharp increment in the permeability values for both test structure and their respective backing planes from frequency of 500 kHz. Both graphs start to decrease at 800 kHz. Both structures yielded an area where the calculated relative permeability is constant, during the frequency range, up to 500 kHz.

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Inductance Test Structure

Discussion

The test results showed that inductance value increased significantly for the magnetic core structures compared to an identical air core test structures. For these reason, application of magnetic backing plane onto the micro-rotating gyroscope would be desirable. Addition of this backing plane could reduce current consumption up to 4 order; this extra magnetic flux would also be able to produced higher speed operation as required.

This was an expected result, as the calculated permeability is in fact the average permeability of the backing plane and the air surrounding the exposed region of the test structure. It is interesting to note that test structure B yielded permeability values that are substantially lower than test structure A. This phenomenon might be explained by difference in mutual inductance between the windings. The inter-winding distance between the conducting coils in the set A test structures were much smaller, resulting in greater mutual conductors between the windings. [21]

6.5 Conclusion

Thus the report elaborated on the selection of materials to be used for the development of the magnetic backing plane to improve the efficiency of the micro-rotating gyroscope. The class of material was researched and decided to be the Nickel–Iron alloy for their balance of *high permeability, moderate resistivity* and *suitable mechanical properties*.

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Following the selection of the suitable class of materials, the development of the method of deposition by electroplating and E-beam evaporation was carried out.

After development of deposition methods, the report continued with the research, development and the fabrication of suitable test structure for evaluating the deposited alloys. The successful testing of the materials using the samples affirmed that design and production of the mask necessary for the fabrication of the test structure was successful.

Test results for the inductance test implied that even in very high frequency, the selected materials exhibit significant high magnetic permeability. The result suggested that the use of FeNi as magnetic backing plane would indeed improve efficiency of the gyroscope. Substantial amount of improvement in operating speed and current consumption would be expected with inclusion of FeNi as magnetic backing plane.

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Conclusion and Recommendation

Chapter Seven

Conclusion and Recommendation

7.1 Conclusion

As stated earlier, the main intention of this project is to explore *magnetic material to be used as backing plane for micro gyroscope development*. Four objectives were set in achieving the main intentions, namely:

1. To develop high permeability magnetic film
2. To establish infrastructure for growing magnetic film
3. To set up reliable magnetometer for rapid, non-invasive and magnetic anisotropy testing
4. To assess magnetic material performance at high frequency application.

The project started with establishment of infrastructure for growing magnetic film. Some of the process required was facilitated by micro machine centre. Electroplating process to serve the purpose was unavailable, hence it was developed.

Integration of available process and electroplating ascertain the infrastructure establishment. Validation of this establishment was performed by fabricating a micro rotating stator utilizing all the process integrated. The stator fabrication was accomplished successfully. This success validates the infrastructure establishment. This success also proved that it was feasible to fabricate gold stator in the

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infrastructure / facility established earlier. The end product of micro stator could be viewed in chapter 4.

High magnetic permeability film was also successfully grown. Utilizing the established process, deposition of FeNi samples were accomplished. Thickness up to μm were achieved with promising result for further thicker deposition.

Objective 3 were satisfied by successful establishment of MOKE magnetometer. The MOKE magnetometer development had refinements to improve its sensitivity and stability. The *intensity stability* of 0.1% was achieved to enable the MOKE magnetometer to obtain hysteresis loops from thin films with *signal to noise ratio* of 40:1 for a data collection of 20 seconds.

The MOKE equipment also showed application in determining anisotropy of magnetic material. It was able to deduce the easy and hard axis of thin film iron sample. Optimization of magnetic material orientation could be done based on this knowledge. This would greatly benefit the gyroscope development.

High frequency performance testing was performed by inductance testing of micro transformer structures. The experiments were done by comparing micro transformer with magnetic (FeNi) core and air core. Effect of frequency change against inductance value was plotted. Calculations using formula from reference were performed to determine relative permeability, which was also plotted against frequency. Time

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constraint prevent fabrication of complete set of transformers, hence the calculation result should only be viewed as qualitative analysis.

Nevertheless, test results for the inductance test implied that even in very high frequency, FeNi exhibit significant high magnetic permeability. The result suggested that use of FeNi as magnetic backing plane would indeed improve efficiency of the gyroscope. Substantial amount of improvement in operating speed and current consumption would be expected with inclusion of FeNi as magnetic backing plane.

7.2 Recommendation

Few recommendations about future works are presented. After infrastructure establishment, exploration should be performed in deposition of various thick film materials. Further enhancement would be fabrication complete set of micro stator with magnetic backing plane.

Magnetometer modifications may also be performed for amorphous material assessment. Assessment of amorphous magnetic material is a promising area to look into in the future. Amorphous magnetic materials have significantly higher permeability due to their lack of grain boundaries and dislocations. Consequently better performance under high frequency operation.

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Complete micro transformer structures should be fabricated, this would give quantitative result of material permeability value under high frequency influence. This work will greatly enhance the overall development of the micro gyroscope.

The research project on investigation of magnetic material required for micro rotating gyroscope development has been performed. The project produce promising results that can be further enhanced by following the recommendations stated above.

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