Giant Magneto-impedance Effect In Thin Film Layered Structures

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GIANT MAGNETO-IMPEDANCE EFFECT IN THIN FILM LAYERED STRUCTURES

by

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B.S. Pune University, 2002

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ABSTRACT

Recently, the giant magneto impedance (GMI) effect has been studied extensively because of its potential applications in sensor elements. The focus of this thesis work is to explore different compositions and processing conditions for CoSiB and NiFe thin films to obtain the soft magnetic properties and to evaluate their potential use in GMI sensor applications. Prior to this study, an MH Looper was constructed, which was extremely important and provided the basic magnetic characterization of the many ferromagnetic thin films deposited during this work.

The CoSiB films were co-sputter deposited in an ultra high vacuum chamber. Films with different relative compositions of Co, Si and B were deposited by varying respective target powers. Different substrate bias conditions were also studied. Also, NiFe films were studied by varying relative composition by variation of target powers and also by variation deposition pressure. The effect of annealing was also studied. The magnetic and electrical characterization of these films was done using the MH Looper, Quad-pro four-point probe resistivity measurement, and Low Frequency Impedance analyzer HP4192A.

Finally, CoSiB films with soft magnetic properties were obtained with optimized set of deposition parameters. A sample for GMI measurement was prepared, consisting of a multilayer thin film structure: CoSiB 200nm/ Cu 400nm / CoSiB 200nm. A serpentine pattern was generated on this film by photolithography technique. After obtaining the pattern, GMI studies were performed using LF impedance analyzer. This instrument was capable of providing the drive frequency in the range of 5Hz to 13MHz, but the impedance mis-match of the test fixture limited useful measurements to 9MHz. The highest GMI ratio observed was 6.2% at a 21 Oe
longitudinal magnetic bias field at an 8MHz drive frequency. Transverse permeability measurements were performed by the use of two magnetic field axes of the MH Looper. The permeability behavior of the device reflects the impedance behavior with the external field. Permeability measurements were also performed on NiFe GMI Device with NiFe 600nm/ Cu 1200nm / NiFe 600nm sandwich structure. This sample was not successfully patterned and hence the impedance measurements could not be performed. Correlation of the magnetic properties of the structures was studied with the impedance responses.
Dedicated to My loving Parents and Grandparents
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# TABLE OF CONTENTS

LIST OF FIGURES ............................................................................................ xiii

LIST OF TABLES .............................................................................................. xvii

CHAPTER 1. INTRODUCTION ........................................................................... 1

Introduction ....................................................................................................... 1

GMI Research Review ...................................................................................... 2

CHAPTER 2. THEORY OF GIANT MAGNETO-IMPEDANCE EFFECT .............. 7

Low frequency regime ..................................................................................... 8

Moderate Frequency Regime ......................................................................... 10

High Frequency regime ................................................................................. 11

GMI in wires .................................................................................................... 11

GMI in ribbons and single layered thin films ............................................... 13

GMI in multi-layered ribbons and thin films ................................................. 15

Effect of resistivity difference ...................................................................... 16

CHAPTER 3. M-H LOOPER ............................................................................ 20

Block Diagram Explanation ........................................................................... 20

Principle of M-H Looper ................................................................................. 21

Helmholtz coil operation principle ................................................................. 21

Sense coil operation principle ...................................................................... 22
Design of the Helmholtz coils assembly ................................................................. 24

Temperature gradient calculation ............................................................................. 26

Inductance calculation .............................................................................................. 28

Frequency dependence characteristics of the coil ...................................................... 29

Field uniformity calculations .................................................................................... 29

Sense coil design ........................................................................................................ 32

Block Diagram of the Actual Looper constructed ...................................................... 32

Hardware Interfacing .................................................................................................. 33

Sense coils / PC interface .......................................................................................... 33

Helmholtz coils / PC interface .................................................................................... 33

Software Features and working .................................................................................. 36

Data rate ...................................................................................................................... 36

NI 6052E DAQ Board important features ................................................................. 37

Averaging Cycles ....................................................................................................... 37

Background subtraction ............................................................................................. 38

Overload ...................................................................................................................... 38

Display Parameters ................................................................................................... 39

Save Data ................................................................................................................... 39

Vertical Scale Calibration .......................................................................................... 39

Horizontal Calibration .............................................................................................. 40

Example for a MH Loop for a 17nm Thin NiFe Sample with and without average 41
Comparison of the Looper loops and the loops obtained by Vibrating Sample Magnetometer (VSM) ................................................................. 42

Extended capabilities ........................................................................................................ 46

Minor Loops ................................................................................................................ 46

Permeability measurements ...................................................................................... 48

Conclusions .................................................................................................................. 51

CHAPTER 4. EXPERIMENTAL TECHNIQUES .................................................................. 53

Objective ...................................................................................................................... 53

Materials Used ........................................................................................................... 53

Experiments to achieve a good soft magnetic properties for the thin film ................. 53

CoSiB studies ............................................................................................................. 53

NiFe studies ............................................................................................................. 53

Characterization Instruments ................................................................................... 54

Representation of general methodology for experimentation .................................. 55

GMI Structure and pattern ....................................................................................... 56

Substrate preparation ................................................................................................. 57

Target preparation ..................................................................................................... 57

Thin film deposition .................................................................................................. 57

Experiment #1 Composition variation in CoSiB ...................................................... 58

Post-deposition heat treatment ............................................................................... 61
| Experiment #2 Substrate Bias Variation in CoSiB | ................................................... 62 |
| Experiment #3 Pressure variation in Ni$_{80}$Fe$_{20}$ | ........................................................... 62 |
| Experiment #4 Composition variation of Ni$_{80}$Fe$_{20}$ and Ni$_{84}$Fe$_{16}$ | ................................................... 63 |
| Final Device parameters | .............................................................. 63 |
| Patterning by photolithography | .............................................................. 64 |
| Impedance measurement setup | .............................................................. 66 |

**CHAPTER 5. RESULTS AND DISCUSSION** .............................................................. 68

| Introduction | .............................................................. 68 |
| CoSiB studies | .............................................................. 69 |
| Substrate Bias variation in CoSiB | ................................................... 69 |
| Composition variation in CoSiB | ................................................... 70 |
| Anneal comparison | .............................................................. 75 |

| CoSiB - GMI sample measurements | .............................................................. 76 |
| Magnetic Properties | .............................................................. 76 |
| Impedance and permeability measurements | ................................................... 78 |
| Permeability change for the GMI Device | ................................................... 79 |

| NiFe Studies | .............................................................. 83 |
| Substrate Bias variation in Ni$_{80}$Fe$_{20}$ | ................................................... 83 |
| Stress variation in Ni$_{80}$Fe$_{20}$ | ................................................... 85 |
| Composition variation of Ni$_{80}$Fe$_{20}$ and Ni$_{84}$Fe$_{16}$ | ................................................... 88 |

| NiFe - GMI Sample measurements | .............................................................. 90 |
LIST OF FIGURES

Figure 1 Schematic of layered GMI element (a) top view, and (b) cross-sectional view... 3
Figure 2 Variation of GMI ratio with geometry of the structure, which also shows the effect of adding a insulator separation in the layers. .................................................. 4
Figure 3 Negative magnetostrictive amorphous wire showing circumferential domain structure............................................................................................................................ 12
Figure 4 GMI configuration in single layered thin films........................................... 14
Figure 5 GMI configuration in single layered thin films........................................... 16
Figure 6 Dependence of GMI on inner conductive material ....................................... 17
Figure 7 a,b,c,d: Explanation of permeability behavior with external magnetic field..... 18
Figure 8 General block diagram of a MH Looper .................................................... 20
Figure 9 Current carrying loop with radius, R generating magnetic field, B .............. 22
Figure 10 Sense coil signal VA – VB........................................................................ 24
Figure 11 Integrated VA – VB, i.e. magnetization waveform........................................ 24
Figure 12 Helmholtz coils setup............................................................................. 25
Figure 13 Dimensions of the multi-layered coil ......................................................... 28
Figure 14 Frequency dependence of the output current.............................................. 29
Figure 15 Field uniformity for coil-I ....................................................................... 30
Figure 16 Field uniformity for Coil II....................................................................... 31
Figure 17 Field uniformity in 1- dimension................................................................. 31
Figure 18 Block Diagram of the Actual Looper constructed........................................ 32
Figure 19 Top view of the Looper assembly ............................................................... 34
Figure 20 Side View of the Looper assembly ................................................................. 34
Figure 21 Front View of the Looper Assembly ............................................................. 35
Figure 22 MH Looper Front panel display ................................................................. 36
Figure 23 MH Loop without an average ................................................................. 41
Figure 24 MH Loop with 8 averages ........................................................................ 41
Figure 25 MH Loop for a non-linear short sample measured by MH looper .......... 42
Figure 26 MH Loop for a non-linear short sample measured by VSM .................... 42
Figure 27 MH Loop for a linear short sample measured by MH looper ................. 43
Figure 28 MH Loop for a linear short sample measured by VSM ............................ 43
Figure 29 MH Loop for a wire long sample measured by MH looper .................... 44
Figure 30 MH Loop for a wire long sample measured by VSM .............................. 44
Figure 31 MH Loop for a wire short sample measured by MH looper .................... 45
Figure 32 MH Loop for a wire short sample measured by VSM .............................. 45
Figure 33 Primary Field sweep waveform ............................................................... 46
Figure 34 Major Loops for a 200nm NiFe film .......................................................... 47
Figure 35 Minor Loops with zero DC offset ............................................................ 47
Figure 36 Minor Loops with DC Offset ................................................................. 48
Figure 37 Major Loops for 200nm CoSiB film ......................................................... 49
Figure 38 Set of Minor Loops with 0.6 Oe, 10Hz primary sweep, for various transverse DC fields .......................................................................................................... 50
Figure 39 Dependence of Permeability on external transverse DC field ............... 51
Figure 40 General Structure of the GMI device fabricated .................................... 56
Figure 41 Mask used for patterning the GMI device on a 3” silicon substrate .......... 56

xiv
Figure 42 Array of magnets used for controlling anisotropy in the films .................. 59
Figure 43 Magnetic Bias Holder assembly cross-section........................................... 59
Figure 44 Impedance measurement setup........................................................................ 66
Figure 45 Effect of substrate Bias variation in CoSiB film........................................... 70
Figure 46 Effect of cobalt content variation in CoSiB film.......................................... 71
Figure 47 Effect of cobalt content variation in CoSiB film.......................................... 71
Figure 48 Effect of silicon content variation in CoSiB film.......................................... 72
Figure 49 Effect of silicon content variation in CoSiB film.......................................... 73
Figure 50 Effect of boron content variation in CoSiB film.......................................... 74
Figure 51 Effect of boron content variation in CoSiB film.......................................... 74
Figure 52 Comparison of different anneal temperatures and times on magnetic properties of the single layer CoSiB .......................................................... 75
Figure 53 Magnetic properties of the 200nm CoSiB bottom layer of the GMI sample ... 76
Figure 54 Effect of annealing on the magnetic properties of the GMI sample.............. 77
Figure 55 Magnetic characteristics of the tri-layer GMI sample.................................. 77
Figure 56 Dependence of Z on external magnetic field............................................. 78
Figure 57 Dependence of GMI ratio % on frequency............................................... 79
Figure 58 Dependence of Permeability on the external magnetic field...................... 80
Figure 59 Relation between permeability and GMI Ratio behaviour with magnetic field81
Figure 60 Behavior of Impedance with external magnetic field............................. 82
Figure 61 Effect of Bias on NiFe film................................................................. 83
Figure 62 Effect of Bias on NiFe film ................................................................. 84
Figure 63 Effect of Bias on magnetic properties of NiFe film .............................. 84
Figure 64 Effect of Deposition pressure variation on NiFe magnetic properties .......... 86
Figure 65 Effect of Deposition pressure variation on NiFe magnetic properties .......... 87
Figure 66 Dependence of Hc and Mr on Deposition pressure .................................. 87
Figure 67 Effect of Composition variation on NiFe Magnetic properties .................... 88
Figure 68 Effect of Composition variation on NiFe Magnetic properties ................. 89
Figure 69 Dependence of Hc and Mr on Composition variation in NiFe....................... 89
Figure 70 MH Loops for the 600nm NiFe/ 1200nm Cu/ 600nm NiFe ......................... 90
Figure 71 Dependence of Permeability on external magnetic field [6], equation 5.1 .... 91
Figure 72 Dependence of Impedance on external magnetic field .............................. 93
Figure 73 Comparison of magnetic properties for two thicknesses of the NiFe film .... 94
Figure 74 Comparison of magnetic properties for two thicknesses of the NiFe film .... 94
LIST OF TABLES

Table 1 Materials for GMI sensor applications and their GMI ratio and sensitivities ...... 6
Table 2 Cobalt content variation ....................................................................................... 60
Table 3 Silicon content variation ...................................................................................... 61
Table 4 Boron content variation ....................................................................................... 61
Table 5 NiFe composition variation .................................................................................. 63
Table 6 Co-sputtered target powers .................................................................................. 64
Table 7 CoSiB GMI samples ............................................................................................ 64
CHAPTER 1. INTRODUCTION

Introduction

Giant magneto impedance (GMI) effect was discovered in 1992 [1]. In the last decade, substantial interest has been aroused by the discovery of giant magneto-impedance (GMI) effect in soft magnetic wires, ribbons and thin films, because of its prospective applications in magnetic recording heads and sensor elements [9]. The MI effect is basically the change in complex impedance of the magnetic material, under the application of external DC magnetic field. The GMI ratio is defined by the following equation:

\[
\frac{\Delta Z}{|Z_0|_{H_{\text{ext}}=H}} = \frac{Z_{[H_{\text{ext}}=H]} - Z_{[H_{\text{ext}}=0]}}{Z_{[H_{\text{ext}}=0]}}
\]  
(1.1)

Where, \( Z_{[H_{\text{ext}}=H]} \) is the \(|Z|\) value, at \( H_{\text{ext}} = H \), and \( Z_{[H_{\text{ext}}=0]} \) is the \(|Z|\) value at \( H_{\text{ext}} = 0 \).

GMI sensitivity is defined as the derivative of the GMI ratio with respect to the external DC magnetic field as given by equation (1.2)

\[
\% \text{ Sensitivity} = \left( \frac{d\left( \frac{\Delta Z}{|Z_0|} \right)}{dH_{\text{ext}}} \right) \cdot 100\%
\]  
(1.2)

In the today’s world, micro-sized magnetic sensors with high sensitivity, quick response and low cost are strongly required. GMI sensors have magnetic field resolution comparable with the flux-gate sensors, without a need for exciting and sensing coils [6]. Additionally, GMI sensors have been found to be more field sensitive than the present giant magneto-resistance (GMR) sensors. The GMR materials generally involve large fields to obtain a response of a few percent, whereas the GMI materials can detect very small magnetic fields, producing a few hundred percent
changes in the impedance. The GMI sensitivity observed in some of the amorphous microwires is in the range of 10-100%/Oe at MHz frequencies [18]. This sensitivity is at least an order of magnitude higher than GMR materials. Furthermore, under specific conditions the GMI effect does not exhibit hysteresis, as is the case with GMR materials; hysteresis is uninvited for most of the sensor applications. Extensive research has been done in amorphous materials in the form of wires and ribbons, as they show excellent GMI response due to the very soft magnetic properties that they exhibit. However, the wire elements are incompatible with the present fabrication processes and integrated circuits. The rising interest and research in GMI materials in the form of thin films is a direct consequence of this, thin films being favored in the integrated circuits.

**GMI Research Review**

Till now, there has been only limited research done on the GMI effect in thin films in comparison to their bulk counterparts. Various ferromagnetic amorphous single and multi-layered films produced by sputter deposition have been investigated for their potential use as GMI sensors. The multilayer film structure comprises of a conductive layer sandwiched between two ferromagnetic ones. Mokirawa and co-workers have reported that by using multi-layered films it is possible to increase the MI effect in thin films compared to the same-composition single layered films [6]. If the sandwiched conductive layer carries the ac current, the flux created can be sensed by the neighboring ferromagnetic layers. The resistivity difference in the inner and outer layers affects the GMI response largely as shown by T. Morikawa [6]. Further, he with few others studied the GMI effect in layered thin films with insulator separation [2]. They fabricated CoSiB/SiO₂/ Cu/ SiO₂/ CoSiB with a line structure as shown in the figure 1, and compared the case without the SiO₂ insulator separation. The MI effect was found to almost
double (under specific geometry conditions) in the separator case than the case without one as shown in the figure 2. This enhancement in GMI was attributed to the fact that the driving current flows only through copper and the resistivity difference between the layers is enhanced by insertion of the insulator layer. This obtained the GMI ratio of 700% at 20MHz, 11 Oe. Sensitivity reported was 300% /Oe. This is the highest GMI ratio reported till now in the world of thin films.

Figure 1 Schematic of layered GMI element (a) top view, and (b) cross-sectional view
Furthermore, efforts have been put forth by Yuji Nishibe and co-workers to fabricate the thin film sensing elements on a flexible polyamide substrate, to make the GMI application areas more widespread [29].

In one of their review papers, C. Tannous and J. Gieraltowski list down important properties a material should exhibit in order to show the GMI effect [7]. The conditions that must be satisfied by any material to show a GMI effect are as follows:

1. The material should be magnetically soft. This implies that the material should possess small losses (small Hc) during the magnetization cycle and should be easily magnetized.
2. The hard axis coercivity should be small (about a fraction of an Oersted). The MH Loop should be very thin and narrow.

3. The material should have well-defined anisotropy axis (i.e. minimum possible anisotropy dispersion). The value of anisotropy field (H_k) should be relatively small (about few Oersteds). The typical ratio of H_k to H_c must be about 20.

4. The ac current injected in the material should be perpendicular to the anisotropy direction and the small ac field H_{ac}, it produces around it should be much smaller than H_k.

5. The material should have large saturation magnetization (M_s) in order to boost the interaction with external field.

6. The material should have small magnetostriction, which dictates the possible source of anisotropy. The presence of such mechanical stress might reduce the effective MI effect.
This table [7, *25] provides an overview of research going on in GMI and their results. The highest GMI reported is 800% which is seen in FeCoNi electroplated on CuBe microwire. In the world of ribbons, to achieve the same result, people had to go to trilayer structures. In case of thin films, the maximum reported GMI is 700%, with an insulator separation between the inner and outer layer. Efforts are still being made to achieve high GMI ratio values in the thin films, and make them comparable to that in wires.
CHAPTER 2. THEORY OF GIANT MAGNETO-IMPEDANCE EFFECT

The concept of giant magneto-impedance has its roots in the idea of dependence of impedance on the skin depth of the conductor. The high frequency AC current flowing through a conductor is concentrated at the surface. The current decreases exponentially towards the inner part of the conductor. The distance between the surface of the conductor and the point within the conductor where the amplitude of the current reduces to 37% percent of its original value at the surface is called the skin depth or the penetration depth, $\delta$;

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu}}$$  \hspace{1cm} (2.1)

The skin depth is inversely proportional to the square root of the product of the circular frequency ($\omega$), conductivity ($\sigma$), and permeability ($\mu$). In ferromagnetic materials, $\mu$ depends on the frequency and amplitude of AC current and the direction and magnitude of the external magnetic field. The strong dependence of $\mu$ on the external magnetic field in the magnetically soft ferromagnetic materials gives rise to the GMI effect. The permeability, and hence the skin depth, can be effectively controlled by an external DC magnetic field. For a conductor in the form of a line or wire, the GMI effect is observed as the strong dependence of the transverse AC permeability on the longitudinal applied DC magnetic field.

It is very necessary to understand that the change in permeability is basically a combined contribution of two main magnetization processes, viz. domain wall movement and magnetization rotation. Application of a weak magnetic field produces a domain wall motion, which tries to expand those domains having the highest magnetization along the applied field. Finally, when most of the domains align themselves in the direction of the applied field, there remain some domains with right angles to the applied field direction. These need very high
energy to orient in the desired direction, as the system has to rotate the magnetization from the
easy axis to the hard axis direction, in case the anisotropy exists.

The magnetic field dependence of the impedance is controlled by the ability of the magnetization
to respond to the magnetic field generated by the current [27]. Depending on the frequency of the
AC driving current, GMI can be studied in three different regimes,

1. Low frequency (Magneto-inductance effect)
2. Moderate frequency (Magneto-impedance effect)
3. High frequency (Ferromagnetic resonance)

**Low frequency regime**

In the low frequency range, when the skin effect is weak, the total complex impedance change is
basically due to the change in internal inductance in the conductor. This is also called as
magneto-inductive effect, and the subsequent voltage across the sample is called magneto-
inductive voltage $V_L$.

$$V = IR + V_L$$

$$V_L \propto \frac{dM}{dt}$$  \hspace{1cm} (2.3)

This inductive voltage depends on the frequency of the drive current as well as the effective
permeability in the material. The larger the effective permeability, the larger will be the change
in the magneto-inductive voltage. In a low frequency region, the voltage change is due to a
decrease of the averaged internal inductance $L$ which responds to the transverse permeability
with respect to the applied ac current. This is the magneto-inductive effect in which the
inductance of the wire responds to the external field via the permeability of the wire.
On application of an external magnetic field, the changing magnetization due to domain wall movement is suppressed and the magnetization is rotated towards the applied field. This manifests itself as decrease in the effective permeability, since the component of magnetization, which can interact with the small AC magnetic field, generated by the current is reduced. This leads to a fall in the magneto-inductive voltage, giving rise to the dependence of the impedance on the external DC magnetic field.

For a homogeneous wire, for example, internal inductance is given as,

\[ L_i = \frac{\mu_\phi l}{2} \tag{2.4} \]

Where, \( \mu_\phi \) is the circular permeability, \( l \) is the length of the wire.

Impedance, \( Z = R + j \omega L \)

For a strip sample,

DC Resistance, \( R = \rho \cdot \frac{l}{w \cdot t} \tag{2.5} \)

Reactance, \( X = 2\pi f L = \frac{\mu \pi f l}{4w} \tag{2.6} \)

Where,

\( \mu \) is the transverse AC permeability;

\( l \) is the length of the stripe sample;

\( w \) is the width of the sample;

\( t \) is the thickness of the sample.

In the presence of the external magnetic field, this circumferential permeability in the wire or the transverse permeability in the stripe sample, can change significantly, causing the inductance,
and hence the total impedance to change. This type of GMI effect is typically smaller than that observed at higher frequencies.

**Moderate Frequency Regime**

When the skin depth, \( \delta \), is similar to or greater than the sample thickness or diameter (typically at frequencies in the range of a few MHz), a greater change in the sample impedance is observed. The impedance is inversely proportional to the skin depth, which is in turn inversely proportional to the square root of transverse permeability, which can be controlled by an applied magnetic field. This change involves both, the change in real and imaginary parts of the complex impedance. Mostly, this change is due to the resistive component of the impedance. The skin effect causes the current to flow near the surface of the material, reducing the effective cross-sectional area of the material, and hence leading to an increase in the resistive component of the impedance. See equation 2.1 for \( \delta \). For a thin film sample, dependence of impedance on the skin depth is given as follows,

[Panina et al (1995)]

\[
Z = R_{dc} \cdot \frac{kt}{2} \cdot \coth\left(\frac{kt}{2}\right)
\]

(2.7)

Where \( k = \frac{i + 1}{\delta} \);

\( t \) = thickness of the film;

\( \delta \) = the skin depth.

Application of external magnetic field changes the permeability, which is reflected in the change in total impedance through the skin depth. Hence, the dependence of the permeability on the external DC magnetic field is the key to understanding GMI behavior.
The domain structure and the magnetic anisotropies play important roles in this process. The total permeability change is the outcome of two different processes, namely, domain wall motion and magnetization rotation. The low frequency both mechanisms can contribute to sample permeability. At higher frequencies (where skin effect is stronger), magnetization rotation plays a more important role due to eddy currents damping the domain wall movements. This effect of damping of the domain wall movement at high frequencies also reduces the hysteresis effect, which is very important factor for a successful sensor application.

**High Frequency regime**

Ferromagnetic resonance (FMR) is observed at very high frequencies, where the skin depth is usually much smaller than the conductor thickness (or wire diameter). In this frequency range, the skin depth changes by huge amounts, leading to strong impedance changes in the sample. FMR can be described by the equation,

\[ \omega = \nu \times H_{\text{eff}} \]  

Where, \( \omega \) = angular frequency of resonance;  
\( \nu \) = gyro magnetic constant;  
\( H_{\text{eff}} \) = effective magnetic field, i.e. vector sum of the external applied fields and internal effective fields.

**GMI in wires**

It is now clear that the MI effect is principally controlled by the effective permeability \( \mu \). One of the parameters that control the magnitude of the permeability is the magnetic anisotropy of the material. Generally, the magnetic anisotropy is extrinsically induced. This can be done by introducing strains or stresses, during the production of the material, or heat treatments, such as
magnetic field annealing after the actual production of the material. Typically, for the case of wires, the melt-spinning process introduces stress in the sample. For a significantly high GMI effect, domain walls perpendicular to the current direction are preferred. This ensures that the AC magnetic field generated by the current lies in the direction of easy axis for the magnetization. This should therefore maximize the effective permeability of the sample.

![Figure 3 Negative magnetostrictive amorphous wire showing circumferential domain structure](image)

The stress is introduced by rapid quenching of the wires. Hence, due to different rates of quenching in the surface and central region of the wire, the domain structure consists primarily of two regions as shown in the above figure 3. The inner core is a single domain feature with an axial magnetization running along the length of the wire, and the outer shell shows a multi-domain structure, with circumferential magnetizations. The compressive stress coupled with negative magnetostriction, tends to align the magnetic moments in circumferential direction favoring the minimum system energy.

A recent investigation of the MI effect on FeSiB amorphous wires by Takemura et al (1996) has shown that, by lightly annealing the amorphous wires, the radial domain structure of the as-cast wire weakens, and gives way to a circumferential domain structure; this is due to surface
crystallization. This leads to an increase in the MI effect, which has also been reported by Atkinson et al (1995), and highlights the importance of the domain structure on the MI effect.

For a straight wire of radius $a$, conductivity $\sigma$, and permeability $\mu$, the expression for impedance is given as,

$$\frac{Z}{R_{DC}} = \frac{R + jX}{R_{DC}} = \frac{ka}{2} \frac{J_0(ka)}{J_1(ka)} \tag{2.9}$$

Where $J_i$ is the $i$-th-order Bessel function and $k = (1+j) / \delta$

For the high frequency case, where $\delta \ll a$, taking $a \sim 1\text{mm}$, and $\delta \sim 1\mu\text{m}$, we can expand Bessel function to obtain:

$$\frac{Z}{R_{DC}} = \frac{(1 + j)}{2\delta} \cdot a \tag{2.10}$$

The AC current flowing through the wire generates a driving field in the easy axis, which favors circular magnetization by domain wall motion. On application of the longitudinal DC magnetic field, the domain wall motion is suppressed and rotational portion of the magnetization grows. As a result of this the circumferential permeability decreases rapidly on the application of the external magnetic field. This dependence of the circumferential permeability on the external magnetic field gives rise to magneto-impedance effect in wires at higher frequencies where, skin effect is seen.

**GMI in ribbons and single layered thin films**

13
The largest GMI ratios reported have been for wire samples. But, sputtered films possess an advantage due to the greater potential of size reduction, patterning, and enhanced efficiency. A lot of effort has been made recently to increase the GMI effect in the thin films and make it comparable to the effect in wires. Initially single layered ferromagnetic layers were studied. After few advances, multi-layered structures were made and measured for GMI. The multi-layered geometry shows obvious increase in the GMI effect as compared with the single layered geometry [3].

In the single layer structure, when high frequency AC current passes through the magnetic ribbon or thin film sample, it generates a small AC magnetic field around it, in the direction perpendicular to the current flow. If this direction is set to be along the easy axis of the sample, the AC magnetic field favors the domain wall motion. When external DC magnetic field is applied in the longitudinal direction, i.e. the direction of hard axis of the sample, the domain wall motion is further retarded and magnetization rotation is favored. During this process, the permeability of the magnetic sample decreases till it reaches the longitudinal saturation. This
permeability change reflects in the change of impedance through the skin depth. This effect in ribbons and thin films is not as high as compared with that in the wires.

When a probe current \( I_0 e^{j\omega t} \) is applied to a film of thickness \( t \), the impedance is written as,

\[
\frac{Z}{R_{DC}} = \frac{kt}{2} \cdot \coth\left(\frac{jkt}{2}\right)
\]

Where;

\( R_{DC} \) is the DC resistance of the film;

\[
k = \frac{1+i}{\delta};
\]

\( \delta \) is the magnetic skin depth given by equation (2.1)

Case1. Low frequency magneto-inductive effect (\( kt/2 << 1 \));

\[
\frac{Z}{R_{DC}} = 1 - \frac{2j}{3} \cdot \left(\frac{t}{2\delta}\right)^2
\]

Case2. High frequency magneto-impedance effect (\( kt/2 >> 1 \));

\[
\frac{Z}{R_{DC}} = 1 - j \cdot \frac{t}{2\delta}
\]

**GMI in multi-layered ribbons and thin films**

The magnitude of the MI ratio obtained in the single layered films is very low. To enhance this effect, multi-layered structures were fabricated and measured for the GMI ratio. The multi-layered geometry shows obvious increase in the GMI effect as compared with the single layered geometry. The multi-layered structure consists of a conducting lead sandwiched between the two soft ferromagnetic layers, i.e. F (ferromagnetic)/M (conductive metal)/F (ferromagnetic). In this structure, with adequately big difference in the resistivity of the F and M layers, very high changes in impedance can be achieved. With the multi-layered structure, we start seeing very
large changes in the impedance at much lower frequencies, due to the increase in the inductive reactance of the ferromagnetic layers (greater than the resistance of the inner conductive lead).

The sandwiched metallic layer carries the AC current and creates flux in the neighboring magnetic layer. Hence the effect is enhanced in multi-layered geometry. Also, compared with single layer MI films, the layered MI needs less power dissipation to generate $H_{AC}$ and also, more uniform field is obtained.

Figure 5 GMI configuration in single layered thin films

**Effect of resistivity difference**

Resistivity difference is a very important parameter in order to achieve a high impedance ratio. Hence, ratios as high as 440% at 10MHz have been reported by T. Morikawa et. al. [6] for CoSiB/Ag /CoSiB film structure as compared with 140% for CoSiB/Cu /CoSiB at 1MHz, as shown in figure 6. On the contrary, CoSiB/Ti /CoSiB have been reported to give only 10% at 40MHz, which is near to the single layered structure. Resistivities of Ag, Cu, Ti are 1.62, 1.72,
and 47.8 μΩ-cm, respectively. This effect is less seen in Ti case because the current does not effectively flow through the inner conductor. Some portion of the current wants to flow in the magnetic layers also. Hence, magnetic field is not efficiently applied to the magnetic layers. With larger the resistivity difference, the maximum of the current flows only in the intended conductor and avoids the spread of the current density inside the magnetic layer. This helps in getting uniform magnetic field in the magnetic layers. Furthermore, the DC resistance of the whole structure is reduced due to insertion of the conductive layer.

![Figure 6 Dependence of GMI on inner conductive material](image)

GMI ratio of 700% at 20MHz has been reported [2] in CoSiB/SiO₂/Cu/SiO₂/CoSiB multi layer structure. This increase in the ratio is attributed to the insulator separation that is inserted in between the magnetic layer and the current carrying conductor. This ratio is the highest number reported till now, in the world of thin films.
When the current passes through the sandwiched conductor, in accordance to the Ampere’s law, it sets a small AC magnetic field proportional to the magnitude of the current flowing through it, around it (which is an easy axis for the neighboring ferromagnetic layers). When the external field is zero, the domain structure of the sandwiched films is as shown in the figure 7(a). On application the external magnetic field in the direction perpendicular to the direction of the AC field, the transverse AC permeability increases as shown in figure 7(b). It keeps increasing until the external magnetic field reaches a value equal to the anisotropy field of the ferromagnetic layers, as shown in the figure 7(c). At this point, the permeability reaches the maxima, because most of the domains are already set in the applied field direction the magnetization saturates. Now with the further increase in the external field, the permeability
drops rapidly as rotational magnetization contribution increases and effectively dominates, as shown in figure 7(d). The rate of decrease in the permeability reduces as magnetization rotation dominates the whole process.
CHAPTER 3. M-H LOOPER

An M-H Looper is an instrument that characterizes a magnetic material by plotting an M-H Loop, which is the fingerprint of any magnetic material. The M-H Loop is a simple plot of the magnetization (M) of a magnetic sample versus the applied magnetic field (H). A simple block diagram of the Looper is shown in figure 8. The M-H Loop of any magnetic material makes possible an understanding of the complex magnetization processes in the material. The MH loop identifies four main commonly used material parameters; saturation magnetization ($M_s$), coercive field ($H_c$), anisotropy field ($H_k$), and remnant magnetization ($M_r$).

Figure 8 General block diagram of a MH Looper

**Block Diagram Explanation**

Two pairs of Helmholtz coils serve as sources of external magnetic fields. The primary coils provide a field coaxial to the direction for which magnetization changes are observed by the
sense coils. A secondary pair of Helmholtz coils serves to provide a transverse field to allow more complex measurements. There exist two identical sense coils, one a balance coil and the other, a pick-up coil; placed in the region of uniform field from the Helmholtz coils. The balance coil, with its position in space and number of turns, nullifies the signal output from the pick-up coil when the sample is absent, thus giving a net ‘zero’ output. When a sample is present, the pick-up coil induces a voltage proportional to the time variation of the magnetization of the sample, i.e. \( \frac{dM}{dt} \). This signal is then amplified with a low noise amplifier, which operates in differential mode to cancel the common signal coming in, thus giving a high common mode rejection ratio (CMRR), which is required for the low amplitude signals. This differential voltage signal is then integrated with respect to time to get the magnetization values (M), which are finally plotted against the field points (H).

**Principle of M-H Looper**

**Helmholtz coil operation principle**

Ampere’s Law: Ampere’s law, states that, the integral of the magnetic field around a closed loop in space is proportional to the net current flowing through the loop. This is the basic premise of a Helmholtz coil.

Ampere’s Law can be used to calculate the magnetic field outside of a coil, with N turns, radius R and carrying a current I.
Figure 9 Current carrying loop with radius, $R$ generating magnetic field, $B$

\[
\int_{\text{path}} B \cdot dL = \mu_0 I
\]

For a multi-layered coil with $N$ turns,

\[
B(x = R) = \frac{8\mu_0 NI}{11.18R} = 0.00899178 \cdot \frac{NI}{R}
\]

(3.1)

**Sense coil operation principle**

Faraday’s Law: A changing magnetic flux $\Phi$, through a loop of wire induces an EMF:

\[
E = -\frac{d\phi}{dt}
\]

(3.2)

If coil of wire has $N$ “turns”,

\[
E = -N\frac{d\phi}{dt}
\]

Lenz’s Law: An induced current in a closed conducting loop will appear in such a direction that it opposes the change in magnetic flux that produced it (as indicated by the negative sign in Faraday’s Law)
\[ \int \frac{E}{N \cdot A} \, dt = B \]

Where, \( A \) is the cross sectional area of the sense coil and \( B \) is the magnetic flux density.

\[ V = N \frac{dM}{dt} \]

\[ \therefore M = \int_{0}^{t} \frac{V}{N} \, dt \]  

(3.3)

The Helmholtz coil setup provides a uniform magnetic field for the sample under measurement. The induced voltages across the pick-up (\( V_A \)) and the balance coils (\( V_B \)) are proportional to this field sweep (\( \frac{dH}{dt} \)), when the sample is absent. Being electrically similar, the difference (\( V_A - V_B \)) between these two voltages is zero with the sample absent. When a magnetic sample is introduced in the pick-up coil, the voltage across the pick up coil (\( V_A \)) is proportional to the rate of magnetization of this sample (equation 3.3), in addition to the field sweep (i.e. \( \frac{dH}{dt} + \frac{dM}{dt} \)). Whereas, \( V_B \) is proportional to the sweep field (\( \frac{dH}{dt} \)) only. Hence, from \( V_A - V_B \), we get, \( \frac{dM}{dt} \) (as shown in the figure 10). With the applied field as a function of time known, integration of \( \frac{dM}{dt} \) (figure 11) will give total magnetization of the sample as a function of time.
**Design of the Helmholtz coils assembly**

The Helmholtz coil geometry provides a uniform magnetic field for the sample under measurement. Helmholtz coils can be described as two identical, co-axial coils, separated by
distance equal to the radius of those coils, and connected in either series or parallel, so that equal current flows in the same direction. This is clearly depicted in figure 12.

The basic objective of the Helmholtz coils is to provide uniform magnetic field for the magnetic sample under measurement. This homogenous magnetic field is the result of addition of the two field components parallel to each other (along the coil axes), and the difference between the components perpendicular to the axes. This magnetic field produced by each coil is directly proportional to the number of turns in the coils and the current applied to them. The equation for the Magnetic field (H) in Oersteds at a distance x=R, produced by the current I (amperes) flowing through the coils, each with radius R (cm) and number of turns N is given by,

$$H(x = R) = 0.899178 \times \frac{N \times I}{R}$$

(3.4)

The DC coupled, power amplifier we chose was AE Techron LVC 5050, and it has specifications of 60 Volts maximum output, for 4 Ohms load, in its dual (two channel) mode of operation. The primary set of coils is designed to give maximum of 600 Oersteds of field.
With this information, we can calculate the maximum DC current we can get, which is 15 amperes.

We selected AWG#14 which has a nominal diameter of 0.641” and nominal resistance of 2.524Ω per 1000 feet. With this information, we can calculate the length of the wire that can make to 2Ω of DC resistance, which comes out to be 792 feet. For 9” diameter, each turn will consume 28.27” of its length. Hence, with 9504” we can get 336 turns. Similarly for secondary coils, we can have 37.7” per turn, i.e. 252 turns for each secondary coil, giving 300 Oersteds of secondary axis field.

**Temperature gradient calculation**

We determined the amount of power that could be absorbed by a 5” coil segment, to verify the safety of the coils under the worst possible condition.

\[ P = I^2 \times R \]

\[ \therefore P = 15^2 \times 2.103 \times 10^{-4} \frac{\Omega}{in} \times 5in \]

\[ \therefore P = 0.23659\text{Joules/second} \]

\[ = 0.23659 \times 60\text{seconds} \times 336\text{turns} \]

\[ = 4769.6544\text{Joules} \]

This is the thermal energy in Joules, absorbed by the 5” segment of the coil, per minute. Temperature gradient every minute can be calculated as follows;

\[ Q = m \times c \times \Delta T \]

Where,

\[ m = \text{mass of the section in gm} \]
\[ c = \text{specific heat of Copper} = 0.386 \frac{J}{\degree C \cdot gm} \]

Density of copper = \(8.9 \frac{gm}{cm^3}\)

Volume of copper segment for 5 inch length = 690 cubic cm

\(\Delta T\) = rate of rise in temperature in \(\degree C\) per minute

\[ \therefore 4769.6544 \text{ Joules} = [(\sqrt{336} \times 0.641)^2 \times 5 \text{ inch} \times 2.54^3] \text{ cm}^3 \times 0.386 \frac{J}{\degree C \cdot gm} \times 8.9 \frac{gm}{cm^3} \times \Delta T \]

\[ \therefore \Delta T = 0.1227^\circ C / \text{ min} \]

This value of the rate of increase of temperature is not bad at all. This means that, it will take 2 hours for the coil to reach a temperature of about 40\(\degree C\) from room temperature. This looks like a safe deal.
Inductance calculation

Figure 13 Dimensions of the multi-layered coil

For calculation of the inductance of the coil, following formula is used [30]:

\[
L = 4 \cdot 10^{-7} \cdot a \pi N^2 \cdot \left[ (0.5 + \frac{S_1}{12}) \cdot \ln\left(\frac{8}{S_1}\right) - 0.84834 + 0.2041 \cdot S_1 \right] \text{ henries}
\]

\[
S_1 = \frac{c}{2a}^2
\]

\[
S_1 = 0.018237624
\]

\[
L = 0.03388 \text{ H}
\]
Frequency dependence characteristics of the coil

Figure 14 Frequency dependence of the output current

The current drops to nearly zero by the time frequency reaches 10 kHz. Hence, the Looper can be best used in lower possible frequencies.

Field uniformity calculations

Radius of the primary coils, R = 0.16m

Number of turns, N = 368

Current, I = 20A

Range of the sample, within the field space, x = -0.038m to +0.038m

Distance between the coils, D = 0.152m

Points where measurement is made x1 and x2 are defined as
\[ x_1(x) = \frac{D}{2} - x \]

\[ B_1(x) = \frac{0.00899178 \cdot N \cdot I \cdot R^2}{\left[ R^2 + x_1(x)^2 \right]^{3/2}} \]

---

**Figure 15 Field uniformity for coil-I**

\[ x_2(x) = \frac{D}{2} + x \]

\[ B_2(x) = \frac{0.00899178 \cdot N \cdot I \cdot R^2}{\left[ R^2 + x_2(x)^2 \right]^{3/2}} \]
Figure 16 Field uniformity for Coil II

\[ B_{\text{Total}}(x) = B_1(x) + B_2(x) \]

Figure 17 Field uniformity in 1- dimension

Non-uniformity over the sample area

\[ B_{\text{Total}}(0.038) = 604.375 \text{ Oe} \]
\[ B_{\text{Total}}(0) = 609.673 \text{ Oe} \]
\[ Non - uniformity = \frac{B_{\text{Total}}(0) - B_{\text{Total}}(0.038)}{B_{\text{Total}}(0)} \times 100\% \]

\[ Non - uniformity = 0.869\% \]

**Sense coil design**

Shape of the sense coil was designed to fit maximum of a 3” sample, 0.25” thick. The sense coils have 2000 turns each of AWG # 38 hand-wound on a rectangular cross section acrylic block. Each coil has resistance of 1.16kΩ. A 10kΩ resistor is connected across the bucking coil, and another 10kΩ potentiometer is connected across the pick-up coil. This makes possible adjustments for the balance of the coils.

**Block Diagram of the Actual Looper constructed**

![Block Diagram of the Actual Looper constructed](image_url)
**Hardware Interfacing**

**Sense coils / PC interface**

A 10kΩ resistor is connected across the bucking coil, and another 10kΩ potentiometer is connected across the pick-up coil. This potentiometer is used to balance the sense coil, appropriately. The output of the balance coil and the pick-up coil are fed to the A and B inputs of the Stanford Research Systems 560 Low noise Pre-amplifier, which is programmed to operate in “A-B” mode. Filter mode is set to operate in Low pass filter with cut-off frequency of 1 kHz. Output of this amplifier is fed to the National instruments DAQ 6052E board. The gain and the filter mode are initialized at the start of the program execution. The gain can be adjusted during the execution of the program.

**Helmholtz coils / PC interface**

A Labview 6.1 program is used for generation of a sinusoidal voltage signal. This signal is fed to the AE Techron LVC 5050 Linear Power supply amplifier, through the NI DAQ board. There is a 0.1Ω resistor (with heat sinks) connected in series with both, the primary and the secondary pair of Helmholtz coils. These current sense resistors indicate the current passing through the coils. The voltages across these resistors serve as the source of magnetic field data for plotting the M-H loop.
Figure 19 Top view of the Looper assembly

Figure 20 Side View of the Looper assembly
Figure 21 Front View of the Looper Assembly
Software Features and working

Software used was Labview 6.1

Front panel is as shown in the following figure 22.

![Figure 22 MH Looper Front panel display](image)

The software written to automate the system is user friendly and easy to use. Special features in the software are as follows:

Data rate

Each analog input signal is sampled at 6000 samples per second. These signals include:

1. The voltage across the current sense resistor, connected in series with the primary Helmholtz coils that serve as the primary magnetic field indicator.
2. The voltage across the current sense resistor, connected in series with the secondary Helmholtz coils that serve as the primary magnetic field indicator.

3. Output voltage from the SRS 560 Low noise amplifier that serve as the magnetization data of the sample.

Output signals are sent, point-by-point, at the same data rate. There are two analog output channels in the DAQ board. Following are the signals sent out from the PC:

1. Channel #1 input as a drive signal for the LVC5050 Power supply amplifier, for the Primary coils.

2. Channel #2 input as a drive signal for the LVC5050 Power supply amplifier, for the secondary coils.

**NI 6052E DAQ Board important features**

1. Resolution: 16-bit

2. Number of Analog input channels: 16 single ended and 8 differential

3. Number of Analog output channels: 2

4. FIFO Buffer size: 2048 samples

5. Maximum Update rate: 333kSamples/s

6. Voltage output: ±10Volts maximum

**Averaging Cycles**

Averaging is very special feature of the software, which may be used for offsetting noise, which might not be eliminated by the background subtraction. Especially in case of very thin films in nanometers scale, the signal to noise ratio becomes weak and it is difficult to get a decent looking Loop. In this case, averaging of the signal ‘n’ number of times should prove helpful.
60Hz noise can be very effectively removed with the help of averaging. However, the greater the number of averages involved, the slower is the measurement speed. Also, the data displayed on the graph is no longer real-time, if number of averages is more than one.

**Background subtraction**

The software provides the user, a chance to measure the background, with the sample absent and then subtract it later from the original signal, with the sample present. The front panel as seen in the above figure 22 has three buttons provided for this purpose, namely, background, signal and signal minus background. The graph displays the signal corresponding to the button pushed i.e. either background only, signal only or signal minus background. The background button, when pushed, measures the signal and stores it as “background”. It is the user’s task to be sure that the sample not present in the sense coils during this step. Similarly, the signal button, when pushed, measures the signal and stores it as “signal”. The sample should be present in the sense coils during this step. Signal-Background button, when pushed measures the signal and stores it as “signal”, and displays “Signal-Background”, which is the actual loop for the sample. Different orientations with respect to the field axis can be checked to get different loops of the sample, magnetically anisotropic in behavior. To do so, the sample can be rotated carefully and slowly within the pick-up coil. The corresponding loop can be observed simultaneously, as the sample is rotated.

**Overload**

The overload sense is the indicator on the front panel, which indicates overload at the output of the SRS 560 pre-amplifier. When the signal at the output of the amplifier is higher than the range allowed by the amplifier for a particular gain chosen, the signal gets clipped off at its overshoots.
With this going on, the loop displayed may have uncertainties corresponding to the data points missing in the process of clipping off the peaks. In order to make sure that there are no missing data points in the displayed loop, the signal must be within the output range. The gain is initialized at the start of the program execution. It can also be adjusted during the execution of the program. If the overload indicator starts flashing, the SRS gain needs to be reduced in order to be in proper execution mode, otherwise the software pops a message repeatedly, to do so, until it is done, and stops sampling data at the input.

**Display Parameters**

The various important parameters like saturation magnetization, $M_s$, remnant magnetization, $M_r$, and coercive field, $H_c$, are displayed on the front panel. There is a ‘parameters’ button provided for this purpose. Correct data is displayed while the button is ON. The parameters are calculated directly from the M-H waveforms, by calculating the zero-crossings of the magnetization and drive field waveform. Their relation is then derived using the indices of their zero-crossing points in the corresponding arrays.

**Save Data**

The loop data, along with the parameters can also be saved in the excel format, for further analysis.

**Vertical Scale Calibration**

The default unit is Volts-Seconds. In order to display in units of “EMUs”, a nickel foil sample, with known weight in grams, is used to calibrate the vertical scale units, automatically.
**Horizontal Calibration**

The software also allows the user to calibrate the horizontal axis, which is not often required. The software automatically gives a signal to the coils and measures the signal back, and compares it with the actual field present, which the user has to measure and then enter in the provided field. Using this comparison, the software updates its previous calibration constants to the new ones.
Example for a MH Loop for a 17nm Thin NiFe Sample with and without average

**Figure 23 MH Loop without an average**

**Figure 24 MH Loop with 8 averages**
Comparison of the Looper loops and the loops obtained by Vibrating Sample Magnetometer (VSM)

Figure 25 MH Loop for a non-linear short sample measured by MH looper

Figure 26 MH Loop for a non-linear short sample measured by VSM
Figure 27 MH Loop for a linear short sample measured by MH looper

Figure 28 MH Loop for a linear short sample measured by VSM
Figure 29 MH Loop for a wire long sample measured by MH looper

Figure 30 MH Loop for a wire long sample measured by VSM
Figure 31 MH Loop for a wire short sample measured by MH looper

Figure 32 MH Loop for a wire short sample measured by VSM
**Extended capabilities**

**Minor Loops**

The Looper has capability for measuring the minor loops in the samples, with or without DC offset fields.

Following graphs show the major loops, minor loops with and without DC offset. The sweep signal used is the sine waveform as shown below.

Primary Sweep Field waveform

![Primary Field Sweep Graph](image)

*Figure 33 Primary Field sweep waveform*
Figure 34 Major Loops for a 200nm NiFe film

Figure 35 Minor Loops with zero DC offset
Permeability measurements

Transverse permeability can be measured with the help of the field provided by the secondary coils. This measurement needs several minor loops to be taken for various secondary DC fields. Primary sweep field is set to be at 10Hz (or similar), ±H Oersteds, where \( H < H_c \) of the sample, in easy axis. This emulates the high frequency AC field generated by the current, in case of impedance measurements. The DC field provided by the secondary coils serves as the external field. Each minor loop has a slope, which is proportional to the permeability of the sample. These types of measurements have been done on the GMI samples. The permeability curve resembles the impedance measurements, and will be presented in the subsequent chapters.

Example of such set of minor loops for a composite amorphous CoSiB film is shown below.
Figure 37 Major Loops for 200nm CoSiB film
Slope for all the minor loops is calculated and then plotted against the corresponding field in the next graph.
Conclusions

The MH Looper system was built and automated to characterize magnetic thin films utilizing the Magneto Inductive effect. This measurement system made it possible to investigate various magnetic thin film properties, which proved useful in making better magnetic films for the high sensitivity GMI sensor. Various thin films like NiFe and NiFeCo alloy, CoSiB co-sputtered thin films were measured with very good resolution.

The Looper is capable of measuring the magnetic properties of thin films down to 10nm. The lower sample volumes affected adversely, the magnetic measurements in terms of signal to noise
ratio. The solution to this would be to increase the signal frequency in order to get more signal than noise.

The averaging capability of our Looper makes it possible to have reliably noise free loops, even for the very thin films in the range of tens of nanometers.

Comparisons of hysteresis loops with measurements done at Sensormatic Electronics Corporation with the help of their Vibrating Sample Magnetometer have shown that results can be taken to be reliable.
CHAPTER 4. EXPERIMENTAL TECHNIQUES

Objective

1. To obtain a low remnant magnetization, low coercivity and high resistivity magnetic film for a sensitive magneto-impedance device.

2. Measure the magneto-impedance.

Materials Used

Ferromagnetic material: CoSiB, Ni$_{80}$Fe$_{20}$, Ni$_{84}$Fe$_{16}$

Conductor: Copper

Experiments to achieve a good soft magnetic properties for the thin film

CoSiB studies

1. Composition variation in CoSiB
   a. Cobalt variation
   b. Silicon variation
   c. Boron variation

2. Substrate Bias variation in CoSiB

3. Annealing experiments on CoSiB films

NiFe studies

1. Stress variation in Ni$_{80}$Fe$_{20}$

2. Composition variation of Ni$_{80}$Fe$_{20}$ and Ni$_{84}$Fe$_{16}$
**Characterization Instruments**

1. MH Looper
2. Quad-pro four-point probe resistivity
3. Low Frequency Impedance analyzer HP4192A
Representation of general methodology for experimentation

START

Make single layer films

Measure with MH Looper

Measure resistivity

If $H_{C_{\text{Hard}}} \leq 4\text{Oe}$ and $H_{C_{\text{easy}}} \leq 15\text{Oe}$ and $M_r \sim M_s$

Yes

Make sandwich films

Measure Loops and permeability with MH Looper

Measure resistivity

If $H_{C_{\text{Hard}}} \leq 4\text{Oe}$ and $H_{C_{\text{easy}}} \leq 15\text{Oe}$ and $M_r \sim M_s$

No

Pattern

Measure Magneto-impedance

STOP
GMI Structure and pattern

Figure 40 General Structure of the GMI device fabricated

Figure 41 Mask used for patterning the GMI device on a 3” silicon substrate
The final device structure cross-section was as shown in the figure 40. The pattern for the device was as shown in the figure 41. The measurements were done using the end contacts of the serpentine, with the help of alligator clips.

**Substrate preparation**

1000 Å thick SiO2 was thermally grown on the Si wafers. The wafers were washed clean with the help of de-ionized water and soap. This was followed by acetone and methanol wash. Finally, the substrate was washed with the de-ionized water and blow dried with the compressed dry N2.

The substrates for the films studied in this thesis were not pre-sputtered for deposition, as it was found that it had no effect on the magnetic properties of the films.

**Target preparation**

The CoSiB amorphous films were co-sputtered using separate Co, BN and silicon targets, in an argon ambience. In order to make sure that silicon target does not gather oxide or contaminants during the deposition, due to its low power of operation; it was pre-cleaned by sputtering at 45W DC for about 15 minutes, against the shutter and then adjusted to the operation power during actual sputtering. Similarly, BN target was pre-cleaned at 125W RF for about 15 minutes.

**Thin film deposition**

The films were deposited using an ultra-high vacuum DC or RF magnetron sputtering. The base pressure in the chamber was approximately 1X10⁻⁸ Torr. Specific parameters like pressure, substrate bias, and target power were varied to arrive at a set point, so as to get good device properties. It was found that the pre-cleaning procedure (30W RF for 15 minutes) was not helpful in improving the magnetic properties of the film and hence, the substrate was not pre-
sputtered for any of the samples presented in this thesis, unless mentioned. Most of the initial experimentation phase was concerned with the deposition and optimization of the magnetic properties of the thin film for its device application.

**Experiment #1 Composition variation in CoSiB**

In this experiment, we primarily varied the target power for each of the targets, i.e. cobalt, silicon, and boron, one at a time, to carry out a systematic test in order to get to get soft magnetic properties for the film. The cobalt and silicon are DC sputtered and boron nitride is RF sputtered, together at the same time. The magnetic field present during the deposition was 200 Oe, which was used to get anisotropy in the film. The magnetic anisotropy describes the preference of the magnetization to lie in a particular direction. This was provided by the array of magnets especially patterned to form a circle, as shown in the figure 42. The substrate holder was designed to hold this magnet array as shown in the following figure 43. As seen in the diagram, the substrate can be easily rotated in any orientation with respect to the magnetic axis, in steps of 45º.
Figure 42 Array of magnets used for controlling anisotropy in the films

Figure 43 Magnetic Bias Holder assembly cross-section
Common parameters for the experiment were:

Base Pressure of the chamber: $1 \times 10^{-8}$Torr

Deposition Pressure: 4mTorr

Gas flow: 20sccm Argon

**Cobalt content variation**

Keeping the target powers for silicon and boron nitride constant, cobalt power was varied and various results were obtained.

With Si: 20WDC, BN: 125WRF- Constant, cobalt was varied

<table>
<thead>
<tr>
<th>Series. #</th>
<th>Co (DC-W)</th>
<th>Si (DC-W)</th>
<th>BN (RF-W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>20</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
<td>20</td>
<td>125</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>20</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
<td>20</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>110</td>
<td>20</td>
<td>125</td>
</tr>
</tbody>
</table>

**Silicon content variation**

Keeping the target powers for cobalt and boron nitride constant, silicon power was varied and various results were obtained.

With Co: 90WDC, BN: 125WRF- Constant, silicon was varied
Table 3 Silicon content variation

<table>
<thead>
<tr>
<th>Series. #</th>
<th>Si (DC-W)</th>
<th>Co (DC-W)</th>
<th>BN (RF -W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>90</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>90</td>
<td>125</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>90</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>90</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>90</td>
<td>125</td>
</tr>
</tbody>
</table>

*Boron content variation*

Keeping the target powers for silicon and cobalt constant, boron nitride power was varied and various results were obtained.

With Co: 90WDC, Si45W- Constant, BN was varied

Table 4 Boron content variation

<table>
<thead>
<tr>
<th>Series. #</th>
<th>BN (RF -W)</th>
<th>Si (DC-W)</th>
<th>Co (DC-W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75</td>
<td>45</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>45</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>125</td>
<td>45</td>
<td>90</td>
</tr>
</tbody>
</table>

The BN and Si targets were initially sputtered against the shutter at 125W RF and 45W DC, respectively for 15 minutes to remove any surface oxides and contaminants. The pre-sputter times were reduced to 5 minutes for further depositions of the same target.

**Post-deposition heat treatment**

The heat treatments used to anneal the samples in this study was performed at a temperature of 200°C for 60 minutes in a low vacuum of the order of 10⁻⁸ Torr, in presence of magnetic field of
200 Oe. Another anneal was performed at 150\(^0\)C for 4 hours. These temperatures were found to be sufficient to allow the as-deposited stresses in the films to be partially relieved, but sufficiently low that crystallization of the films did not occur. Crystallization of the film can severely affect the magnetic properties (due to its high magneto-crystalline energy) by generally increasing the coercive and anisotropy fields. This was not observed in case of this sample.

The annealing process relieves the internal stresses which can occur during deposition of the films. This can be a result of the thermal expansion coefficients mismatch between the film and substrate and the dynamics of the sputtering process itself.

The annealing process proved good in terms of anisotropy control as will be seen in the next chapter. This treatment was carried out in a UHV so as to reduce contamination of the film due to oxidation. For the conclusion of the annealing process, the sample was allowed to cool gradually to room temperature in the vacuum.

**Experiment #2 Substrate Bias Variation in CoSiB**

Base Pressure of the chamber: 1\(*10^{-8}\)Torr
Deposition Pressure: 4mTorr
Gas flow: 20sccm Argon
RF Substrate Bias: 20W, 30W
Co: 110W, Si: 20W, BN: 125W

**Experiment #3 Pressure variation in Ni\(_{80}\)Fe\(_{20}\)**

Base Pressure of the chamber: 1\(*10^{-8}\)Torr
Gas flow: 20sccm Argon
No RF Substrate Bias

Deposition Pressure: 1mT, 2mT, 4mT, 6mT, 8mT, 12mT

**Experiment #4 Composition variation of Ni$_{80}$Fe$_{20}$ and Ni$_{84}$Fe$_{16}$**

Base Pressure of the chamber: $1\times10^{-8}$Torr

Deposition Pressure: 2mT

Gas flow: 20sccm Argon

No RF Substrate Bias

Co-sputtered target powers

<table>
<thead>
<tr>
<th>Series#</th>
<th>Ni$<em>{80}$Fe$</em>{20}$</th>
<th>Ni$<em>{84}$Fe$</em>{16}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0W</td>
<td>200W</td>
</tr>
<tr>
<td>2</td>
<td>50W</td>
<td>150W</td>
</tr>
<tr>
<td>3</td>
<td>100W</td>
<td>100W</td>
</tr>
<tr>
<td>4</td>
<td>150W</td>
<td>50W</td>
</tr>
<tr>
<td>5</td>
<td>200W</td>
<td>0W</td>
</tr>
</tbody>
</table>

**Final Device parameters**

CoSiB 200nm / Cu 400nm / CoSiB 200nm

CoSiB deposition parameters:

Base Pressure of the chamber: $1\times10^{-8}$Torr

Gas flow: 20sccm Argon

Pressure: 4mT

No RF Substrate Bias
Cu was DC sputtered at 200W, 20sccm Argon at 4mT.

Two such samples were prepared, as follows:

### Table 6 Co-sputtered target powers

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>90W</td>
</tr>
<tr>
<td>Si</td>
<td>45W</td>
</tr>
<tr>
<td>BN</td>
<td>125W</td>
</tr>
</tbody>
</table>

### Table 7 CoSiB GMI samples

<table>
<thead>
<tr>
<th>CoSiB 200nm / Cu 400nm / CoSiB 200nm</th>
<th>As-deposited</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoSiB 200nm / Cu 400nm / CoSiB 200nm</td>
<td>DC Field Annealed at 200ºC for 1 hr</td>
</tr>
</tbody>
</table>

**Patterning by photolithography**

The photolithography technique was used to fabricate the device. This technique involves transferring a pattern, which in our case is a serpentine pattern; from a photographic mask onto a film.

For practical use as sensors, the zero-field impedance of the device should be high enough to realize high output voltage. Therefore, patterning was performed to raise the DC resistance of the sample. Following is the flow chart for the process.
Clean the sample with Acetone, Methanol and De-ionized water, Blow dry

Spin Positive Photo-resist on the sample for 30 seconds at 3000 rpm

Wash clean with acetone and blow dry

Align mask and expose on the Karl Suss Mask Aligner for 10 seconds

Develop the photo-resist in the Developer for about 1 minute

Look for sharp edges of the pattern

Soft bake the resist for 3 minutes in 100°C Oven

Acceptable? Yes No

Uniform?

Yes

No

Good enough?

Yes

Hard bake the resist for 10 minutes in 100°C Oven

Etch the sample in Ferric chloride solution

Wash with Acetone and Blow dry

STOP
Impedance measurement setup

Impedance measurement setup used to perform GMI measurements is arranged as shown in the figure 44. The setup was not automated at the time of measurements.

The LF impedance analyzer was set to have four point probe measurements. The basic principle of the measurement is that a low amplitude AC current, with varying frequency is made to pass through the device and the corresponding impedances are measured as a function of applied field. The model used was Hewlett-Packard LF4192A impedance analyzer. The frequency range used for measurement was 1MHz to 8MHz and the drive current amplitude was 9mA.
The device was orientated such that the magnetic field of the Helmholtz coils was in the direction parallel to the current direction. The electrical contacts to the sample were made using alligator clips. Low impedance coaxial cabling was used to connect the sample to the analyzer terminals so as to screen out unwanted signals. To verify that no external false signals were present in the measurement system, a similar serpentine pattern was fabricated on a 400nm Copper film and substituted for the MI device. The data after 8 MHz was found to be not reliable.

Also, permeability measurements were carried out for the same sample, which will be discussed in the subsequent chapter.
CHAPTER 5. RESULTS AND DISCUSSION

Introduction

The results obtained from the experiments mentioned in chapter four are presented in this chapter. Various experiments were performed to optimize the soft properties of the magnetic thin film. Finally, an optimized combination of deposition parameters was chosen and the GMI device was fabricated, using photo-lithography. Magneto-impedance measurements were then carried out, using the impedance analyzer. A theoretical model is used to verify the experimental results. For the frequency range of the impedance analyzer (5Hz-13MHz); in order to observe a MI effect, skin depth should fall in the range of the film thickness. For 13 MHz, the thickness should be roughly around a micron or so, so that we can clearly see the MI effect. We performed various experiments on variation of thickness in CoSiB films, but failed achieve good magnetic properties for the films of such high thickness. We obtained a thickness trend with coercivity. Also, the source of anisotropy in the film was different than the array of magnets, which confounded the directionality as we tried higher thicknesses in the films. We also examined the NiFe films and a similar trend was observed with thickness. Our current understanding is that a perpendicular anisotropy is induced in the films as we go thicker which is caused by magnetostriction and allows a different domain structure to be developed in the film. We performed experiments to achieve magnetically thicker NiFe layers as combinations of thinner layer separated by spacer layers to decouple the magnetic layers from each other. We deposited 2nm Tantalum seed layer for 300nm of NiFe followed by another 2nm Tantalum for next 300nm NiFe. The intermediate tantalum layer gives the similar surface for the next 300nm NiFe. This ensures that the top 300nm of the 600nm NiFe also has the same surface as the first 300nm
deposited. This approach proved useful in getting to a magnetically thicker NiFe layer, but proved problematic in the next step, i.e. patterning. Permeability measurements of this film show very steep change in permeability with external magnetic field.

Finally, MI measurements for the CoSiB 200nm / Cu 400nm / CoSiB 200nm sample are presented in this chapter.

**CoSiB studies**

Basically, addition of silicon and boron together, help make the film amorphous, and increase resistivity of the film. Cobalt is the magnetic component in these films.

**Substrate Bias variation in CoSiB**

Co: 110W, Si: 20W, BN: 125W

This experiment was carried out to see the effect of RF-bias on the substrate during the deposition. Application of bias, as seen from the loops in figure 45, has tremendous effect on coercivity and anisotropy of the film. The film lost its anisotropy direction with the application of RF bias. This study was done previously on the NiFe films (figures 61-62), where, it was found that the RF bias actually improves the quality of the loops and hence, the soft magnetic properties in general. Hence, it was also performed on the CoSiB films to see whether we get the similar trend in the magnetic properties of the film. In conclusion, the best properties were achieved without RF-bias to the substrate.
Figure 45 Effect of substrate Bias variation in CoSiB film

Composition variation in CoSiB

**Cobalt variation: Si: 20WDC, BN: 125WRF**

Film Thickness: 85nm

The objective of this experiment was to vary cobalt content, relative to the silicon and boron, in the magnetic film and see what effect it has on the properties. The MH Loops for the films are as shown in the figures 46 and 47. It is clearly seen that higher the cobalt content in the film, higher is the coercivity in easy as well as hard axes of the film. Conversely, if the cobalt content in the film decreases, the effective magnetization in the film will reduce and this is not desirable. We had to fix a certain point in the composition, where the cobalt content is high enough so that we have good magnetization and also low enough, so that we have low coercivity, for it to be less lossy. Hence we fixed Co 90W, BN 125WRF, and silicon 20W, for further experiments. Also, it
was observed that resistivity of the film was not much affected by the cobalt content variation. Hence, further in the study, we varied silicon and boron content in the film, to see its effect on resistivity.

Figure 46 Effect of cobalt content variation in CoSiB film

Figure 47 Effect of cobalt content variation in CoSiB film
**Silicon variation Co: 90W, BN: 125W**

Film Thickness: 65nm

The objective of this experiment was to vary silicon content, relative to the cobalt, in the magnetic film and check its effect on the magnetic and resistive properties of the film. The MH Loops for the films are as shown in the figure 48 and 49. It is observed that higher the silicon content in the film, lower is the anisotropy field in hard axes. No significant coercivity relation is observed with silicon content variation. The loop at silicon 70W shows that it has higher remnant magnetization than the others. Resistivity was found to be highly dependant on the silicon content in the film. Now, if the silicon is sputtered at lower powers, there is a doubt that it might get oxidized and cause the film to incorporate silicon oxide instead of silicon. This might cause higher coercivity in the magnetic film. Hence we fixed Co 90W, BN 125WRF, and silicon 45W, for further experiments.

![Figure 48 Effect of silicon content variation in CoSiB film](image)
Boron variation: Co: 90W, Si: 45W

Film Thickness: 50nm

We also studied boron content variation in the film, to achieve the best possible combination for the films. The results are shown in the figures 50 and 51. As seen from the hard axes loops, lower the boron content, higher is the anisotropy field in the film. But his variation is not very significant and can be neglected. However, as seen in the set of easy axes loops, the coercivity increases as the boron content decreases. This may be related to the fact that, decreasing boron, effectively increases relative cobalt content and causes a minor rise in the coercivity of the film.

In this study, BN 125WRF, Si 45W, and Co 90W was chosen to be the best possible combination in the available set of data.
Figure 50 Effect of boron content variation in CoSiB film

Figure 51 Effect of boron content variation in CoSiB film
Anneal comparison

Two different kinds of anneal were performed on the films to see their effect on the magnetic properties of the film. It is seen that the annealing conditions under consideration did not have much effect on the coercivity of the film. There seems to be a good effect definitely, in terms of the sharpness of the loops, which indirectly affects the sensitivity in the GMI response through anisotropy dispersion factor. The easy axis coercivity and the hard axis anisotropy, is improved with annealing. Annealing helps in relieving any residual stresses in the film caused during the deposition due to difference in the thermal coefficient of expansion of the film and the substrate. Annealing at 200ºC for 1 hour did not have much different effect on the magnetic properties than annealing at 150ºC for 4 hours. Hence, we chose the annealing at 200ºC for 1 hour, for the final device.

Figure 52 Comparison of different anneal temperatures and times on magnetic properties of the single layer CoSiB
CoSiB - GMI sample measurements

Magnetic Properties

Figure 53 shows the MH loops for the 200nm bottom layer of the sample. This shows that the film has coercivity of 3.5 Oersteds and Mr is about 95% of its Ms value, in the easy axis. The hard axis coercivity of the loop is about 3.5 Oe and anisotropy field is about 22 Oe.

![MH Loops for the bottom layer 200nm](image)

Figure 53 Magnetic properties of the 200nm CoSiB bottom layer of the GMI sample

400nm of copper is deposited on top of this film, as a conductive layer in the GMI device. The 200nm CosiB top layer is then co-sputtered on top of copper. The copper provides a different surface to the top magnetic layer, as compared with the SiO2 in case of the bottom layer. This makes the films look magnetically different. This effect is clearly seen in the MH loops of the tri-layer structure in figure 54. The difference in the switching fields of the top and bottom layer is...
manifested as a distortion in the combined easy axis loop of the sample. With annealing carried out in vacuum at $1 \times 10^{-8}$ Torr, 200°C for 1 hour, the stresses in the film are partially relieved, which shows up as the relaxation in anisotropy and coercivity, as shown in the figure 54.

Figure 54 Effect of annealing on the magnetic properties of the GMI sample

Figure 55 Magnetic characteristics of the tri-layer GMI sample
Impedance and permeability measurements

This figure 56 shows the comparison of a set of %GMI ratio with the magnetic field, for various frequencies ranging from 1MHz to 9MHz.

![GMI % Vs Field](image)

**Figure 56 Dependence of Z on external magnetic field**

The impedance characteristics of the CoSiB/ Cu/ CoSiB film exhibit a peak at 21 Oe, which is the anisotropy field, indicated in the MH Loop of the sample. The maximum impedance change ratio, \( \Delta Z / |Z_0| \), is 6.2% for the field of 21 Oe, at 8MHz. Also, figure 58 shows permeability change with external magnetic field. The drive frequency used during permeability measurements was 10Hz for simplicity. The impedance curve reflects the permeability versus field characteristics. Figure 59 shows comparison of permeability change and % GMI change.
with the external magnetic field. Both curves exhibit a peak at around 21 Oe, which is clearly the anisotropy of the sample. The DC resistance of the device was dominated by the inner copper layer. Resistivity of sample was measured to be 2.2\(\mu\Omega\)-cm and the DC resistance of the device was 74\(\Omega\), for the serpentine end to end. The resistivity of the CoSiB layer was 250\(\mu\Omega\)-cm.

As we can clearly see from the figure 57, maximum \%GMI is achieved at 8MHz and it drops at 9MHz. This is not what is expected for the given thickness of the device under consideration. This effect was due to the impedance mis-match in the setup.

**Permeability change for the GMI Device**

The permeability increases with increase in the external magnetic field, reaching a peak at external field equal to the anisotropy field for the sample and then decreasing back to zero-field

![GMI ratio % vs frequency](image)

*Figure 57 Dependence of GMI ratio \% on frequency*
impedance or near value with further increase in magnetic field. This behavior can be explained by the rotational magnetization model [6]

\[ \mu_r = 1 + \left( \frac{4\pi M_s}{H_k \cos 2\Phi + H_{\text{ext}} \sin \Phi} \right) \sin^2 \Phi \]

Where,

\[ \sin \Phi = \frac{H_{\text{ext}}}{H_k}, \quad H_{\text{ext}} \leq H_k \]

\[ = 1, \quad H_{\text{ext}} > H_k \]

![Normalized permeability as a function of Field](image)

**Figure 58 Dependence of Permeability on the external magnetic field**

The loss in the steepness of the experimental permeability curve may be attributed to the hysteric properties of the GMI device. The theoretical graph suggests that the rotational contribution increases with increase in external magnetic field, for \( H_{\text{ext}} \leq H_k \). It then decreases with further
increase in external field. For, $H_{\text{ext}} > H_k$, rotational magnetization becomes dominant, where the magnetization then remains constant, thus resulting in decrease of permeability (which is a measure of change in magnetization). The peak in the theoretical permeability curve is sharp because it assumes that the anisotropy dispersion ($\Delta \theta_k$) in the device is close to zero, which is the ideal case. Practically, as the anisotropy dispersion is not zero, the peak looks broader which is a result of possible domain wall motion contribution to the permeability [13]. The non-zero $\Delta \theta_k$ can be easily seen in the non-sharp MH-loop in the hard axis direction, figure 55.

GMI effect mainly arises from the skin depth changing as a result of permeability change. Hence, the impedance of the thin film depends on the transverse permeability through the skin depth. Permeability is a sensitive function of longitudinal magnetic field, if the magnetization domains are in transverse direction, which is our case [13].

![Graph](image.png)

**Figure 59 Relation between permeability and GMI Ratio behaviour with magnetic field**
The non-magnetic skin depth is given as [13],

\[ \delta = \frac{c}{\sqrt{2\pi\sigma\omega}} \]  \hspace{1cm} (5.2)

High frequency impedance is written as [13],

\[ Z = R \frac{a}{2\delta} \left( \sqrt{\mu_R} - j \sqrt{\mu_L} \right) \]  \hspace{1cm} (5.3)

Where \(2a = \) thickness of the film

\( \mu_R = \) resistive component of the complex permeability = \(|\mu\varphi| + \mu\varphi''\)

\( \mu_L = \) inductive component of the complex permeability = \(|\mu\varphi| - \mu\varphi''\)

![Impedance Vs Field](image)

**Figure 60 Behavior of Impedance with external magnetic field**

The figure 60 shows the variation of impedance obtained at 8MHz. Experimental result is represented by the bold line, whereas the calculated impedance is represented by dashed line. According to the calculated result, we should have observed 71.4% GMI, instead of 6.2%. The
source of this difference is believed to be the high residual impedance of the leads and/or serpentine pattern used to measure the thin film sample.

**NiFe Studies**

**Substrate Bias variation in Ni$_{80}$Fe$_{20}$**

![Bias comparison graph](image)

*Figure 61 Effect of Bias on NiFe film*
Figure 62  Effect of Bias on NiFe film

Figure 63  Effect of Bias on magnetic properties of NiFe film
As seen from the graph, the RF-Substrate bias has better effect in the magnetic properties of the film than no-bias condition. The magnetic anisotropy is well defined in case of substrate bias on. The substrate bias is also responsible to control the stress in the film, as will be seen from similar data in stress studies.

**Stress variation in Ni$_{80}$Fe$_{20}$**

Stress studies were performed on NiFe films to as to achieve an optimized combination of deposition parameters, to get near zero magnetostriction and minimum coercivity. As seen from the previous literature data [25] related to the NiFe system of alloys, there exists a specific relative atomic percents for the combination of Ni and Fe to have near zero magnetostriction. This value of relative atomic contents is different from that needed to have zero coercivity in the NiFe system. In this experiment, we tried to get a suitable combination of deposition parameters that will yield lowest coercivity and lowest magnetostriction, possible. It is found that the amorphous films exhibit excellent soft magnetic properties when they are stress free and have low-coercivity [20]. Hence, we carried out a series of pressure variation to study the effect of stress in the films. As seen from the figures 64-65, clearly as we reduce the deposition pressure, it gets better and better in terms of the soft magnetic properties. The gradual decrease in the coercivity with pressure can be attributed to the tensile stress being induced gradually during the film deposition [26]. As seen from the graph of pressure dependence on the hard-axis coercivity, 1mT is the best suit. However, at 1mT the target voltages were not stable enough to carry out depositions for longer times. So we stopped at 2mT, which gives a sharp switching in magnetization in easy axis. Clearly, the Mr in the easy axis is getting better with reduction in deposition pressure. At 2mT, the individual domains are oriented in the anisotropy direction.
quite nicely. This gives better results in terms of sharp switching in the loops. Quite similar trend in the data is seen in the previous work on application of RF-substrate bias for CoSiB film deposition.

Figure 64 Effect of Deposition pressure variation on NiFe magnetic properties
Figure 65 Effect of Deposition pressure variation on NiFe magnetic properties

Figure 66 Dependence of Hc and Mr on Deposition pressure
Composition variation of Ni$_{80}$Fe$_{20}$ and Ni$_{84}$Fe$_{16}$

To explore the effect of composition variation in NiFe system, Ni$_{80}$Fe$_{20}$ and Ni$_{84}$Fe$_{16}$ were co-sputtered with different relative powers. As seen from the figure 68, the hard axis coercivity decreases as we get richer in iron. Finally, the loop corresponding to the 200W of Ni$_{80}$Fe$_{20}$ is the best suit for our application. We did not have more of the iron rich targets during the experimentation, so we could not investigate the effect of more iron-rich compositions on the film.

Figure 67 Effect of Composition variation on NiFe Magnetic properties
Figure 68  Effect of Composition variation on NiFe Magnetic properties

Figure 69  Dependence of Hc and Mr on composition variation in NiFe
NiFe - GMI Sample measurements

Magnetic Properties

Figure 70 shows the MH loop for the 600nm NiFe/ 1200nm Cu/ 600nm NiFe tri-layer GMI sample. This shows that the device has coercivity of 5 Oersteds and Mr is about 97% of its saturation magnetization value. The hard axis coercivity of the loop is about 0.3 Oe and anisotropy field is about 5 Oe. Due to insertion of intermediate Ta layers, the easy axis of the Loop reflects four different coercivities corresponding to the four physically different NiFe layers.

Figure 70 MH Loops for the 600nm NiFe/ 1200nm Cu/ 600nm NiFe

Permeability measurements

The permeability characteristics (figure 71) of the NiFe/ Cu/ NiFe film exhibit a peak at 5 Oe, which is the same as anisotropy field Hk, pointed out in the MH Loop of the sample (figure 70).
The drive frequency used during permeability measurements was 10Hz for simplicity. The impedance curve reflects the permeability versus field characteristics. The permeability increases with increase in the external magnetic field, reaching a sharp peak at anisotropy field and then reducing back to zero-field impedance or near value with further increase in magnetic field. This behavior can be explained by the rotational magnetization model [6], equation 5.1.

![Normalized permeability as a function of Field](image)

**Figure 71** Dependence of Permeability on external magnetic field [6], equation 5.1.

The loss in the initial part of permeability change may be attributed to the hysteric properties of the GMI device. The theoretical graph in figure 71 suggests that the rotational contribution increases with increase in external magnetic field, for $H_{\text{ext}} \leq H_k$. It then decreases with further increase in external field. For, $H_{\text{ext}} > H_k$, the magnetization remains constant, thus resulting in decrease of permeability (which is a measure of change in magnetization). The peak in the theoretical permeability curve is slightly sharper because it assumes that the anisotropy
dispersion ($\Delta \theta_k$) in the device is close to zero, which is the ideal case. Practically, as the anisotropy dispersion is not zero, the peak looks a little broader which is a result of possible domain wall motion contribution to the permeability [13]. However, the curve fits quite closely to the theoretical one. The non-zero $\Delta \theta_k$ can be easily seen from the sharpness of the MH-loop in the hard axis direction, figure 70.

GMI effect mainly arises from the skin depth changing as a result of permeability change. Hence, the impedance of the thin film depends on the transverse permeability through the skin depth. Permeability is a sensitive function of longitudinal magnetic field, if the magnetization domains are in transverse direction, which is our case [13].

The non-magnetic skin depth is given as [13],

$$\delta = \frac{c}{\sqrt{2\pi\sigma\omega}}$$

High frequency impedance is written as [13],

$$Z = R \cdot \frac{a}{2\delta} \cdot (\sqrt{\mu_r} - j\sqrt{\mu_l})$$

Where $2a = $ thickness of the film

$\mu_r = $ resistive component of the complex permeability = $|\mu\phi| + \mu\phi''$

$\mu_l = $ inductive component of the complex permeability = $|\mu\phi| - \mu\phi''$

The figure 72 shows the variation of calculated impedance at 8MHz, which is a square root function of the permeability.
**Thickness dependence**

We observed some trend in coercivity and anisotropy with thickness going on in the NiFe system, similar to CoSiB. In order to investigate the cause of this, we monitored the deposition with RGA (Residual Gas Analyzer), for any changes in the process gas composition. There was no change observed in the system with respect to the gas phase, during deposition. Also, RBS results indicate no drastic compositional changes occurring in the films. This might be an effect of perpendicular anisotropy induced in the film, which might be favored for low system energy. This reasoning is not supported with clear data, so the cause of this behavior still remains unsure. According to literature studies, there could be perpendicular anisotropy as a consequence of magnetostriction or of columnar growth in the films [26]. Also, we measured the sign of magnetostriction in these films, which was negative. Hence, the in-plane anisotropy is changed
to perpendicular one, due to biaxial tensile stress and a negative, non-zero magnetostriction in these films. In the figures 73 and 74, the y-axis shows relative magnetization in emus.

Figure 73 Comparison of magnetic properties for two thicknesses of the NiFe film

Figure 74 Comparison of magnetic properties for two thicknesses of the NiFe film
In order to get thicker film, we deposited a Ta seed layer at the bottom of the structure. Then to ensure that the top portion of the NiFe has same substrate as the bottom one, we deposited another Ta layer in between two 300nm of NiFe. Hence the final sample had the following structure:

Si/SiO2 100nm / Ta 2nm / NiFe 300nm /Ta 2nm / NiFe 300nm/ Ta 2nm / Cu 1200nm / Ta 2nm / NiFe 300nm/ Ta 2nm / NiFe 300nm/Ta 2nm

Insertion of the intermediate Ta layers did not have any effect on the magnetic properties of the film. Permeability measurements were performed on the sample. Results are shown in the figure 71. The permeability response has a sharp peak at the external field of value equal to anisotropy field. The permeability is nearly zero for the zero fields, as expected. This change shows that this device might show greater GMI effect than the CoSiB device studied earlier.

Unfortunately, due to the Ta intermediate layers, etching did not work out well for patterning the device. Therefore, we could not carry out magneto-impedance measurements on this sample, at this time.

As mentioned earlier, we could not successfully fabricate the device, hence the graph 60, is not supported with the experimental curve.
CHAPTER 6. CONCLUSIONS

An M-H looper was designed and fabricated to measure the magnetic properties of thin films as thin as 10 nm of NiFe. Subsequently, this instrument was used to support an investigation of the low frequency (DC) magnetic properties of CoSiB and NiFe thin films prepared for use in GMI devices.

Different composition and stress conditions were analyzed in CoSiB and NiFe films to achieve the soft magnetic properties for their potential applications in GMI sensors. The CoSiB films were co-sputter deposited in an ultra high vacuum chamber, using separate Co, Si and BN targets. Films with different relative compositions of Co, Si and B were deposited by varying respective target powers. Different substrate bias conditions were also studied. The optimized set of the deposition parameters was obtained as 90W Co, 45W Si, 125W RF BN co-sputtered at 4mT in Argon flow of 20sccm. This combination results in approximate composition of Co$_{70}$Si$_{13}$B$_{17}$. 200nm CoSiB/ 400nm Cu/ 200nm CoSiB sandwich film structure was sputter deposited and annealed at 200°C for 1 hour in a vacuum of $10^{-8}$ Torr. MH Loops for the same were studied in detail and permeability graphs were obtained, using the MH Looper. The in-plane anisotropy in the film was well controlled by the array of magnets patterned in circular shape with total magnetic field of 200 Oe. The permeability of the GMI sample was studied and compared to the theoretical rotational model. The impedance dependence on external magnetic field was obtained experimentally and was compared with the calculated values of the impedances. The experimentally achieved value for GMI ratio was 6.2% at 8MHz, for 21 Oe. This value is very small as compared to the calculated 71%, which should have been observed in this sample. The source of this difference is believed to be the high parasitic impedance of the
test leads and/or serpentine pattern used to measure the thin film sample. However, the respective GMI ratio peaks were obtained at the external field of 21 Oe for all the frequencies under consideration, which was the anisotropy field for the device. This is in agreement with the GMI literature and theory. The discrepancy in permeability graph is attributed to the coercivity, and hence domain wall motion contribution to the total permeability. This is indirectly related to the dispersion in the anisotropy that is seen in the sharpness of switching in the magnetic characteristics of the device.

NiFe films were studied on similar basis, by varying relative composition and overall stress with the help of variation in target powers and deposition pressure, respectively. Bias variation in NiFe films is also studied. Finally, an optimized set of parameters was obtained as NiFe20 sputtered at 2mT pressure and argon flow of 20sccm. NiFe 600nm / Cu 1200nm/ NiFe 600nm tri-layer structure was deposited. Permeability study was performed on this GMI sample. This study shows steeper permeability change than the CoSiB case. Theoretical values were obtained by magnetization rotational model and compared to the experimentally achieved values. This seemed to be a close fit to the practical case. Due to the difficulties in the etching process, the sample could not be patterned and impedance spectra for the same could not be obtained. Theoretical impedance change behavior is presented, but not supported with experimental data.

In the end, the magnetic properties, i.e. the MH Loops were correlated with the permeability and impedance spectra.
LIST OF REFERENCES


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[28] http://www.ee.surrey.ac.uk/Workshop/advice/coils/air_coils.html#mly

