

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NANOTECHNOLOGY

MAGNETIC CHARACTERIZATION OF THIN FILM COATED
SPHERICAL SURFACE

ÖZLEM AKIN
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
NANOTECHNOLOGY INSTITUTE

GEBZE

2019

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NANOTECHNOLOGY

MAGNETIC CHARACTERIZATION OF
THIN FILM COATED SPHERICAL
SURFACE

ÖZLEM AKIN
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
NANOTECHNOLOGY INSTITUTE

THESIS SUPERVISOR
PROF. DR. M. HASAN ASLAN

GEBZE
2019

T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
NANOTEKNOLOJİ ENSTİTÜSÜ

İNCE FİLM KAPALI KÜRESEL YÜZEYİN
MANYETİK KARAKTERİZASYONU

ÖZLEM AKIN
YÜKSEK LİSANS TEZİ
NANOTEKNOLOJİ ENSTİTÜSÜ

DANIŞMANI
PROF. DR. M. HASAN ASLAN

GEBZE
2019

GTÜ Nanoteknoloji Enstitüsü Yönetim Kurulu'nun 10/06/2019 tarih ve 2019/11 sayılı kararıyla oluşturulan jüri tarafından 26/06/2019 tarihinde tez savunma sınavı yapılan Özlem AKIN'ın tez çalışması Nanobilim ve Nanomühendislik Anabilim Dalında YÜKSEK LİSANS tezi olarak kabul edilmiştir.

JÜRİ

ÜYE

(TEZ DANIŞMANI)

: Prof. Dr. M. Hasan ASLAN

ÜYE

: Doç. Dr. Fikret YILDIZ

ÜYE

: Doç. Dr. İlhan YAVUZ

ONAY

Gebze Teknik Üniversitesi Nanoteknoloji Enstitüsü Yönetim Kurulu'nun
...../...../..... tarih ve/..... sayılı kararı.

Prof. Dr. Ahmet Yavuz ORAL
Enstitü Müdürü

SUMMARY

In this study, firstly several micron sized arrays were obtained by using a photolithography method. Then, thin film was coated on these spherical structures with different thicknesses. The magnetic properties of the material were analyzed depending on the effect of the thickness and the shape of the material. FMR, MOKE and XRD systems were used for analysis. SEM and EDX analysis were done for the surface morphology. The original aspect of this study is to determine the changes in the magnetic properties of the thin film by forming thin film on the spherical structures obtained by photolithography. This will provide a different perspective for scientists in future studies. When designing devices with different magnetic behaviors, scientists will benefit from these developments.

In this thesis, the first part gives information about theoretical foundations. In the second part, experimental methods and analysis methods. In the third part, information is given about experimental studies. In the fourth and last part, the results of the experiment and analysis are given and their interpretation is made.

Keywords: Metamaterials, Magneto-Optic Effect, Spherical Surface, Photolithography.

ÖZET

Bu çalışmada ilk önce fotolitografi yöntemini kullanarak birkaç mikron boyutunda arraylar elde edilmiştir. Ardından bu arraylara farklı kalınlıklarda manyetik özelliğe sahip ince filmler kaplayarak malzemenin manyetik özelliklerindeki değişim analiz edilmiştir. Analiz için FMR, MOKE, XRD sistemleri kullanılmıştır. EDX analizini ve yüzey morfolojisini analiz etmek için SEM kullanıldı. Bu çalışmanın özgün yanı fotolitografi ile elde edilen küresel yapılar üzerine thin film büyüterek, thin filmi oluşturan malzemenin manyetik özelliklerinde değişiklikler yapabilmektir. Bu da gelecek yıllarda yapılacak olan çalışmalarda bilim adamlarına farklı bir bakış kazandıracaktır. Farklı manyetik davranışlara sahip device tasarlarken bilim insanları bu gelişmelerden de faydalanacaklardır.

Bu tez çalışmasında birinci bölümde kuramsal temeller hakkında bilgi verilmiştir. İkinci bölümde deneysel yöntem ve analiz yöntemleri hakkında bilgi verilmiştir. Üçüncü bölümde deneysel çalışmalar hakkında bilgi verilmiştir. Dördüncü ve son bölümde ise deney ve analiz sonuçları verilmiş ve bunların yorumlamaları yapılmıştır.

Anahtar Kelimeler: Metamalzemeler, Manyetik-Optik Etki, Küresel Yüzeyler, Fotolitografi.

ACKNOWLEDGEMENTS

I would like to thank to my beloved consultant Prof. Dr. M. Hasan ASLAN, who always opened new horizons and supported me with both his scientific knowledge and his spiritual support.

I would like to thank to Do.Dr. Fikret YILDIZ, Aylin ERSOY who contributed greatly to this study. I would like to thank my friends, Fatmanur KOCAMAN and Zrbiye APKU, who have always been by my side during my studies.

In the course of this study, I would like to extend my gratitude to my family and my husband for listening to all my troubles and giving me strength with their assets.

TABLE of CONTENTS

	Page
SUMMARY	IV
ÖZET	V
ACKNOWLEDGEMENTS	VI
TABLE of CONTENTS	VII
LIST of ABBREVIATIONS and ACRONYMS	IX
LIST of FIGURES	XII
LIST of TABLES	XVI
1. INTRODUCTION	1
2. NANOSTRUCTURE	5
3. MAGNETISM	6
3.1. Magnetic Materials	7
3.2. Magnetic Variable	8
3.2.1. Magnetic Permability	8
3.2.2. Curie Temperature	9
3.2.3. Easy Axis and Hard Axis	9
3.2.4. Satisfaction Point	10
3.2.5. Residual Magnetization	10
3.2.6. Coercivity	10
3.3. Magnetism Types	10
3.4. Hysterisis Cyle	12
3.5. Magnetic Anisotropy	13
3.5.1. Magnetocrystalline Anisotropy	14
3.5.2. Shape Anisotropy	15
3.5.3. Surface Anisotropy	15
4. MAGNETIC RESONANCE	16
5. FERROMAGNETIC RESONANCE	17
5.1. Equation of Motion for Magnetization	20
5.1.1. General Equation of Motion	20

5.1.2. Damping	22
5.1.3. Resonance Condition	24
5.1.4. General Expression of Resonance Condition	25
5.1.5. Effect of Shape Anisotropy on Resonance Frequency	28
5.1.6. Demagnetization Account for Different Shapes	31
6. MAGNETO-OPTIC KERR EFFECT (MOKE)	35
6.1. L-MOKE System	35
6.2. P-MOKE System	36
6.3. Traverse MOKE	37
7. FABRICATION METHODS	38
7.1. Photolithography	38
7.1.1. Mask Printing	40
7.1.2. Sample Coating	40
7.1.3. Lithography Process	41
7.2. Thin Film Deposition	44
8. MEASUREMENT METHODS	47
8.1. X-Ray Diffraction (XRD)	47
8.2. Scanning Electron Microscopy (SEM)	48
8.3. FMR Measurement System	50
8.3.1. Microwave Source System	51
8.3.2. Cavity-Guide System	51
8.3.3. Magnet System	51
8.3.4. Modulation and Detector System	52
8.4. MOKE Measurement System	52
9. FABRICATION STUDIES	54
9.1. Photolithography Process	54
9.1.1. Mask Printing	54
9.1.2. Substrate Cleaning	55
9.1.3. Substrate Coating	56
9.1.4. Alignment and Expose Operation	57
9.1.5. Postbake Process	57

9.1.6. Develop Process	58
9.1.7. Thermal Reflow Process	58
9.2. Thin Film Depositon Process	59
9.3. Lift-off Process	61
10. RESULTS and DISCUSS	63
10.1. Results of $\text{Ni}_{80}\text{Fe}_{20}$	63
10.2. Results of $\text{Ni}_{55}\text{Fe}_{45}$	71
11. CONCLUSION	78
REFERENCES	79
BIOGRAPHY	82

LIST of ABBREVIATIONS and ACRONYMS

<u>Symbols and</u> <u>Abbreviations</u>	<u>Descriptions</u>
ϵ_r	: Permittivity
μ	: Magnetic Permeability
μ_0	: Magnetic Cermeability Constant of the Cavity
μ_r	: Relative Permeability of the Gap
μ_B	: Bohr Magnetone
γ	: Damping Constant
γ	: Gyromagnetic Ratio
g	: Spectroscopic Cleavage Factor
$\hbar$	: Plank Constant
ω_0	: Resonans Frequence
ω_p	: Plasma Frequency
GHz	: Giga Hertz
MHz	: Mega Hertz
mT	: Mili Tesla
nm	: Nanometer
um	: Micrometre
Oe	: Oerstad
λ	: Damping Coefficient
B	: Magnetic Flux Density
B	: Magnetic Induction
F	: Free Energy Density
F_D	: Domain Wall Energy
F_{de}	: Demagnetization Energy
F_{ex}	: Exchange Energy
F_{mc}	: Crystal Anisotropy Energy
F_{me}	: Magneto Elastic (streght) Anisotropy

F_z	: Zeeman Energy
G	: Gilbert Damping Parameter
H	: Magnetic Field
H_{in}	: Internal Magnetic Field
H_{out}	: External Magnetic Field
H_c	: Coersivite
n	: Refractive Index
DC	: Direct Current
DUV	: Deep Ultraviolet
ESR	: Electron Spin Resonance
EPR	: Electron Paramagnetic Resonance
FMR	: Ferromagnetic Resonance
IPG	: In Plane Geometry
LEED	: Low Energy Electron Diffraction
L-MOKE	: Longitudinal Magneto-Optic Kerr Effect
M	: Magnetization
MBE	: Molecular Ray Epithelium
MOKE	: Magneto-Optic Kerr Effect
MW	: Microwave
N	: Demagnetization
NMR	: Nuclear Magnetic Resonance
OPG	: Out-of Plane Geometry
PLD	: Pulse Laser Deposition
P-MOKE	: Polar Magneto-Optic Kerr Effect
RF	: Radio Frequency
RHEED	: Reflection High Energy Electron Diffraction
SEM	: Scanning Electron Microscopy
STM	: Scanning Tunnel Microscope
UHF	: Ultra High Frequency
UV	: Ultraviolet
PIMM	: Pulse Inductive Microwave Magnetometer

VNA : Vector Network Analyzers
XPS-AES : X-Ray Photoelectron-Nail Electron Spectroscopy
XRD : X-Ray Diffraction

LIST of FIGURES

Figure no:		Page
1.1:	Application of snell refraction law in right- hand and left- handed environment.	2
3.1:	Interaction of light with magnetic material: Faraday and Kerr effect.	6
3.2:	Hysteresis curves of hard and soft magnetic materials.	7
3.3:	a) Easy axis, b) Hard axis	9
3.4:	Magnetic domains in material.	11
3.5:	Magnetization curves and spin configurations of diamagnetism, paramagnetism and antiferromagnetism.	11
3.6:	Magnetization curves and spin configurations of ferromagnetism and ferrimagnetism.	12
3.7:	Hysteresis cycle and general characteristics.	13
3.8:	Magnetization curves in different directions for iron with crystal structure.	14
3.9:	Magnetization curves in different directions for nicel with crystal structure.	15
5.1:	Microwave broadband FMR absorbtion data for single- layer permalloy films.	19
5.2:	Magnetic dipole moment	20
5.3:	Around $\vec{H}_{int}$ free (undamped) precession movement, precession angle, and $ M $ constant as described in equation 4.8.	22
5.4:	Damped motion of the magnetization vector M.	23
5.5:	The representation of the coordinate axis assembly for the system with the total magnetization M below the H magnetic field.	26

5.6:	The main axis of demagnetization factors component presentaion.	29
5.7:	Facricated surface and modelled surface.	34
6.1:	MOKE system.	35
6.2:	Longitudinal MOKE.	36
6.3:	Polar MOKE.	37
6.4:	Traverse MOKE.	37
7.1:	Air flow pattern is Clean Room with Laminar Flow, Air flow model is Turbulent Flow Clean Room.	39
7.2:	Photoresist coated.	41
7.3:	Different vacuum conditions.	42
7.4:	The intensity of light in different vacuum conditions.	42
7.5:	Mercury lamp spectrum.	43
7.6:	Lithography process.	43
7.7:	Thin-film deposition system used during thesis study.	45
7.8:	Experimental representation of sputter technique.	46
8.1:	Demonstration of X-ray diffraction in crystal plane.	47
8.2:	Three dimensional crystal structure of material.	48
8.3:	SEM analysis experiment scheme.	48
8.4:	Formation of backscattered and secondary electrons.	49
8.5:	Schematic representation of the ESR device.	50
8.6:	Component of MOKE device.	52
9.1:	Heidelberg dwd device.	54
9.2:	Image of a mask taken with an optical microscope.	55
9.3:	(a) the bench was used for lithography (b) hot plate was used for lithography.	56
9.4:	Spin coater was used for lithography.	57
9.5:	Mask aligner device was used for lithography.	57
9.6:	SEM images of cylinder pattrens that is obtained by lithography process.	58

9.7:	After the thermal reflow process, SEM images of spherical structure is taken from surface.	59
9.8:	After the thermal reflow process, SEM images of spherical structure is taken from side.	58
9.9:	Magneto-Sputtering experimental schema.	60
9.10:	After the thin film growth process, SEM images of spherical structure is taken from surface.	61
9.11:	After the thin film growth process, SEM images of spherical structure is taken from side.	61
10.1:	Schematic representation of cross-sections of film-grown surfaces.	63
10.2:	SEM images before and after lift-off operation of the film-grown surface, respectively.	63
10.3:	XRD measurement of permalloy coated surfaces.	64
10.4:	MOKE measurement results for $\text{Ni}_{80}\text{Fe}_{20}$.	65
10.5:	Stack graph of magnetic spectrum curves for $\text{Ni}_{80}\text{Fe}_{20}$ grown on silicon substrate.	67
10.6:	Magnetic spectrum curves stack graph for $\text{Ni}_{80}\text{Fe}_{20}$ coated surface after lithography process.	67
10.7:	Magnetic spectrum curves stack graph for $\text{Ni}_{80}\text{Fe}_{20}$ coated surface after lift-off.	69
10.8:	Resonance field graph for $\text{Ni}_{80}\text{Fe}_{20}$ grown on silicon substrate.	69
10.9:	Resonance field graph of $\text{Ni}_{80}\text{Fe}_{20}$ coated surface after lithography.	70
10.10:	Resonance field graph of $\text{Ni}_{80}\text{Fe}_{20}$ coated surface after lift-off.	70
10.11:	Schematic representation cross-section of film grown surface.	71
10.12:	SEM images obtained from the surface and side for 5 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$, for 5 μm resolution from the surface, for angle 10 μm resolution.	71
10.13:	SEM images obtained from the surface and side for 10 nm-thickness $\text{Ni}_{55}\text{Fe}_{45}$.	72

10.14:	SEM images obtained from the surface for 20 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$ and angled.	72
10.15:	XRD measurements made for three different thickness studies.	73
10.16:	Magnetic spectrum stack graph for 5 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.	74
10.17:	Magnetic spectrum stack graph for 10 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.	75
10.18:	Magnetic spectrum stack graph for 20 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.	75
10.19:	Resonance field graph for 5 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.	76
10.20:	Resonance field graph for 10 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.	77
10.21:	Resonance field graph for 20 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.	77

LIST of TABLES

<u>Table No:</u>		<u>Page:</u>
5.1:	Depending on the orientation of applied magnetic field demagnetization constants components.	31
5.2:	Approximate effective ("integral") demagnetizing factor along applied magnetic field.	32
5.3:	Representation of the hollow sphere.	39
7.1:	Clean rooms are divided into different classes according to the amount of particles they contain	33
8.1:	Component of MOKE device.	53

1. INTRODUCTION

The materials are divided into two as natural materials and artificial materials. Natural materials exist in nature and have specific properties. One of the most important features of natural materials is the positive permittivity and positive magnetic permeability. Permittivity is the interaction of the environment depending on the amount of electric field applied when the electric field is applied in an environment. Permeability is the measure of the response of the material exposed to the magnetic field. In natural materials, these properties are considered fixed by some limitations. For example, magnetic permeability is 1 in optical regimes. In order, permittivity and magnetic permeability are ϵ and μ .

$$\epsilon_r(\omega) = 1 - \frac{\omega_{p,e}^2}{(\omega^2 - \omega_{0,e}^2 + i\gamma_e\omega)} \quad (1.1)$$

$$\mu_r(\omega) = 1 - \frac{\omega_{p,m}^2}{(\omega^2 - \omega_{0,m}^2 + i\gamma_m\omega)} \quad (1.2)$$

In here γ is the damping constant that defines any loss in the material, ω_0 is the resonance frequency and ω_p is the plasma frequency. Permittivity and magnetic permeability are positive in natural materials. And therefore, the responses to the incoming light are examined in certain patterns in natural materials. Under normal conditions, a part of the light coming into the material is absorbed by the material, a part of it reflects from material and a part of it passes through the material. What determines the amount of absorption, reflection and transition is the refractive index of the material. Refractive index is $n = \pm\sqrt{\epsilon\mu}$. Depending on the refractive index, the reflection, refraction and absorption of the light are determined using the right-hand rule. In addition, Snell's law is used for the positive values of ϵ, μ .

When we examine the materials of metamaterial, it is observed that all these behaviors of light change. Metamaterial does not exist in nature, it is a system made with developing technologies, and consisting of successive, ie array. Metamaterial materials do not take their properties from the materials in which they are made. The

properties of metamaterial come from the shapes, orientations, dimensions and geometries of the materials they are made of. One of the most important features of metamaterials is the negative permittivity and negative magnetic permeability. Due to the negative permittivity and negative magnetic permeability, metamaterials exhibit different behavior from natural materials when they are exposed to electric field and magnetic field. In addition, the behavior of light on these materials changes.

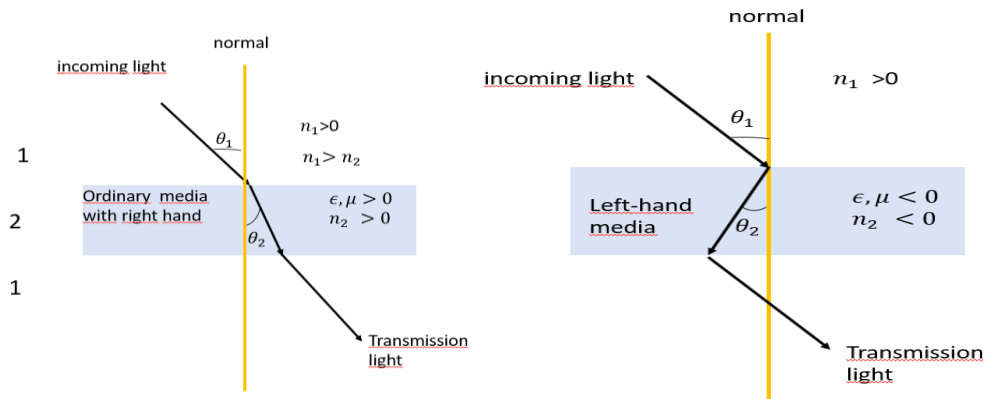


Figure 1.1: Application of Snell's refraction law in right-hand and left-handed environment.

If we look at the historical development of the Metamaterial: At the end of the 19th century, Chunder launched the first work on metamaterials. Chunder made a microwave experiment using twisted structures. Thus, metamaterial studies have started. In 1898, Jagadis Chock produced the first metamaterial material using artificial elements [1]. In the following years respectively 1914 and 1948, Lindman and Kock have studied the metamaterials. Lindman made an artificial chiral environment by doping with small wire augers randomly directed into a substrate [2]. Kock produced micro lenses by adding metal strips, cables and discs periodically to the substrate, unlike the work of Lindman in 1948 [3]. In 1968 Victor Veselago theoretically examined the propagation of the planar wave in the material having negative electrical permeability and magnetic permeability [4]. In 1996, Pendry et al. produced artificial electrical plasma using an artificial wire structure with a negative electrical permeability. Following this study, slot ring resonators were obtained in 1999. Magnetic plasma with negative magnetic permeability was produced by slit ring resonators [5]. In 2000, Smith and Schultz showed that Snell's law was working in

reverse, due to the difference in the refraction of light with the work. This work is known as the Left-hand rule [6,7].

In the following years, thanks to developing technologies, the production of metamaterials have become easier. In the early 2000s, the development of nanotechnology has made great contributions to the production of metamaterial. New technologies not only facilitated the production of the material but also provided opportunities for researchers to bring new properties to the material. In particular, metamaterials, which consist of arrays of very small sizes, have started to be produced. With these developments, the magnetic, optical and electronic properties of the materials have been developed and new properties have been added to these materials in metamaterials. With these features, micro electro mechanic systems, which were started to be studied in the 1950s, began to be further developed in the 1990s. Thanks to the advances in nanotechnology in the 1990s, the door of a very new world was opened for researchers. With the nanotechnology, the material has been started to be further judged.

One of the technologies that make the greatest contribution to nanotechnology has been thin film technology. By means of thin film, layers of thickness, from nano sizes to micro sizes, were started to be obtained. By changing the thickness of the same material, new properties are introduced.

In this study, we firstly obtained several micron sized arrays using photolithography method. Then we covered thin films with different thicknesses over these arrays. We analyzed the change in the magnetic properties of the material with the effect of the thickness of the material and the shape of the material. We used FMR, MOKE, XRD systems for analysis. We used SEM to analyze EDX analysis and surface morphology. The original aspect of this study is to determine the changes in the magnetic properties of the thin film by forming thin film on the spherical structure obtained by photolithography. This will provide a different perspective for scientists in future studies. When designing devices with different magnetic behaviors, scientists will benefit from these developments.

In this thesis, the first part information is given about theoretical foundations. In the second part, information is given about experimental methods and analysis methods. In the third part, information is given about experimental studies. In the

fourth and last part, the results of the experiment and analysis were given and their interpretation was made.

2. NANOSTRUCTURE

Nanostructures are structures that have least one dimension that is from one nanometer to 100 nanometer [8]. These structures are divided three classes: thin films, nanowires and nanodots. These structures have many application such mechanical, electronical, optical, biological and most important field of uses is semiconductors [8].

3. MAGNETISM

The interaction of light with magnetic material is called magneto-optical effect. In 1845, Michael Faraday first examined the polarization of light by passing light from a glass material that was exposed to the magnetic field and noticed changes in polarization. Then, Faraday examined the same process on the iron metal which was exposed to the magnetic field, and this was the effect that it was waiting for. In 1877, John Kerr tried Faraday's experiment with a polished electromagnet and observed the magneto-optical effect by examining the polarization of reflected light. As a result of these studies, Faraday revealed the change in the polarization of the light passing through the material, i.e. the light passing through the material [9,10]. They are known as the Faraday effect and the Kerr effect. In 1985, Moog and Bader developed a very simple and inexpensive technique and the SMOKE technique which quickly identified hysteresis curves in magnetization research. They used this technique to study surface magnetization of the Kerr effect [10]. Kerr effect is more preferable. Because the effect of Faraday very fine magnetic samples are required [11].

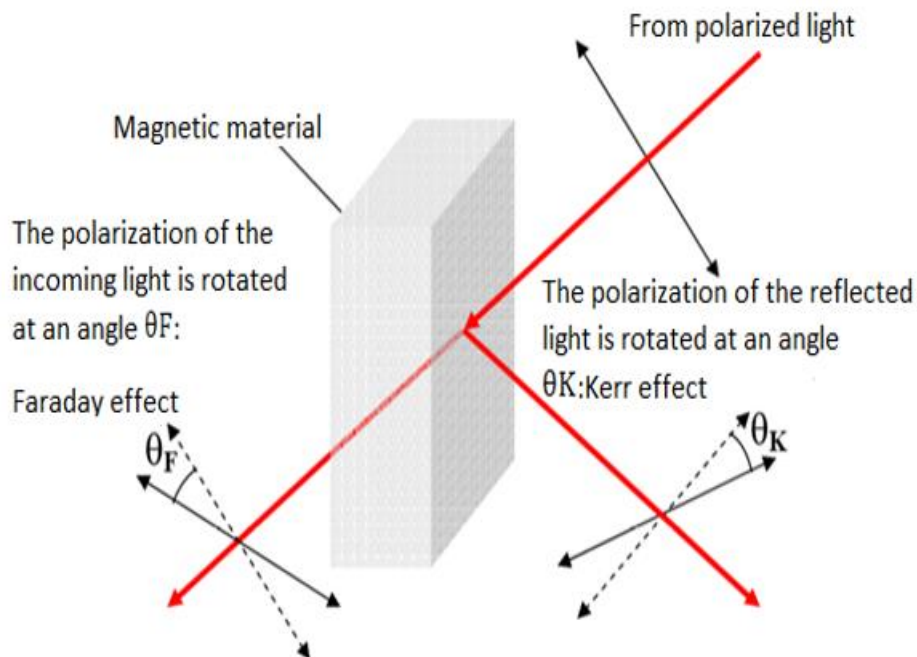


Figure 3.1: Interaction of light with magnetic material: Faraday and Kerr effect.

3.1. Magnetic Materials

The magnetic materials are divided into soft and hard magnetic materials according to the H value and the difference of the hysteresis curves. In Figure 3.2, hysteresis curves of hard and soft magnetic materials is shown [12]. The soft materials are magnetized easily when exposed to the magnetic field, and again easily they are demagnetized by being easily influenced by the environment. The energy loss is low in soft materials. Because these materials have low coercivity, they have high permeability. Soft materials have a high B value even though they have a narrow hysteresis curve.

In the case of hard materials, the opposite is the case. Hard materials are not easily affected by the magnetic medium in which they are placed. In other words, hard materials are difficult to magnetize. It is also difficult to demagnetize by changing these conditions when they are also magnetized [13,14]. Iron-Silicon, Iron-Nickel, Iron Cobalt, Ferrite Garnet are examples of soft materials [10]. AlNiCo, ferrite, SmCo_5 , $\text{Sm}_2\text{Co}_{17}$, $\text{Nd}_2\text{Fe}_{14}\text{B}$ are hard materials [13].

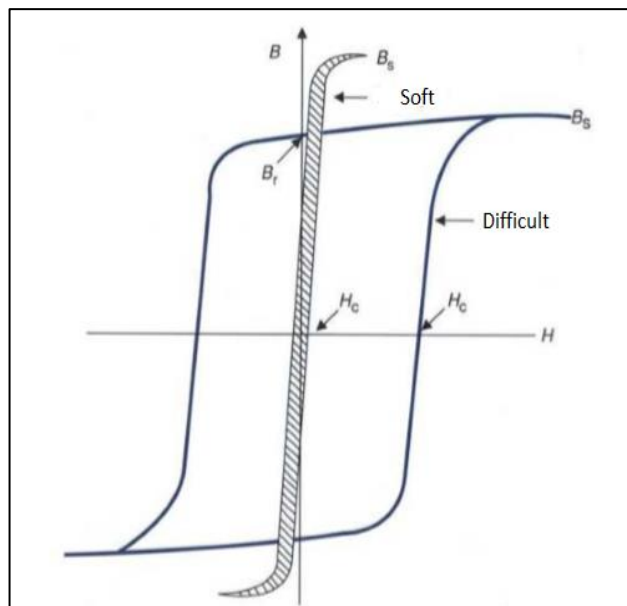


Figure 3.2: Hysteresis curves of hard and soft magnetic materials.

3.2. Magnetic Variables

In order to better understand the ferromagnetic resonance analysis of ferromagnetic materials, some basic magnetic variables must be known. These magnetic variables consist of magnetic permeability, curie temperature, easy axis, hard axis, saturation magnetization, residual magnetization and coercive.

3.2.1. Magnetic Permeability

The material exposed to a the magnetic field is magnetized. Magnetic permeability is defined as the magnetizing intensity of the material exposed to the magnetic. Magnetic permeability is indicated by μ . Easy magnetization of the material depends on the magnetic permeability of the material. Magnetic permeability is not only dependent on the property of the material but also on the external magnetic field applied to the material. The magnetic permeability is the ratio of the internal magnetic field of the material to the magnetic field applied to the material:

$$\mu = \frac{H_{in}}{H_{out}} \quad (3.1)$$

The magnetic permeability constant of the cavity is $\mu_0 = 4\pi 10^{-7} \text{ NA}^{-2}$. Relative permeability of any medium is $\mu_r = \mu / \mu_0$. In this case, the relative permeability of the gap is calculated as $\mu_r = 1$. Materials are classified according to their relative magnetic permeability. The relative magnetic permeability is constant as a function of the magnetic field for diamagnetic and paramagnetic materials, and for diamagnetic materials this value is slightly smaller than 1 and slightly greater than 1 for paramagnetic materials. However, the relative permeability value of ferromagnetic materials varies depending on the magnetic field of the material. For ferromagnetic materials this value is inversely proportional to the magnetic field.

3.2.2. Curie Temperature

Temperature is a factor that can make significant changes on matter. The average energy of atomic vibrations varies depending on the temperature. As the temperature increases, the average energy of atomic vibrations increases. Accordingly, the atom passes from stable to unstable and the atomic magnetic moments in its structure are disrupted. Ferromagnetic materials having parallel and regular atomic moments show a spontaneous magnetization due to these properties. But above a certain temperature these sequences are disturbed and the ferromagnetic material loses its self-magnetization. This temperature value is called the curie temperature of the material. The antiferromagnetic materials also have a curie temperature.

3.2.3. Easy Axis and Hard Axis

Ferromagnetic materials have axes which enable the self-magnetization even in a very small magnetic field. These axes are called easy axes. Some axes of ferromagnetic materials require very large energy for self-magnetization. The axes that require this energy are called the difficult axis. In Figure 3.3, easy axis and hard axis graph is shown. As it is understood in this graph, the residual magnetism value of the easy axis is higher than the residual magnetism value of the hard axis. And, the coercive field of the easy axis is lower than the coercive field of the hard axis.

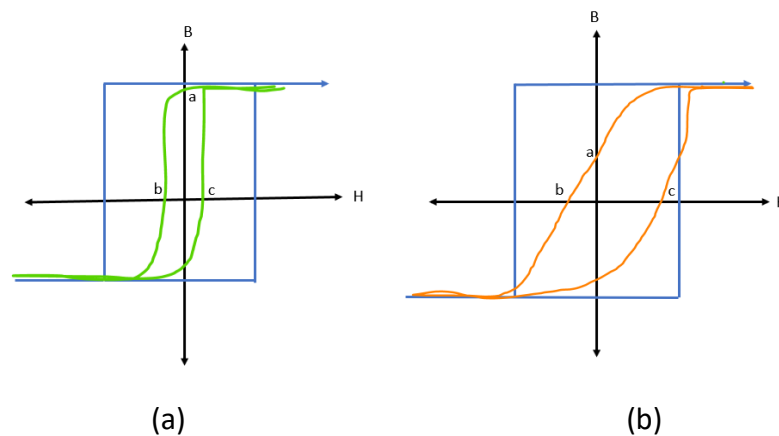


Figure 3.3: a) Easy axis, b) Hard axis.

3.2.4. Satisfaction Point

In a ferromagnetic material, the value of the applied external magnetic field is increased and with this effect all magnetic moments in the material are arranged parallel to this external magnetic field. After the magnetic moments have been introduced into this arrangement, increasing the magnetic field does not change the magnetization value in the material. This magnetization value is called saturation magnetization.

3.2.5. Residual Magnetization

Ferromagnetic materials exposed to the magnetic field are magnetized and reached saturation. Then, even if the effect of the magnetic field is removed, the magnetization value is not completely lost and the material has some magnetization. After the magnetic field is removed, the material still has some magnetization, this magnetization value is called as residual magnetization.

3.2.6. Coercivity

The inverse magnetic field, which must be applied to the material to reduce the magnetization value of the ferromagnetic material to zero, is called coercivity. Coercivity is indicated by H_c . Coercivity is a compelling effect against magnetization. Because it effects the magnetization properties, coercivity is a distinguishing feature for materials.

3.3. Magnetism Types

The magnetic moment has the orbital angular momentum and spin angular momentum of unpaired electrons in the atom. While studying the magnetic behaviors of solids, the magnetic moments of atoms are examined with each other and with their external magnetism. In Figure 3.3, magnetic domains is shown [15].

The magnetic aspects of atoms were randomly sorted in the paramagnetic and diamagnetic materials. In Figure 3.4, magnetization curves and spin configurations of diamagnetism, paramagnetism and antiferromagnetism are shown [16].

When an external magnetic field is applied to them, the paramagnetic material has a magnetic field that is the same direction and magnitude of the applied magnetic field, while the diamagnetic materials have a magnetic field that is the same magnitude and opposite to the direction of the applied magnetic field. But when this external effect is eliminated, the magnetism of the materials is eliminated [17].

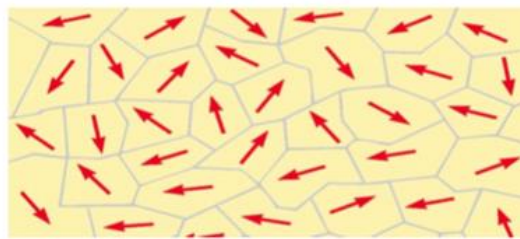


Figure 3.4: Magnetic domains in material.

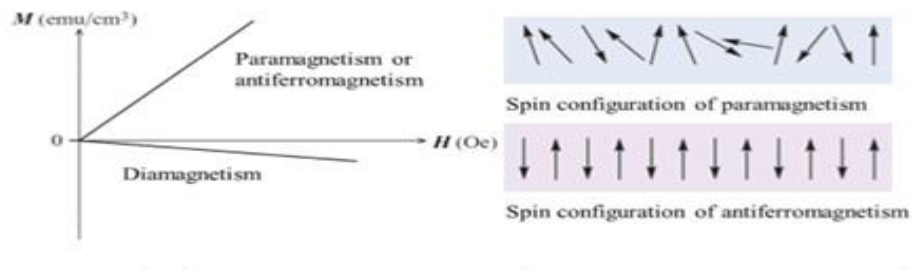


Figure 3.5: Magnetization curves and spin configurations of diamagnetism, paramagnetism and antiferromagnetism.

When it comes to ferromagnetic and ferrimagnetic materials, the magnetic moments of atoms are seen. When an external magnetic field is applied, the magnetic moments are aligned in parallel. Even if this external magnetic field is removed, this arrangement will not deteriorate and the material will have a permanent magnetic moment. This is called permanent magnetization [17]. In Figure 3.5, magnetization curves and spin configurations of ferromagnetism and ferrimagnetism are shown [16].

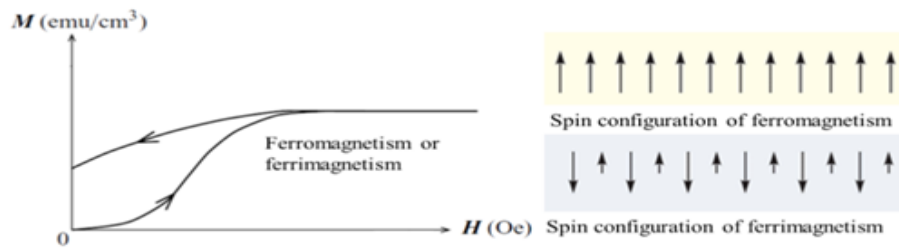


Figure 3.6: Magnetization curves and spin configurations of ferromagnetism and ferrimagnetism.

The general characteristics of ferromagnetic materials are summarized below.

- Relative magnetic permeability is greater than 1.
- Relative magnetic permeability is variable depending on the type of material, magnetic processes previously applied to the material and the value of the magnetic field strength.
- In paramagnetic and diamagnetic materials, there is a linear relationship between magnetic flux density B and field strength H , this relationship is not linear in ferromagnetic materials.
- Has a magnetic hysteresis.
- Ferromagnetic materials pass to the state of paramagnetic material on Curie temperature [18].

3.4. Hysteresis Cycle

With the effect of the applied external magnetic field, the ferromagnetic materials are composed of atoms with magnetic moments in the same direction. This is called the magnetic domain. The hysteresis of ferromagnetic material is used when examining the structure and behavior of these domains [19]. In Figure 3.6, hysteresis cycle and general characteristics is given [20].

External magnetic field is applied to a material that does not have magnetism, and flux density is measured with this outer area to create a non-visceral curve of the material. An external magnetic field is applied to a material that does not have a

magnetic property, a flux density occurs on the material depending on the magnetic field. When this flux density reaches the maximum point of slip saturation, this time it is desirable to transfer the flux density to zero by applying the magnetic field in the opposite direction. The chart does not go the way it first comes to the zero point, which varies depending on the nature of the material. After reaching the zero point, the magnetic field applied in the opposite direction is continued and saturation is reached in the negative direction. And then again the magnetic field is applied in the positive direction and zero point is reached to the saturation point and the material's hysteresis curve is drawn [17, 19].

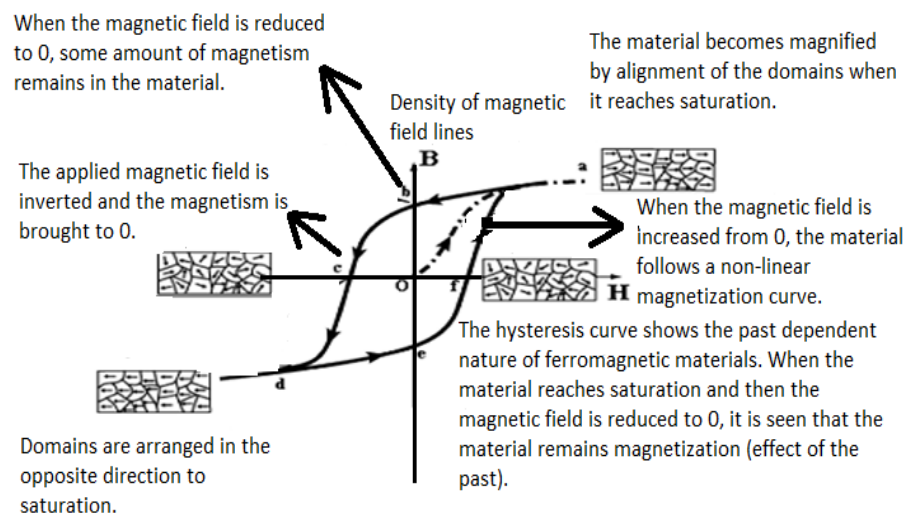


Figure 3.7: Hysteresis cycle and general characteristics.

3.5. Magnetic Anisotropy

The properties of the magnetic materials show differences according to the direction in which the atoms are measured, depending on their arrangement within the material. This change which depend on the direction of the magnetic properties, called magnetic anisotropy. Magnetic anisotropy consists of three different anisotrpes: magnetocrystalline anisotropy, shape anisotropy, surface anisotropy.

3.5.1. Magnetocrystalline Anisotropy

The magnetic materials generally have a cryptic direction in which the magnetic moments prefer to be oriented. This crystal direction is called an easy axis. Even when a very small magnetic field is applied to the crystal structure in an easy axis direction, the magnetic moments will easily orientate and magnetize the material. When this crystalline material is intended to be directed in a direction other than the easy axis, a magnetic field larger than the magnetic field applied to the axis easily should be applied.

The difference between the energy required to direct the magnetic moments to the easy axis and the energy required to direct the magnetic moments to any axis other than the axis is called the magnetocrystalline anisotropy energy. For example, if we examine the situation where the iron crystal is saturated with different magnetic moments: The magnetic moment in the orientation of iron [100] is an easy axis and requires less energy to reach saturation, while the magnetic moments with orientations [110] and [111] need a larger energy to achieve saturation. This energy difference between orientations and magnetocrystalline anisotropy energy. That is, the difference between the energy required to direct the material on any axis except the easy axis and the energy required to direct the material on the easy axis is called the magnetocrystalline anisotropy energy. The grap of this example is given Figure3.7 [21, 22].

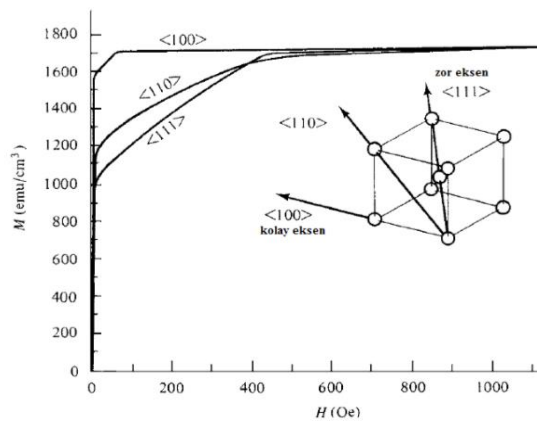


Figure 3.8: Magnetization curves in different directions for iron with crystal structure.

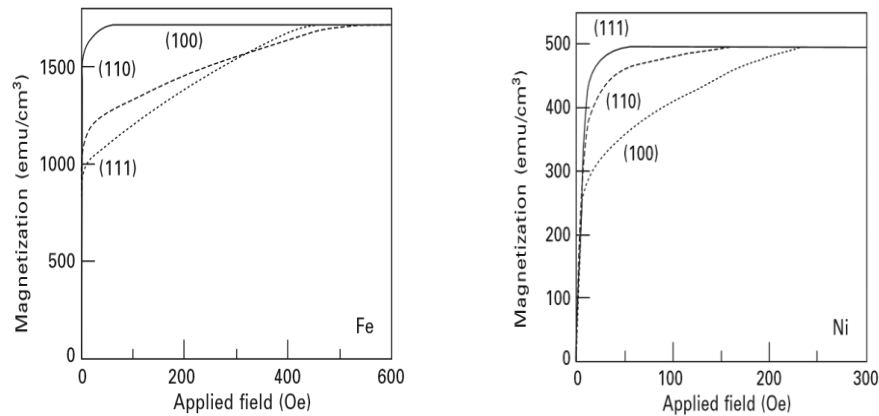


Figure 3.9: Magnetization curves in different directions for iron and nickel with crystal structure.

3.5.2. Shape Anisotropy

Sometimes, materials with the same crystal structure may have different easy axis and difficult axis of the material, depending on the shape of the material. Because of this axis difference, the energy required to magnetize the material is different. Since this energy difference originates from the shape of the material, this is called the shape anisotropy.

3.5.3. Surface Anisotropy

Depending on the state of the spins on the surface of the magnetic material and the exchange energy on the surface, there may be a change in the energy required to magnetize the material. These changes are defined as surface anisotropy. The surface anisotropy differs from the crystal and shape anisotropy of the material and emerges from changes in the surface of the material.

4. MAGNETIC RESONANCE

Magnetic resonance is observed in systems having magnetic moments and angular momentum. Resonance is called the harmonic behavior of an external effect with the natural frequency of the magnetic system. This frequency is called the gyroscopic precession of the magnetic moment in the stationary external magnetic field.

The specific frequencies of the atomic spectrum are similar. And the magnetic resonance frequencies often fall into the radio frequency domain or the frequency domain of the microwave. For these reasons, magnetic resonance frequencies are also referred to as radio frequency spectroscopy and microwave spectroscopy [19].

The ferromagnetic materials placed in a static magnetic field are equilibrated by making a precession movement in the system with a specific ω_0 Larmor frequency. From the outside, a ω frequency magnetic field is applied to this system and after a while, the frequencies ω_0 and ω are equal. There is a power absorption in the system at the time of this equality. This phenomenon is called magnetic resonance. The magnetic resonance event depends on both the internal structure of the material and the size of the external magnetic field. Magnetic resonance provides information at the atomic level [23]. The groups of expected magnetic resonance are:

- Substances having transition elements with unfilled inner layers, such as iron group and rare earth elements.
- Conduction electrons in metals
- Ferro and ferrimagnets
- Disorders that can capture electrons and holes in the insulator [21].

5. FERROMAGNETIC RESONANCE

FMR is a spectroscopic technique that gives information about the magnetic properties and magnetization of ferromagnetic materials. It is a standard method used to investigate spin waves and spin dynamics. V. K. In 1911, Arkad V.yev accidentally realized that ferromagnetic substances absorbed ultra-high frequency (UHF) radiation, which resulted in V. K. Arkad discovered FMR. Ferromagnetic resonance occurs by absorption of high frequency electromagnetic radiation by ferromagnetic materials. Therefore, ferromagnetic resonance is closely related to the field of radiospectroscopy. Radio-spectroscopy generally investigates the interaction of electromagnetic waves with different substances. These interactions are usually in the 1 mm-10 cm wavelength or 10^9 - 10^{11} s⁻¹ frequency range, which is in the infrared region. The area where the ferromagnetic resonance takes place is also the range of high frequency (UHF) 300 MHz-3000 GHz or microwave (MW) 0.3 GHz-300 GHz. As it is known from quantum mechanics and atomic physics, energy is exchanged in the interaction of the matter with the electromagnetic wave. This energy exchange is not random but with certain energy quantum.

The basics of radio-spectroscopy are what we call the Zeeman cleavage; it is based on the cleavage of the energy levels of the atom by an external magnetic field. These energy levels are related to the magnetic moments resulting from the electron movement. When examining the subject of ferromagnetic resonance, the spin and orbital moments of the electrons in the half-filled electron shells are considered as the main source of magnetism.

Dynamic magnetization of samples was investigated using ferromagnetic resonance technique. FMR technique is used to measure two different geometries in such samples. The first is Out-of Plane Geometry (OPG) where the static external magnetic field is perpendicular to the plane of the film, and the other is In Plane Geometry (IPG) where the static external magnetic field is parallel to the plane of the film. In these two different orientations, the anisotropic behavior of the materials is analyzed.

The basis of ferromagnetic resonance technique is the concept of magnetic resonance. Each system has a natural vibration frequency. This natural frequency is the frequency of the spinning moment (Larmour rotation) of the magnetic moments within the magnetic field. In other words, the magnetic moments of the material exposed to the magnetic field are split into allowed energy levels in proportion to the Larmour frequency. Then, a frequency is sent perpendicular to the stationary magnetic field applied externally. If the frequency of this alternative field sent on the material is in the microwave region of the electromagnetic spectrum, the technique used is Electron Spin Resonance (ESR) or Electron Paramagnetic Resonance (EPR).

Here, the interaction of the magnetic moments of electrons in the atom is examined. However, if the electromagnetic wave sent to the material is in the radio wave region and the interaction of the core spins is examined, this technique is called the Nuclear Magnetic Resonance (NMR) technique. When the microwave frequency applied perpendicular to the magnetic field coincides with the Larmour frequency, resonance occurs. In this case, the magnetic field is called the resonance field, while the frequency is called the resonance frequency. In ESR signals, the g value, called spectroscopic cleavage multiplier, is an important parameter that gives information about the structural, electrical and magnetic properties of the materials as it has different values for the non-coupled electrons with different magnetic circles.

FMR examines the magnetization due to the magnetic moments of electrons that are not matched by the exchange interaction. Using the FMR, information is obtained about the area in which the magnetization is resonated and the direction in which the magnetic field is applied to the sample and the magnetic anisotropy. In FMR, it is possible to apply a magnetic field in different directions to the sample. By rotating about the sample normal or sample plane, the easy direction of magnetization can be determined. With the theoretical fit of experimental FMR data, parameters such as the magnitude of anisotropy, effective magnetization, and spectroscopic split factor g can be calculated.

FMR is a magnetic measurement method used to describe the dynamic properties of magnetic materials. Two methods are used for magnetic measurement with FMR: the first is a cavity based system and the second is electrical measurements. In the cavity based system, the sample is placed in an environment

with a certain frequency, illuminated by microwave radiation and having a resonant cavity. And then the sample is scanned during this resonance condition by applying a magnetic field. Then, the resonances of the resulting waves are determined and a specific graph is created. According to this graph, the magnetic orientations and magnetic properties of the sample are determined. In this approach, measurements are made at different frequencies. A few of these frequencies are: X-band frequency range 9 GHz [24], Q band frequency range approximately 34 GHz [25] and 270 GHz [26].

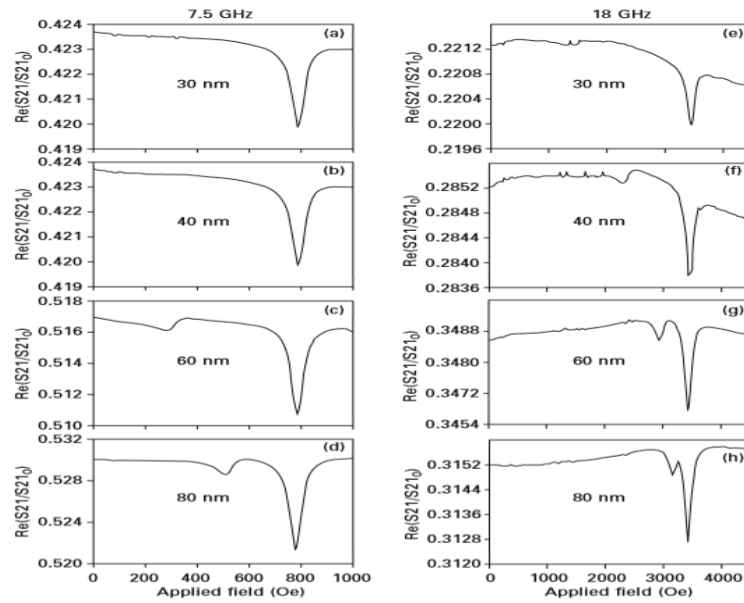


Figure 5.1: Microwave broadband FMR absorption data for single-layer permalloy films. The microstrip transducer is 1.5 mm in width. (a)-(d): driving frequency is 7.5 GHz. (e)-(h): driving frequency is 18 GHz. Film thickness: (a) and (e): 30 nm; (b) and (f): 40 nm; (c) and (g): 60 nm; (d) and (h): 80 nm. Reproduce with permission from Kennewell et.al.

In the second method, electrical measurement method, measurements are made by using striplines and co-planar waveguides. This method is very important for magnetic thin films. The electrical measurement method performs special measurements using systems such as striplines, vector network analysis, and pulse inductive microwave magnetometer PIMM [27]. VNA is very important for electrical FMR measurements [28]. The following Figure 5.1 shows the measurements obtained for the permalloy thin film using the VNA-FMR method [29].

5.1. Equations of Motion for Magnetization

5.1.1. General Equations of Motion

Even if the equations of motion of magnetization are derived from quantum mechanics, the semi-classical solution will be easier and more understandable.

In the semi-classical approach, the electrons rotate in a circular orbit around the core. It is similar to the fact that the circle formed by a circular wire passing through the current creates a magnetic moment perpendicular to the field plane.

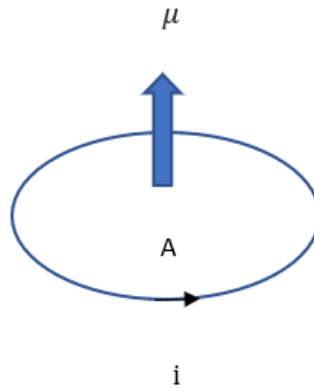


Figure 5.2: Magnetic dipole moment.

Here; i the current passing through the wire, the A field and n the normal vector perpendicular to the plane, μ the magnetic dipole moment. Dipole moment:

$$\vec{\mu} = (\vec{i} \cdot \vec{A}) \hat{n} \quad (5.1)$$

The relationship between dipole magnetic moment and angular momentum is as follows:

$$\vec{\mu} = \frac{q_e}{2m_e} \vec{L} \quad (5.2)$$

Similarly, the relationship between the magnetic moment caused by the electron spin and electron spin is as follows:

$$\vec{\mu} = \gamma \vec{S} \quad (5.3)$$

Proportional constant γ is called the gyromagnetic ratio and is approximately equal to twice the orbital momentum.

$$\gamma = \frac{g q_e}{2 m_e} = \frac{g \mu_B}{h} \quad (5.4)$$

Here, g is spectroscopic cleavage factor, μ_B is Bohr magnetone. g is 2,0023 for free electrons.

The total angular momentum change $\frac{d\vec{J}}{dt}$ is directly proportional to the torque $\vec{m} \times \vec{B}_{int}$. The magnetic flux in a ferromagnet differs from the external magnetic field due to effects such as demagnetization area, anisotropy area, magnetostrictive area. Therefore, the equations of motion can be written considering that the external magnetic field B_{ext} applied and the internal magnetic field B_{int} are quite different from each other.

$$\frac{d\vec{m}}{dt} = \gamma \frac{d\vec{J}}{dt} = \vec{\tau} = \vec{m} \times \vec{B}_{int} \quad (5.5)$$

The magnetization M is the magnetic moment in unit volume:

$$\vec{M} = \sum \frac{\vec{m}_{int}}{V} \quad (5.6)$$

And magnetic induction is expressed as follows:

$$\vec{B}_{int} = \mu_0 \vec{H}_{int} \quad (5.7)$$

The using the above equations, the equation of motion of magnetization is written as follows:

$$\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \mu_0 [\vec{M} \times \vec{H}_{int}] \quad (5.8)$$

Geometrically, this equation indicates that the magnetization vector $\vec{M}$ oscillating around the magnetic field $\vec{H}_{int}$.

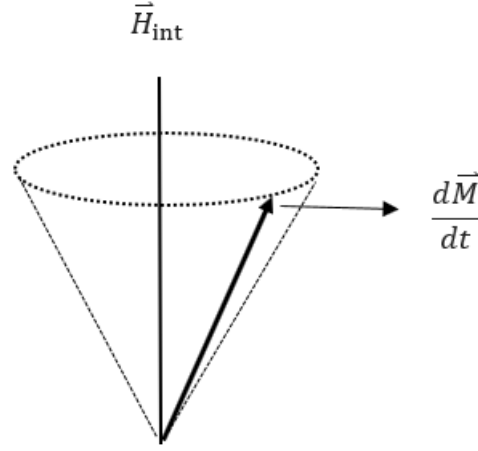


Figure 5.3: Around $\vec{H}_{int}$ free (undamped) precession movement, precession angle, and $|\vec{M}|$ constant as described in equation 4.8.

If both sides of Equation 3.8 are scalar multiplication,

$$\vec{M} \frac{d\vec{M}}{dt} = \frac{1}{2} \frac{d\vec{M}^2}{dt} = |\gamma| \mu_0 [\vec{M} \times \vec{H}_{int}] = 0 \quad (5.9)$$

appears. This means that $\vec{M}$ is constant. The same applies to the angle between $\vec{M}$ and $\vec{H}_{int}$.

$$\frac{d(\vec{M} \cdot \vec{H})}{dt} = |\gamma| \mu_0 \vec{H}_{int} [\vec{M} \times \vec{H}_{int}] = 0 \quad (5.10)$$

These two equations reveal that the magnetization vector makes a precession movement in the circular orbit around the magnetic field.

5.1.2. Damping

In a real example, the magnetization will not make an infinite precession movement as shown in Figure 5.4. After a while, the magnetization will become

parallel to the magnetic field. In Figure 5.4, we see that the magnetization is parallel to the magnetic field.

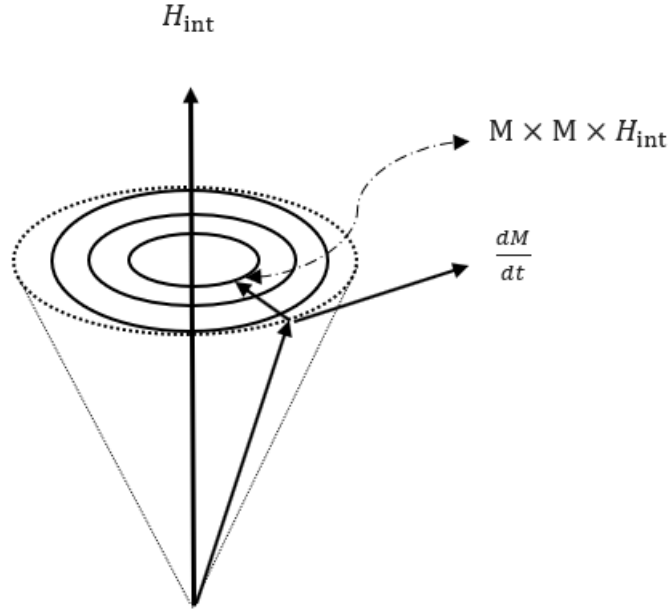


Figure 5.4: Damped motion of the magnetization vector M .

Damping can be written according to the Landau-Lifshitz form. And this means a torque that draws the magnetization vector in the direction of the magnetic field.

$$\frac{d\vec{M}}{dt} = |\gamma_{LL}|\mu_0[\vec{M} \times \vec{H}_{int}] - \frac{\lambda}{\mu_0 M_s^2} [\vec{M} \times (\vec{M} \times \vec{H}_{int})] \quad (5.11)$$

λ is the damping coefficient of unit $\lambda = \frac{1}{s}$. This term applies to weak damping situations. In the case of strong damping, Gilbert stated the following:

$$\frac{d\vec{M}}{dt} = -|\gamma_G|\mu_0[\vec{M} \times \vec{H}_{int}] - \frac{G}{\lambda_G M_s^2} [\vec{M} \times \frac{d\vec{M}}{dt}] \quad (5.12)$$

Here is the G , Gilbert damping parameter. In the new literature, the $\alpha = \frac{G}{\gamma_G M_s}$ dimensionless damping parameter is used more frequently.

Between the Landau-Lifshitz and Gilbert's giromagnetic ratios,

$$\gamma_{LL} = \frac{\gamma_G}{1+\alpha^2} \quad (5.13)$$

And between their damping parameters,

$$\lambda_{LL} = \left(\frac{\alpha}{1+\alpha^2}\right)\gamma_G\mu_0M_s \quad (5.14)$$

there are such as (4.13), (4.13) relationships.

5.1.3. Resonance Condition

The energy levels divided by the magnetic field are called $\varepsilon_i, \varepsilon_k$. The energy ranges must be equal to the electromagnetic quants.

$$\hbar\omega_{ik} = \varepsilon_i - \varepsilon_k = \Delta\varepsilon_{ik} \quad (5.15)$$

Above is the ω_{ik} transition frequency. Energy transitions are determined by Zeeman interaction:

$$\Delta\varepsilon_{ik} = g\mu_B m_i H - g\mu_B m_k H = \Delta g\mu_B m_{ik} H \quad (5.16)$$

The SHF (MW) magnetic field H_{MW} , which provides experimental and theoretical transitions, must be perpendicular to the fixed magnetic field H_0 that provides the Zeeman cleavage.

The resonance frequency from the above equations is as follows;

$$\hbar\omega_{ik} = \hbar\omega_{res} = \Delta\varepsilon_{ik} = \Delta g\mu_B m_{ik} H_0 \quad (5.17)$$

It will be the selection rule $\Delta m_{ik} = \pm 1$ only for the transitions between energy levels that are cut by the Zeeman energy effect. So becomes,

$$\omega_{res} = \frac{g\mu_B H_0}{\hbar} = \frac{ge\hbar}{2m_e c \hbar} H_0 = \frac{ge}{2m_e c} H_0 = \gamma H_0 \quad (5.18)$$

As can be seen from this equation, there are two ways to find the Lande g factor. The first is to keep the H_0 constant and change ω_{res} the frequency, the second is to keep the ω_{res} frequency constant and change the magnetic field. In terms of experimental convenience, the second way is more suitable than the first one, and this method is often used.

At equation (4.18), the Plank constant is not seen. So this formula can be reached without the help of quantum theory. Indeed, it was obtained by Larmour before quantum theory emerged [30].

5.1.4. General Expression of Resonance Condition

The general equation of motion for magnetization is as given in equation 4.8. At this time, we do not consider the damping terms. It would be more convenient to use the global coordinate system. Accordingly, the magnetization vector and the components of the external magnetic field;

$$\begin{aligned} M_x &= M \cdot \sin \theta \cdot \cos \varphi \\ M_y &= M \cdot \sin \theta \cdot \sin \varphi \\ M_z &= M \cdot \cos \theta \end{aligned} \tag{5.19}$$

and

$$\begin{aligned} H_{M(radial)} &= H_x \sin \theta \cos \varphi + H_y \sin \theta \sin \varphi + H_z \cos \theta \\ H_{\theta(polar)} &= H_x \cos \theta \cos \varphi + H_y \cos \theta \sin \varphi + H_z \sin \theta \\ H_{r(azimuthal)} &= -H_x \sin \varphi + H_y \cos \varphi \end{aligned} \tag{5.20}$$

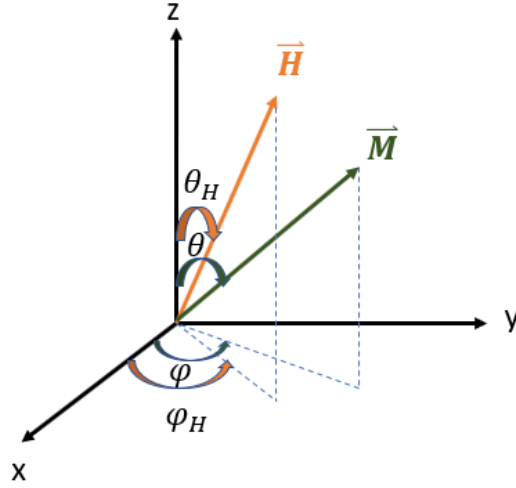


Figure 5.5: The representation of the coordinate axis assembly for the system with the total magnetization $\vec{M}$ below the $\vec{H}$ magnetic field.

The expression of magnetization was expressed in equation 4.8. For equation of moving;

$$\frac{d\theta}{dt} = \gamma H_{\varphi} \quad (5.21)$$

$$\frac{d\varphi}{dt} \sin \theta = -\gamma H_{\varphi} \quad (5.22)$$

was obtained.

Magnetization vector $\vec{M}$ in thermodynamic equilibrium state prefers the total effective magnetic field direction. Total effective magnetic field is given as derivative of free energy density (F).

$$\vec{H}_{eff} = \frac{\partial F}{\partial \vec{M}} \quad \text{or} \quad \vec{H}_{eff} = -\nabla_M F \quad (5.23)$$

In the case of equilibrium, the magnetization becomes parallel to $\vec{H}$ and no θ and φ component of $\vec{H}$. Therefore, the equilibrium state is found in the minimum conditions of free energy.

$$\begin{aligned}
F_\theta &\equiv \frac{\partial F}{\partial \theta} = 0 \\
F_\varphi &= \frac{\partial F}{\partial \varphi} = 0
\end{aligned} \tag{5.24}$$

We have to make some preliminary assumptions to solve the equations of motion analytically. First, let the system do little oscillations around the state of equilibrium, not in a state of equilibrium. In this case and its components are no longer 0;

$$\begin{aligned}
H_\theta &= -\frac{F_\theta}{M} \\
H_\varphi &= -\frac{F_\theta}{M \sin \theta}
\end{aligned} \tag{5.25}$$

For minor shifts from equilibrium;

$$\begin{aligned}
\delta\theta(t) &= \theta(t) - \theta_0 \\
\delta\varphi(t) &= \varphi(t) - \varphi_0
\end{aligned} \tag{5.26}$$

by writing, free energy derivatives with the help of Taylor expansion is as follows.

$$\begin{aligned}
F_\theta &= F_{\theta\theta}\delta\theta + F_{\theta\varphi}\delta\varphi \\
F_\varphi &= F_{\varphi\theta}\delta\theta + F_{\varphi\varphi}\delta\varphi
\end{aligned} \tag{5.27}$$

Here, $F_{\theta\theta}$, $F_{\varphi\varphi}$, and $F_{\varphi\theta}$ represent, respectively, that the derivative is taken twice according to θ , according to φ and according to before θ and after φ . Equations (4.22), (4.24) and (4.26) are expressed together;

$$\begin{aligned}
F_\theta &= \frac{M \sin \theta_0}{\gamma} \dot{\varphi} = F_{\theta\theta}\delta\theta + F_{\theta\varphi}\delta\varphi \\
F_\varphi &= -\frac{M \sin \theta_0}{\gamma} \dot{\theta} = F_{\varphi\theta}\delta\theta + F_{\varphi\varphi}\delta\varphi
\end{aligned} \tag{5.28}$$

and when deviations are around the balance state, $\dot{\varphi} = \delta\dot{\varphi}$ and $\dot{\theta} = \delta\dot{\theta}$ can be taken, because $(\frac{d\delta\theta}{dt} = \frac{d(\theta-\theta_0)}{dt} = \frac{d\theta}{dt})$. So;

$$\begin{aligned}\frac{M \sin \theta_0}{\gamma} \delta\dot{\varphi} &= F_{\theta\theta} \delta\theta + F_{\theta\varphi} \delta\varphi \\ -\frac{M \sin \theta_0}{\gamma} \delta\dot{\theta} &= F_{\varphi\theta} \delta\theta + F_{\varphi\varphi} \delta\varphi\end{aligned}\quad (5.29)$$

It is known that the solution of the differential equations given above will be a harmonic function. The coefficients determinant must be zero for the solution of this equation system.

$$F_{\varphi\theta}^2 - F_{\theta\theta}F_{\varphi\varphi} + \frac{\omega^2}{\gamma^2} M^2 \sin^2 \theta_0 = 0 \quad (5.30)$$

From this, the resonance condition is obtained.

$$\omega_0 = \gamma H_{eff} = \frac{\gamma}{M \sin \theta} \{F_{\theta\theta}F_{\varphi\varphi} - F_{\varphi\theta}^2\}^{1/2} \quad (5.31)$$

or

$$\left(\frac{\omega_0}{\gamma}\right)^2 = \frac{1}{M^2 \sin^2 \theta} \left\{ \frac{\partial^2 F}{\partial \theta^2} \cdot \frac{\partial^2 F}{\partial \varphi^2} - \left(\frac{\partial F}{\partial \theta} \cdot \frac{\partial F}{\partial \varphi} \right)^2 \right\} \quad (5.32)$$

5.1.5. Effect of Shape Anisotropy on Resonance Frequency

Consider a homogeneous and magnetically isotropic pattern. In this case, the above expression of free energy is expressed as the sum of the energy of the Zeeman energy and the demagnetization energy.

$$F = F_z + F_{de} \quad (5.33)$$

In fact, in the expression of free energy, it is necessary to include the following factors in the collection.

F_{mc} = crystal anisotropy energy

F_{me} = magneto elastic (streght) anisotropy

F_{ex} = exchange energy

F_D = domain wall energy

We will consider Zeeman and demagnetization expressions for an isotropic sample for now.

$$F = -\vec{M}\vec{H} + \frac{1}{2}(N_x M_x^2 + N_y M_y^2 + N_z M_z^2) \quad (5.34)$$

The first term is the Zeeman energy. The second term is,

$$F_{de} = -\frac{1}{2}\vec{M}\vec{H}_{de} = -\frac{1}{2}\vec{M}(-\tilde{N}\vec{M}) = \frac{1}{2}\vec{M}\tilde{N}\vec{M} \quad (5.35)$$

were found. $\tilde{N}$ is a demagnetization factor due to geometry and for mani axes;

$$\begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$

Figure 5.6: The main axis of demagnetization factors component presentaion.

The sum of demagnetization factors for the main axes will be;

$$N_x + N_y + N_z = 4\pi \quad (5.36)$$

Consider a ferromagnetic sample in the form of an ellipsoid, with demagnetization factors N_x, N_y, N_z . Internal magnetic field components of the sample are;

$$\begin{aligned}
H_{x(i)} &= H_{x(0)} - N_x M_x \\
H_{y(i)} &= H_{y(0)} - N_y M_y \\
H_{z(i)} &= H_{z(0)} - N_z M_z
\end{aligned} \tag{5.37}$$

$H_{(i)}$ the effective internal field $H_{(0)}$ is the applied magnetic field. Equations of motion take the shape;

$$\begin{aligned}
\frac{dM_x}{dt} &= \gamma [H_{0(eff)} + (N_y - N_z)M] M_y \\
\frac{dM_y}{dt} &= \gamma [H_{0(eff)} + (N_x - N_z)M] M_x \\
\frac{dM_z}{dt} &= 0 \text{ or } M_z = M_s
\end{aligned} \tag{5.38}$$

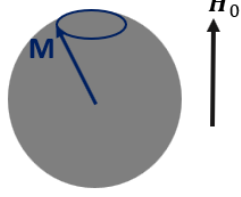
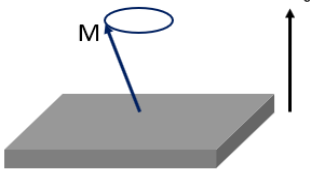
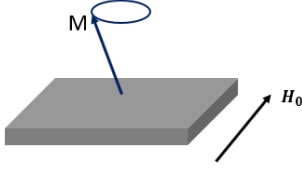
from here;

$$\omega_0^2 = \gamma^2 [H_{0(eff)} + (N_y - N_z)M_s] \times [H_{0(eff)} + (N_x - N_z)M_s] \tag{5.39}$$

The Kittel formula [30] is reached.

When we use the kittel formulas for sphere, cylinder and thin film shapes, resonance frequencies of special cases are obtained.

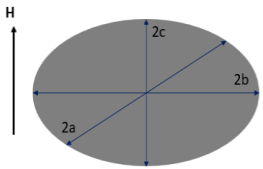
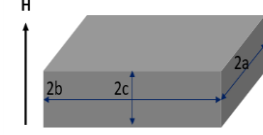
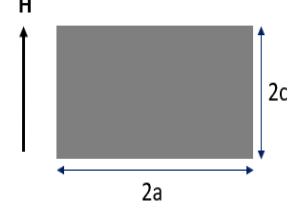
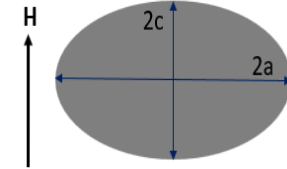
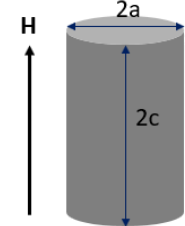
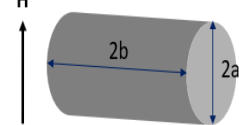
Table 5.1: Depending on the orientation of applied magnetic field demagnetization constants components.

Sphere		$N_x = N_y = N_z = 4\pi/3$ $\omega_0 = \gamma H_0$
Rectangular cuboid-1		$N_x = N_y = N_z = 4\pi/3$ $\omega_0 = \gamma H_0$
Rectangular cuboid -2		$N_x = N_z = 0, N_y = 4\pi$ $\omega_0 = \gamma \sqrt{H_0(H_0 + 4\pi M_s)}$

5.1.6. Demagnetization Account for Different Shapes

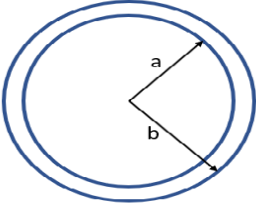
In section for some different shape demagnetization constants are accounted. This accounts are given at Table 5.2 [31].

Table 5.2. Approximate effective (“integral”) demagnetizing factor along applied magnetic field.

Shape	Geometry	Demagnetizing factor along applied field
Ellipsoid		$N = \frac{1}{2} \frac{b}{a} \frac{c}{a} \int_0^\infty \frac{ds}{(s + \frac{c^2}{a^2}) R(s)}$ $R(s) = \sqrt{(s + 1) \cdot (s + \frac{b^2}{a^2}) \cdot (s + \frac{c^2}{a^2})}$
Rectangular Cuboid		$N^{-1} = 1 + \frac{3}{4} \frac{c}{a} (1 + \frac{c}{a})$
Strip Rectangular		$N^{-1} = 1 + \frac{3}{4} \frac{c}{a} \quad \text{For } c/a \leq 5$ $N^{-1} = 1 + \frac{2}{3} \frac{c}{a} \quad \text{For } c/a \geq 5$
Strip Elliptical		$N^{-1} = 1 + \frac{c}{a}$
Cylinder Axial		$N^{-1} = 1 + 1.6 \frac{c}{a}$
Cylinder Travers		$N^{-1} = 2 + \frac{1}{\sqrt{2}} \frac{a}{b}$

We used hemispherical shape in this study. When calculating the demagnetization area for this figure, we benefited from the article that is demagnetization of hollow sphere [32].

Table 5.3: Representation of the hollow sphere.

	a= inner radius b= outer radius p=a/b= aspect ratio H_a =uniform applied field, X= susceptibility
---	---

Owing to the symmetry, the average field and magnetization inside the body have only nonezero z- component. For calculated demagnetization factors, the z- component of H inside the body is experssed by,

$$H_z = H r \cos \theta - H \theta \sin \theta \quad (a < r < b, 0 < \theta < \frac{\pi}{2}) \quad (5.40)$$

So that the z- components of the local demagnetization field and demagnetization are

$$H_{dz} = H_z - H_a \quad (5.41)$$

$$M_z = X H_z \quad (5.42)$$

Making volume average of (5.42) and (5.43) $a \leq r \leq b$ and $0 \leq \theta \leq \frac{\pi}{2}$ N are obtanied,

$$N = \langle H_{dz} \rangle_{vol} / \langle M_z \rangle_{vol} = \frac{1}{3} - \frac{2p^3 X}{6X+9} \quad (5.43)$$

The shape we used in our studies is a hemispherical shape. When we modelled this figure to make a demagnetization factor calculation, we thought of it as a shape

formed by a combination of five different surfaces instead of a complete hemisphere. In this way, our global lines have been considered as a structure derived from the combination of five strip rectangular surfaces. We have observed that the applied magnetic field comes with a different angle to each shape. Depending on this angle value, the reaction of the surface to the magnetic field is different. Therefore, different orientations and different magnetizations have emerged in our FMR measurements. This has changed the magnetic properties of our material on a flat surface and added new features to the material.

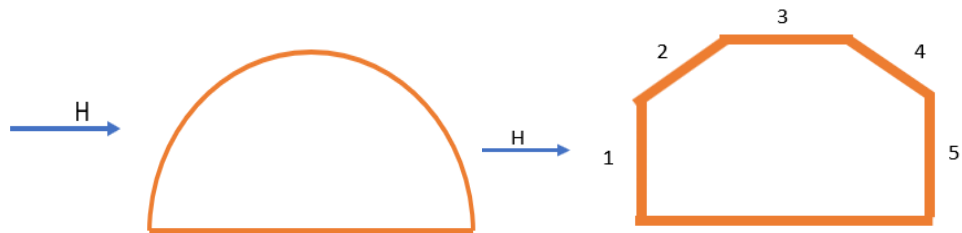


Figure 5.10: Fabricated surface and modelled surface.

6. MAGNETO-OPTIC KERR EFFECT (MOKE)

Changes in the polarization of light reflected from a ferromagnetic surface is called the magneto-optic Kerr effect (MOKE). There are three kinds of Magneto-Optic Kerr effects (MOKE). These effects depend on the direction of the magnetization vector according to the sample and reflection plane [33].

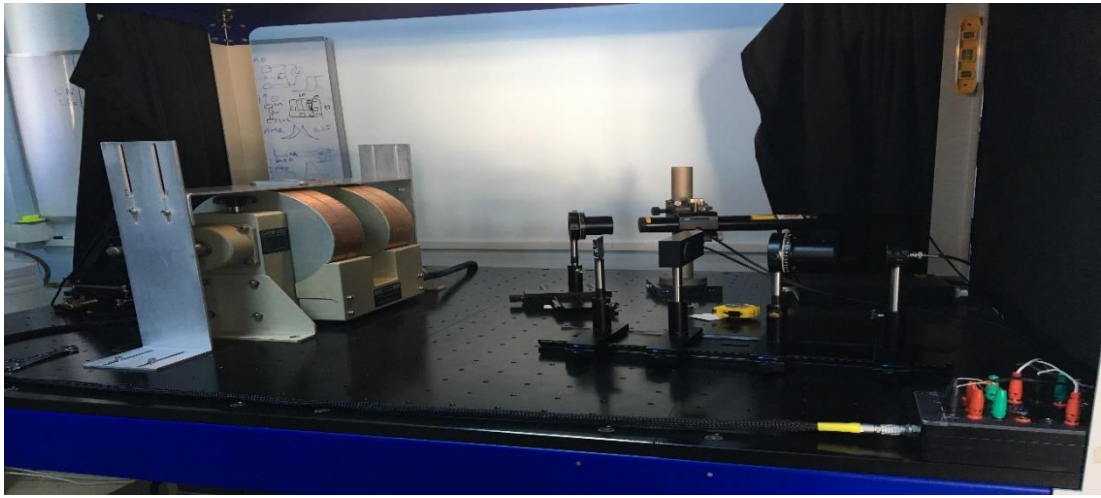


Figure 6.1: MOKE system.

6.1. L-MOKE System

With the L-MOKE system, magnetization curves and magnetic anisotropy of the thin film with magnetic properties are determined. This process is repeated by rotating the sample at certain angles between 0 and 360 degrees. The rotation is carried out with a step motor, which is placed on the sample holder. For these angles, the magnetization values and the coercive field intensities of the sample are determined. In the L-MOKE system, the assembly is as follows.

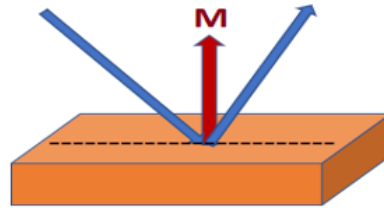


Figure 6.2: Longitudinal MOKE.

The sample is placed so that the magnetic field is parallel to the sample. When the sample is placed, the sample is glued onto the holder with double-sided tape. The beam emitted from the laser passes through the polarizer, then this beam is adjusted to the specimen at a narrow angle, and the sample is dissociated. The reflected beam is directly dropped onto the detector by passing the pin hole, the modulus, the analyzer, respectively. Then, the signals are measured for reflections at different angles by changing the angle of the sample by means of the step motor on the sample holder. And so the hysteresis curve of the material is drawn and information about its magnetization is obtained.

6.2. P-MOKE System

With the P-MOKE system, magnetization curves of thin film with magnetic properties are drawn. In P-MOKE, an angular measurement is not performed as in L-MOKE. The sample is placed in the magnetic field so that the magnetic field is perpendicular to the sample. Here, the above listed parts are all placed in the same order. In P-MOKE, the only difference is that the reflected beam does not come directly to the pin hole. Because, depending on the way in which it is placed, the reflected beam falls to the back of the beam. The beam that falls behind the back is carried by a mirror onto the pin hole. And from here, this beam comes to the modulator, the analyzer and finally the detector. This time the magnetic field is applied vertically, unlike L-MOKE. Therefore, the beam must carry a different signal. Thus, the behavior of the material in P-MOKE is different. After all these

measurements, the hysteresis curve of the material is plotted, the coercive field and magnetization are commented.

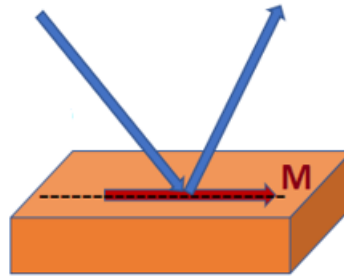


Figure 6.3: Polar MOKE.

6.3. Traverse MOKE

Here, the magnetization is parallel to the plane perpendicular to the arrival plane.

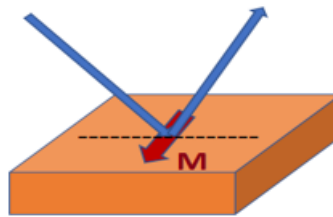


Figure 6.4: Traverse MOKE.

7. FABRICATION METHODS

7.1. Photolithography

Clean rooms are one of the most important requirements in the device production stages. Because the visible or invisible particles in the production environment affect the produced device in all production stages. Clean rooms are used to limit the number of these particles and ensure that they are less than the amount in the outdoor environment. The accuracy, precision and quality of the device produced depend on media cleanliness, ie the number of unwanted particles in the environment.

Clean room technology was first used to limit the number of bacteria in operating rooms in hospitals. Then, with the advancing technology, it has become an industry that is frequently used in industry to provide the conditions required for device production [34].

Particles in the environment may disrupt the properties of our device for different reasons. For example, these particles may adhere to our sample during production and affect the amount of resistivity on the sample, leading to unsuccessful results in the lithography, or between the sample and the mask, leading to a distortion of the pattern in the sample, or the deterioration of the vacuum between the sample and the mask, or the mask may stick to the mask and cause the pattern to be drawn on the mask. Clean rooms are divided into two according to air flow systems [35].

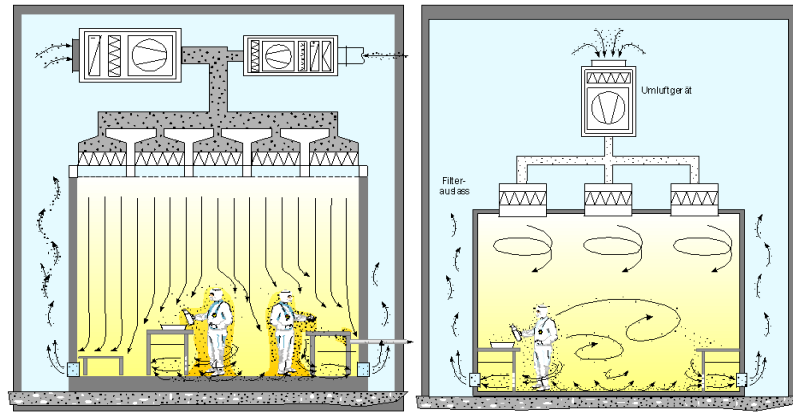


Figure 7.1: Air flow pattern is Clean Room with Laminar Flow, Air Flow model is Turbulent Flow Clean Room.

Clean rooms are divided into different classes according to the number of particles. The classes are shown at Tablo 7.1 [36].

Table 7.1: Clean rooms are divided into different classes according to the number of particles they contain.

ISO 14644-1 CLEAN ROOM STANDARDS							
CLASS	maximum particul/m3						FED STD 209E
	$\geq 0.1 \mu\text{m}$	$\geq 0.2 \mu\text{m}$	$\geq 0.3 \mu\text{m}$	$\geq 0.5 \mu\text{m}$	$\geq 1 \mu\text{m}$	$\geq 5 \mu\text{m}$	equivalent
ISO 1	10	2,37	1,02	0,35	0,083	0,003	
ISO 2	100	2,37	10,2	3,5	0,83	0,029	
ISO 3	1	237	102	35	8,3	0,29	Class 1
ISO 4	10	2,37	1,02	352	83	2,9	Class 10
ISO 5	100	23,7	10,2	3,52	832	29	Class 100
ISO 6	1.0×10^6	237	102	35,2	8,32	293	Class 1,000
ISO 7	1.0×10^7	2.37×10^6	1,020,000	352	83,2	2,93	Class 10,000
ISO 8	1.0×10^8	2.37×10^7	1.02×10^7	3,520,000	832	29,3	Class 100,000
ISO 9	1.0×10^9	2.37×10^8	1.02×10^8	35,200,000	8,320,000	293	Room air

In addition, the temperature and humidity of the clean rooms is one of the important factors to prevent the photoresist from being used [37]. Since the

deterioration of the photoresist used will affect the device to be produced, the temperature and humidity levels in the clean rooms are also adjusted [37].

In the clean room, there are a few things that employees should do in order not to spoil the environment: these are the following. Before entering the clean room, wear special clean room clothes, wear mouth masks, gloves and galoshes and get rid of the particles on the clothes by air shower.

Photolithography is the process of transferring the patterns drawn on the mask using ultraviolet (UV) or deep ultraviolet (DUV) light sources. There are a few things to consider when performing photolithography: they are resolution, sensitivity, low error rate, and alignment [34]. What we call resolution is that the pattern on the mask is adhered to the actual dimensions of the pattern. Photolithography process consist of some stage. The stage is said to above.

7.1.1. Mask printing

Firstly, the devices that are required for device production are shipped with the appropriate program. Then these desing files will be transformed with the appropriate conversion programs and transferred to the computer controlled device. Finally, the chrome-plated glass material which is to be used as a mask is first coated with the appropriate photoresist and placed in the printing device and then started printing after the necessary adjustments are made. The printing time varies according to the size of the pattern to be printed. After printing, the mask is first developed with the appropriate developer and then crom etching is performed. After the crom etching process, appropriate openings are created on the mask. Thus, during lithography, light passes through these openings and transfers the pattern to the sample.

7.1.2. Sample Coating

The sample is cleaned in an ultrasonic bath with acetone and isopropanol before the sample is coated. The sample to be transferred is coated with a negative

or positive photoresist according to the need. While areas exposed to light with positive resistors are opened with the developer, the regions exposed to light in the negative photoresist remain on the sample while other regions are opened with the developer [38]. Photoresist coated process is shown in Figure7.2 [39].



Figure 7.2: Photoresist coated.

7.1.3. Lithography Process

Photolithography is the process of transferring the patterns drawn on the mask using ultraviolet (UV) or deep ultraviolet (DUV) light sources. There are a few things to consider when performing photolithography: they are resolution, sensitivity, low error rate, and alignment [34]. What we call resolution is that the pattern on the mask is adhered to the actual dimensions of the pattern.

The sample covered with the photoresist is neatly placed on the lithography device. Alignment is performed and the distance between the mask and the appropriate vacuum system is adjusted. Finally, the light is sent in the set time using the appropriate light source and the pattern is transferred to the sample. After this operation, the sample is preheated and then developed with the appropriate developer. Thus, the desired pattern is exactly obtained on the sample.

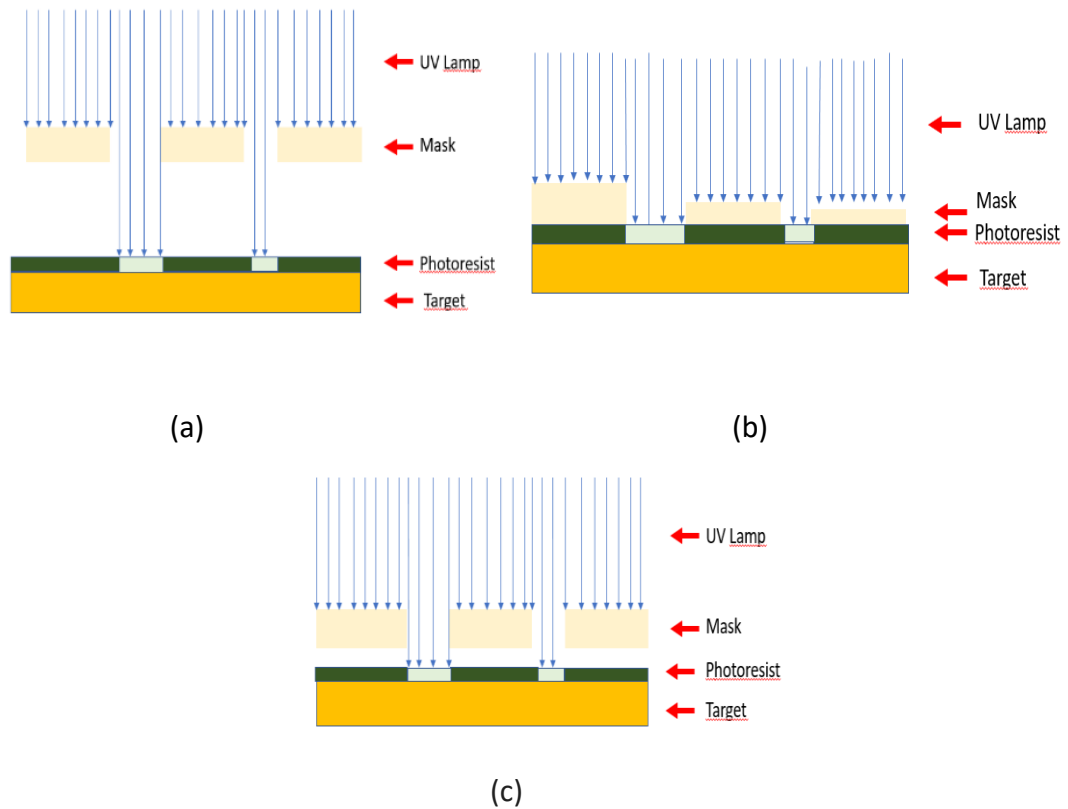


Figure 7.3: Different vacuum conditions. (a) contact vacuum (b) close vacuum (c) projection vacuum.

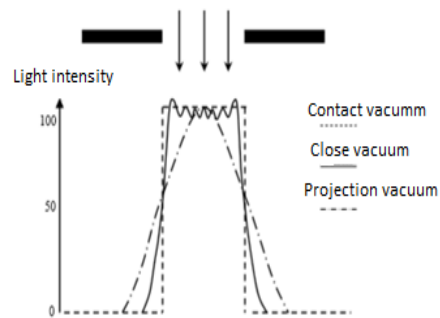


Figure 7.4: The intensity of light in different vacuum conditions.

After the alignment between the sample and the mask is done, the photoresist coated sample is fixed to the bottom of the mask using the vacuum system according to the need and fixed. There are three different vacuum systems: contact vacuum, close vacuum and projection (projection) vacuum. In these vacuum systems, the distance between the mask and the sample increases in order. And the intensity of light sent depends on the vacuum system used [40].

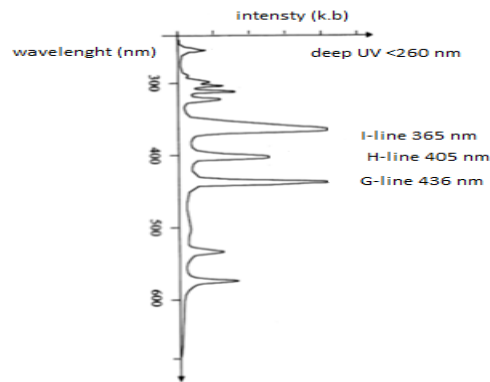


Figure 7.5: Mercury lamp spectrum.

The wavelength of the light source is chosen according to the photoreceptor sensitivity used in photolithography. The light intensity varies depending on the wavelength of the light [34]. And this affects lithography results.

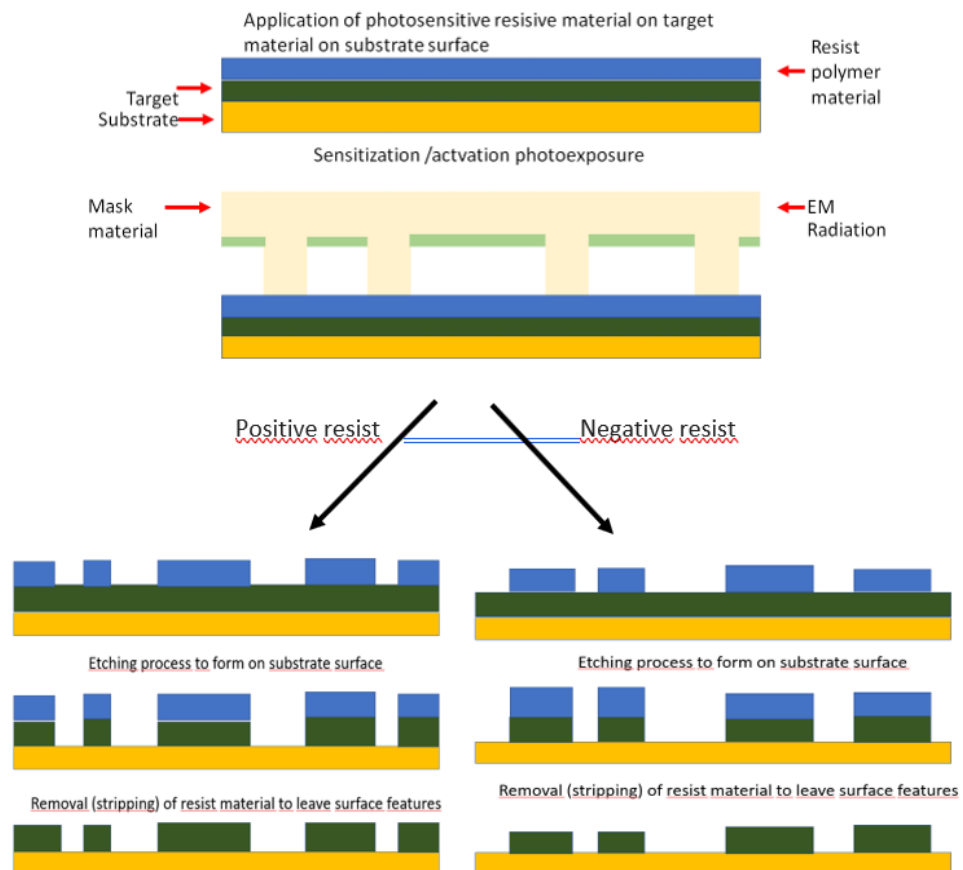


Figure 7.6: Lithography process.

The sample covered with the photoresist is nearly placed on the lithography device. Alignment is performed and the distance between the mask and the appropriate vacuum system is adjusted. Finally, the light is sent in the set time using the appropriate light source and the pattern is transferred to the sample. After this operation, the sample is preheated and then developed with the appropriate developer. Thus, the desired pattern is exactly obtained on the sample. Lithography process is shown in Figure 7.5 [38].

7.2. Thin Film Deposition

The thin film is the process of depositing the atoms or molecules of a desired material on the target substrate surface. We call this substrate a lower stone. In recent years, due to advances in technology, the areas where thin film is needed have become more and more easy to obtain.

The physical and magnetic properties of thin films are influenced by many factors in preparing the film: temperature, thickness, growth medium, properties of the main material to be enlarged and the technique of deposition [41].

In Volmer-Weber type growth, the surface energy of the sub-surface energy is greater than the total surface energy of the film surface energy and the surface energy is between the film and the sub-base. Finally, the relationship between the surface energies varies depending on the increased thickness in the growth of Stanski-Krastanov type, and different growth modes are seen [41].

In this thesis, high vacuum in-situ film deposition systems and analysis systems in Nanomagnetism and Spintronic Laboratory of Gebze Technical University Nanotechnology Institute have been used. These systems include Sputter, Pulsed Laser Deposition (PLD), Molecular Beam Epitaxy (MBE), Low Energy Electron Diffraction (LEED) with Film Deposition Systems, Scanning Tunnel Microscope (STM), X-ray Photoelectron-Nail Electron Spectroscopy (XPS-AES) It consists of High Energy Electron Diffraction (RHEED).

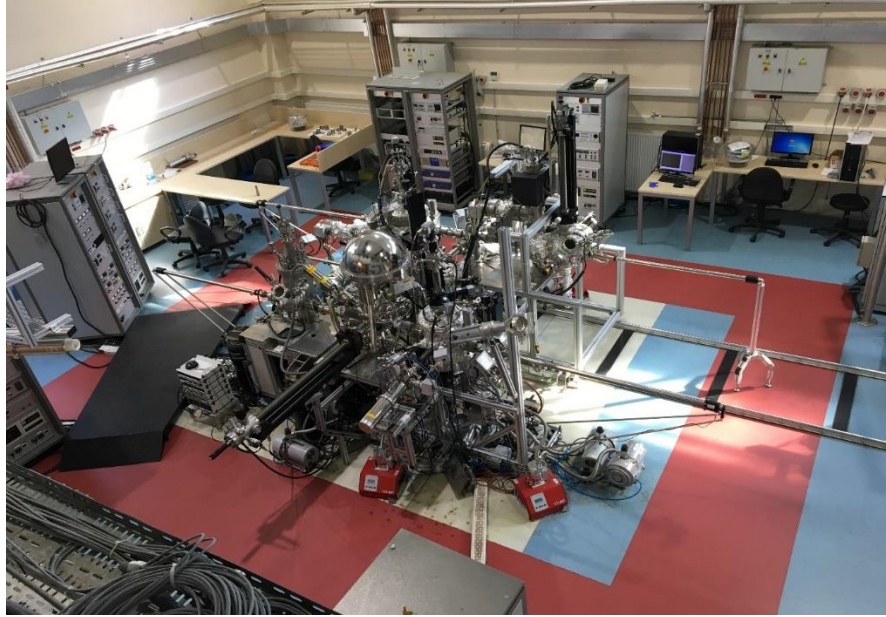


Figure 7.7: Thin-film deposition system used during thesis study.

We used only sputter system. So, here information will be given about only sputter system. There is a vacuum chamber in the sputter system operating at 10^{-8} 10^{-9} mBar pressure and having anode and cathode, and enlarging is done in this room. This room has anode sections where the cathode and the bottomstone where the material to be enlarged is placed will be placed. It is necessary to create a plasma medium in this room before the film is grown. In order to create a plasma, firstly argon gas is introduced into this room, then a potential difference is generated between the power supply to be used and the anode cathode [42]. DC and RF power sources are used depending on the characteristics of the material to be enlarged as a power source. Thus, using this difference, the electrons removed from the cathode move towards the anode. The electrons moving towards the anode collide with argon atoms along the way and still bring ionized argon atoms. Thus, the plasma is formed. Then the growth begins, where the ionized argon atom hits the target material and ruptures the electrons there. Breaking electrons under the effect of the electric field to the bottom of the bottom is attached. Thus, the targeted material is enlarged on the base material which is our main material. A magnet can be placed underneath the target material to make deposition faster. It increases the ionization rate and contributes to the deposition process.

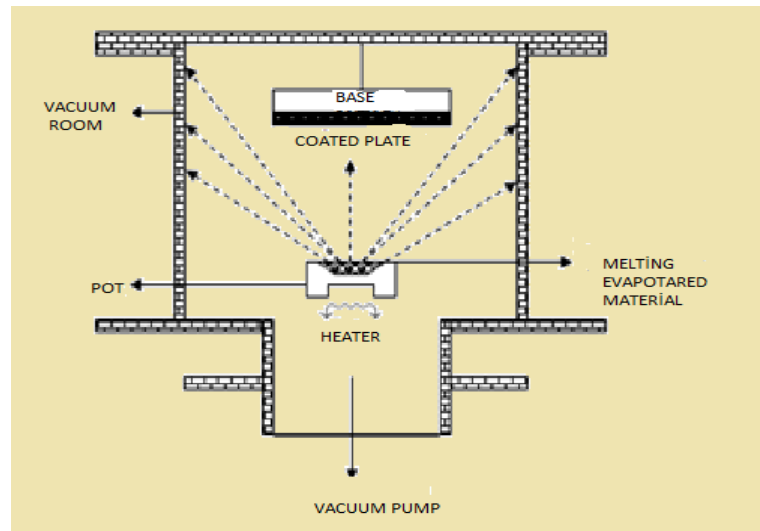


Figure 7.8: Experimental representation of sputter technique.

8. MEASUREMENT METHODS

8.1. X-Ray Diffraction (XRD)

X-Ray diffraction technique materials provide information about crystal mesh parameters, crystal orientations, three-dimensional structure of crystals, in short, the crystal structure of the material. DeBragg Law is used in X-Ray diffraction technique [43]. In this law, atoms stand aligned on two crystal planes parallel to each other. These atoms are sent to the Xs with certain angles and the angle behind which this beam is broken is determined. In the process of this process, constructive and destructive diffraction will occur in the system. While destructive entrances will destroy each other from the diffractions formed, constructive attempts will occur at the full layers of the wave length of X. Diffraction angle read from the system. Calculates the distance d (parallel distance between the parallel planes) by substituting the equation in $\lambda n = d \sin \theta$. Demonstration of X-Ray diffraction in crystal plane is shown in Figure 8.1 [43].

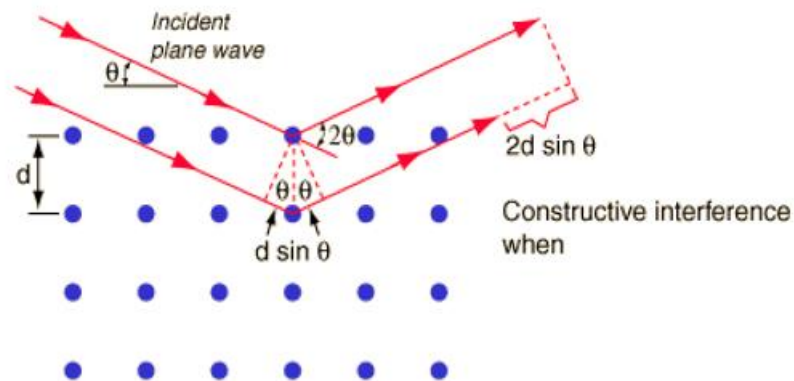


Figure 8.1: Demonstration of X-Ray diffraction in crystal plane.

Miller indices are calculated using this calculated distance d_{hkl} formulas [44]. Miller indices give us the three-dimensional shape of the material [45].

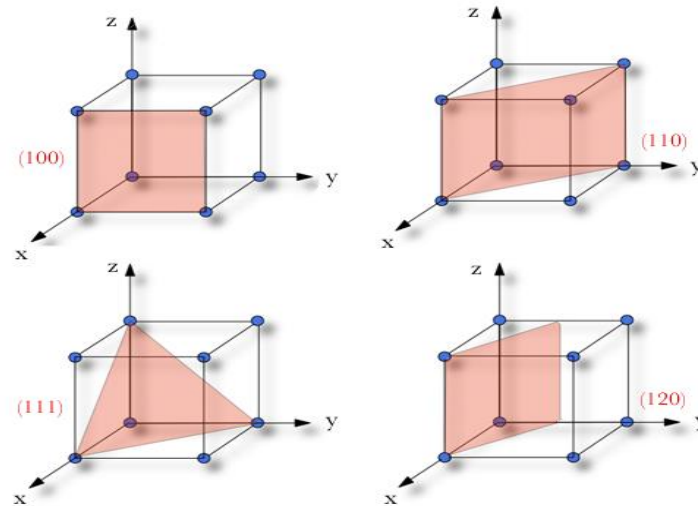


Figure 8.2: Three dimensional crystal structure of material.

8.2. Scanning Electron Microscopy (SEM)

SEM is a type of microscope that is formed by the combination of electric and optical microscope, allowing us to see surfaces as small as it can be seen with the naked eye. SEM was designed by M. Koll in Germany in 1935. At the SEM, the surface of the object is scanned with a light of a specific wavelength, and then the information obtained by scanning with the help of the detectors is converted to electrical data. Thus, information about the morphology of the surface is obtained [46]. SEM analysis experiment scheme is shown in Figure 8.2 [46].

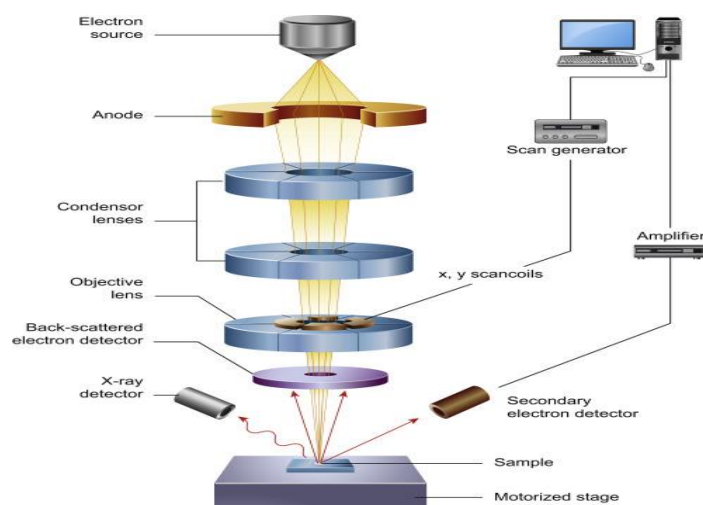


Figure 8.3: SEM analysis experiment scheme.

In the working principle of SEM, the high energy electron beam sent to the sample surface interacts with the outer orbital atoms of the sample atoms. As a result of this interaction, different conditions occur on the surface and these situations are detected by various detectors and converted into electrical signal. And thus the surface image is obtained.

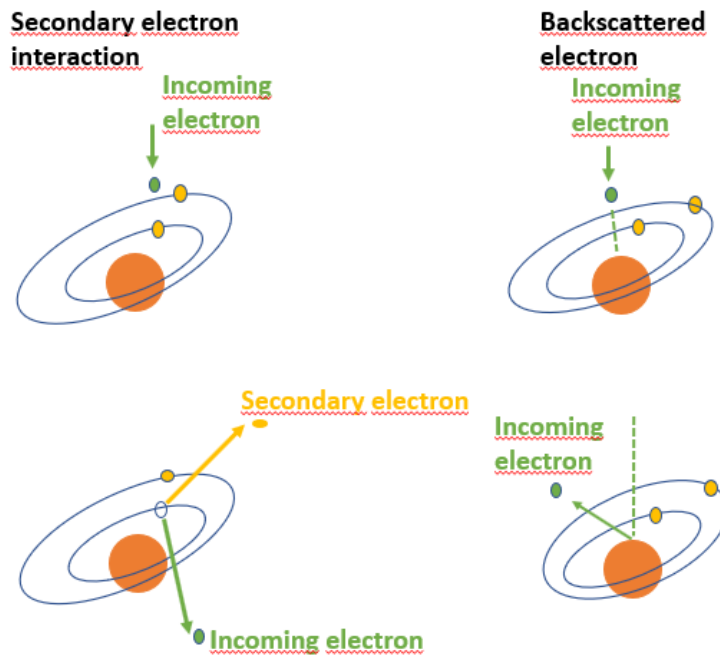


Figure 8.4: Formation of backscattered and secondary electrons.

After the interaction, the electrons recovered are secondary electrons, Auger electrons, X-ray fluorescent photons and different energy photons. In Figure 8.3, formation of backscattered and secondary electrons is shown [46]. If the incoming electron interacts with the orbital bundle, the electrons on the orbit will be scattered. These electrons are the secondary electrons that are scattered and these electrons lose their energies and are collected on the sample surface. Secondary electrons are collected in the SEM in the simillator and converted into a secondary electron image signal. The secondary electrons provide information about the portion from the sample float to a depth of 10 nm. Thus, it gives information about the topological view of the surface.

SEM devices incorporate the Energy Distribution Spectrometer (EDS-EDX) to perform elemental analysis of samples. In this measurement, X-rays that have been

resulted to the sample surface of the high-electrical hardware. The energy and wavelength of the X-rays formed are analyzed to obtain the characteristics of the sample atoms. Thus, as a result of the measurement, information about the chemical characterization of the samples is obtained and the elemental analysis of the sample is performed.

8.3. FMR Measurement System

Electron Spin Resonance (ESR) spectroscopy and ESR devices designed for this purpose are used for Ferromagnetic Resonance (FMR) measurements. ESR spectroscopy is based on examining the relationship between the magnetic moments of electrons in the material using the microwave region of the electromagnetic spectrum.

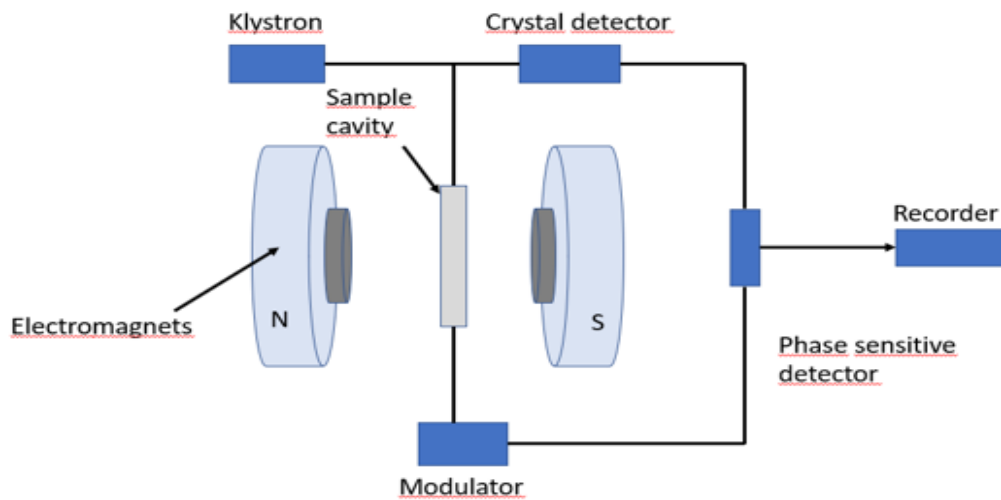


Figure 8.5: Schematic representation of the ESR device.

A standard ESR device consists of 4 basic parts as shown in Figure 8.3, Microwave welding system, Cavity-Guide system, Magnet system, Modulation and detector (detection) system [46].

8.3.1. Microwave Source System

One of the most important elements of this system is known as high frequency generator (klystron) [46]. Klystron is an electron tube that is known for its low noise and operates as a microwave source in a small frequency range. While this system produces microwave in resonance, the electric field between the parallel plates changes sinusoidally. By setting the values of the reflector and accelerator plate voltages, the high frequency generator can oscillate in different voltage zones. On the other hand, while the insulator (insulator) is used to prevent the reflection of the microwave coming out of the source system, the automatic frequency control ensures that the microwave frequency produced by the high frequency generator is stable and stable [46].

8.3.2. Cavity-Guide System

The cavity system is the place where the sample is placed and the waveguide is located, allowing the electromagnetic waves from the microwave source to fall on the sample and allowing the reflected electromagnetic waves to reach the detector after interaction with the sample. The impedance between the waveguide and the cavity is ensured by the iris, while the wave rotating system is used to compensate for the reflection of the electromagnetic waves leading to the cavity.

8.3.3. Magnet System

The Magnet System consists of a pair of oppositely placed electromagnets to produce a fixed and homogeneous magnetic field. Electromagnets fed by direct current power supply produce magnetic fields up to approximately 2.2 Tesla. A Hall probe system is used on one of the magnets to control the generated magnetic field.

8.3.4. Modulation and Detector System

First, the microwaves absorbed by the sample reach the detector. An electric current is generated in the detector, which is proportional to the frequency of the incoming microwaves. So, when the microwave is low the current decreases in detector, when the microwave increases, the current in the detector increases. As a result of the field modulation system and the signal amplifiers, when the sample is near the resonance state, the result of the electric current change corresponding to the resonance against the magnetic field change is obtained as a spectrum by means of the computer.

8.4. MOKE Measurement System

The hysteresis curve of the material was drawn. And the magnetic behavior of the material was examined. These curves were drawn in both P-MOKE and L-MOKE. The MOKE system consists of a helium-neon laser, a polarizer, a sample holder capable of moving the sample in three directions, discs forming the poles providing an external magnetic field, a pin hole, a modulator, an analyzer and a detector that detects the signal generated by the reflected light.



Figure 8.6: Component of MOKE device.

Tablo 8.1: Component of MOKE device.

No	Component name
1	Pin hole
2	Analyzer
3	Polarizer
4	Si photo diot detector
5	Polarizer
6	HeNe laser
7	Electromagnets
8	Control unit of step motor
9	Step motor
10	Non mognetic mirror

Helium neon laser is used to send a polarized light onto the sample in the MOKE system. This HeNe laser has a beam diameter of 35 mW, a diameter of 0.65 mm, and has a beam divergence of 1.24 mrad and is self-polarizing. The polarizer is used to improve the polarisation of light to the magnetic material. The sample holder is used to place the sample in the magnetic field. Since the sample holder can be moved in three directions, the sample can easily be aligned by moving in the magnetic field. An external magnetic field is applied on the sample consisting of magnetic material by using magnetic discs used in the system. Thus it is examined the change of properties of the material with the effect of magnetic field. The light is precisely set in the middle of the detector by means of the so-called pin hole. Because the pin hole is a certain and constant height from the test table and has a hole in the middle. Light reflected from the sample passes through this hole and moves towards the detector. The modulator is used as a strainer to separate the reflected beam from the sample from the other rays in the environment. The analyzer also works like the polarizer. However, the analyzer improves the polaziration of the reflected beam from the sample. Finally, the detector is the last part of the beam to arrive. The signal of the beam is measured here. Thus, we learn about the magnetic properties of the material.

9. FABRICATION STUDIES

The patterns in this study were carried out in three stages. The first stage is lithography, the second stage is the thin-film coating and the third stage is the lift-off process.

9.1. Photolithography Process

The photolithography process consists of several stages. These steps include cleaning the substrate, coating the substrate with photoresist, alignment and expose processes and developer operations. Before these processes, the patterns to be transferred to the substrate by the lithography have to be printed on the mask.

9.1.1. Mask Printing

The mask is a glass coated with chromium and positive resist. The mask is used when transferring the desired patterns to the substrate with lithography. In this study, a mask printing device called Heidelberg dwd was used for mask printing. This device is a computer-aided device. Patterns were drawn with a program called Clevin and were loaded with computer. Then, the intensity, focus, linear dft and z-position parameters were determined and the patterns were printed on the mask.

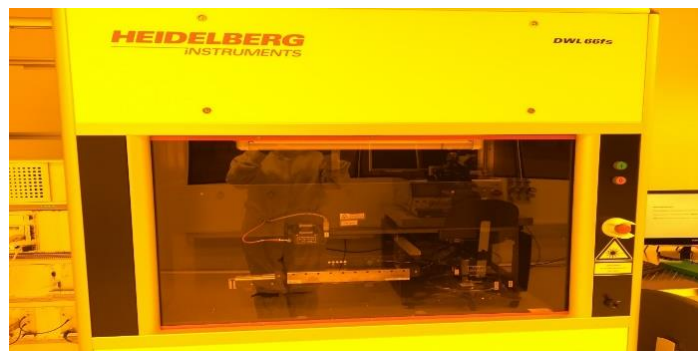


Figure 9.1: Heidelberg dwd device.

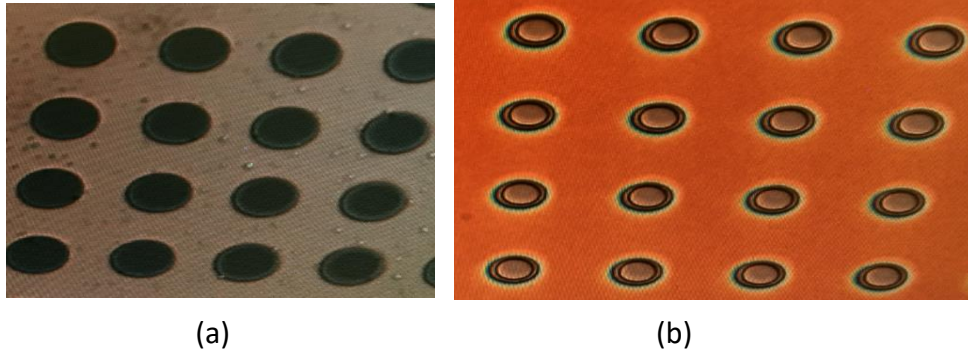


Figure 9.2: Image of a mask taken with an optical microscope (a) before developer
(b) after developer.

9.1.2. Substrate Cleaning

In this study, silicon bottomstone was used for lithography. All substrates used for lithography were applied the same cleaning steps. The silicon substrate was cleaned in two stages as chemical and thermal. First of all, chemical cleaning was done to remove organic residues on the substrate. Acetone and isopropanol were used for this procedure. Each substrate was cleaned by using an ultrasonic bath with acetone and isopropanol for 10 min. Acetone removes organic residues, isopropanol removes organic residues that acetone cannot clean, and pollution from acetone. After chemical cleaning, the substrate was dried using N_2 gas. And then the hot plate, which was preheated to $200\text{ }^{\circ}\text{C}$, was used for thermal cleaning. The substrate placed on the heated hot plate was allowed to stand for several minutes, and then cooled to room temperature. The substrate was heated, and the materials dissolved on the substrate were evaporated. So the cleaning process was finished. For cleaning, the bench and hot plate were used in the picture below.

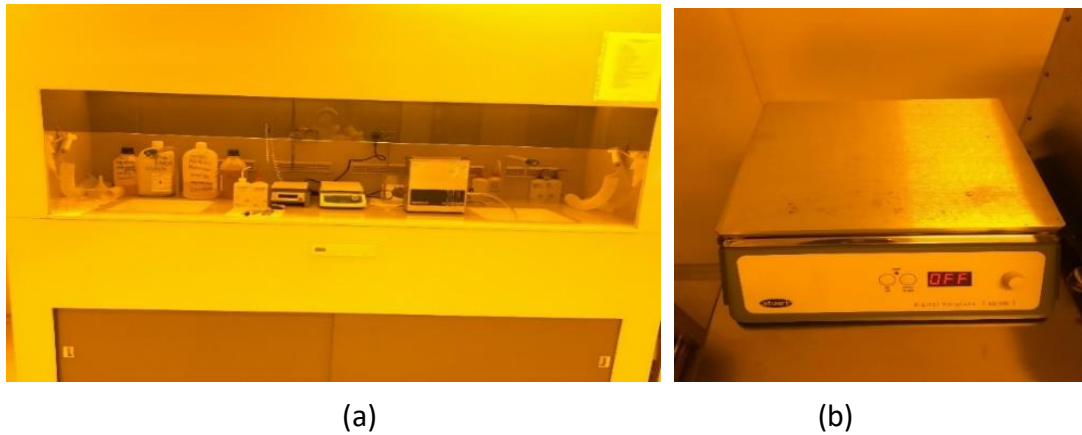


Figure 9.3: (a) the bench was used for lithography (b) hot plate was used for lithography.

9.1.3. Substrate Coating

At this stage, the cleaned substrate is coated with a predetermined photoresist according to its intended use. SU-8 3005 negative resist was used in this study. Because, when expose, the light areas were hardened and remained on the surface of the substrate, while the other parts were required to move away. Spin coater was used for coating process. In the spin coater's interface screen, the speed and time at which the substrate is intended to be rotated is defined. This speed and duration are determined by using the datasheet of the photoresist. The thickness of the photoresist is adjusted depending on the speed and duration. This allows us the ease of thickness control. Before the substrate was placed on the spin coater, the pre-bake process was performed. The substrate was heated at 95 °C on a hot plate for 3 minutes and was cooled to room temperature. Then a few drops of photoresist were dropped onto the substrate attached to the spin coater with vacuum. The amount of this photoresist varies depending on the viscosity of the photoresist. In this study, we wanted to obtain a 5 μm thickness photoresist layer, for which the substrate was rotated at 3000 rpm for 40 sec. After spinning, the soft bake process was performed on the hot plate at 95 °C. With this process, the photoresist was made to harden and get better on the surface. Thus, the photoresist coating process was finalized.



Figure 9.4: Spin coater was used for lithography.

9.1.4. Alignment and Expose Operation

At this stage, after alignment treatment, the mask made in heidelberg and the photoresist coated substrate are exposed to UV light. A mask aligner with 365 nm wavelength laser was used for this procedure. Expose time was adjusted depending on the power supplied by the device. UV light was sent on the substrate with the expose process. And so the patterns on the mask are transferred to the substrate.



Figure 9.5: Mask aligner device was used for lithography.

9.1.5. Postbake Process

The exposed substrate was postbake at 95 °C and then at 65 °C, so that the photoresist was hardened and held onto the surface.

9.1.6. Develop Process

At this stage, the postbaked substrate was immersed in the special developer of the photoresist used and held for 55 sec, then immediately immersed in water. And then it was dried using N₂. With the help of the Developer process, the resist layer that not exposed to light in areas was removed from the substrate surface. Thus the patterns were completely transferred to the substrate surface. With the lithography process, the desired cylinder patterns were created on the surface. In the following image, the patterns are included in the SEM images.

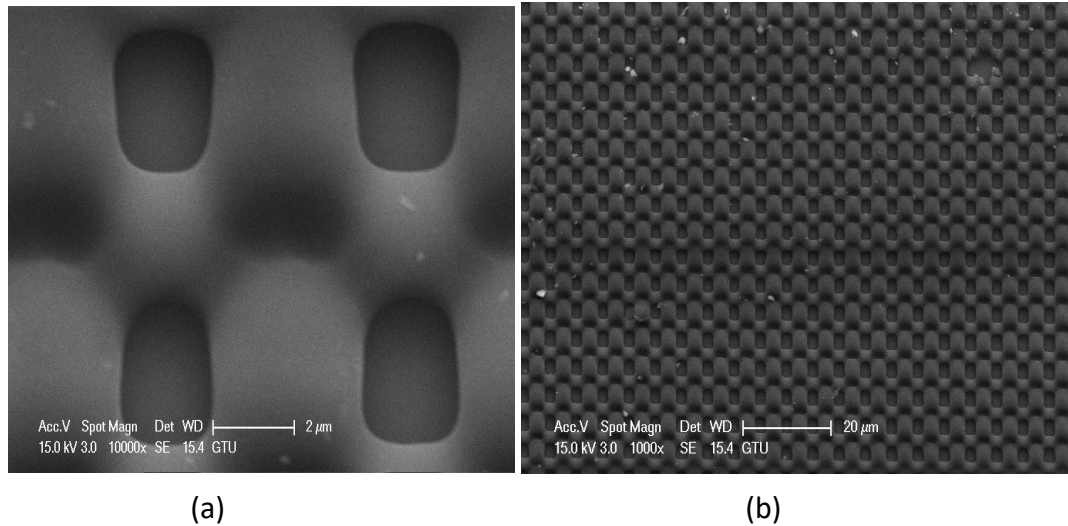


Figure 9.6: SEM images of cylinder patterns that are obtained by lithography process, (a) For 2 μm solution, (b) For 20 μm solution.

9.1.7. Thermal Reflow Process

One of the aims of this study is to obtain spherical surfaces from cylinders obtained by lithography. For this process, thermal reflow process was applied to the substrate made of lithography. Resistive surface tension was used for this procedure. The heated resist expanded and became spherical shape. We used the data sheet and other studies in the literature to determine how many and how much the photoresist would be heated. According to the data sheet, the glass transition temperature value of SU-8 is 200 °C. However, the heating time of the substrate changes depending on

the thickness. The literature was screened for this. As a result of this process we heated the substrate at 200 °C for 4 minutes. And as a result of the reflow, we have obtained spherical patterns.

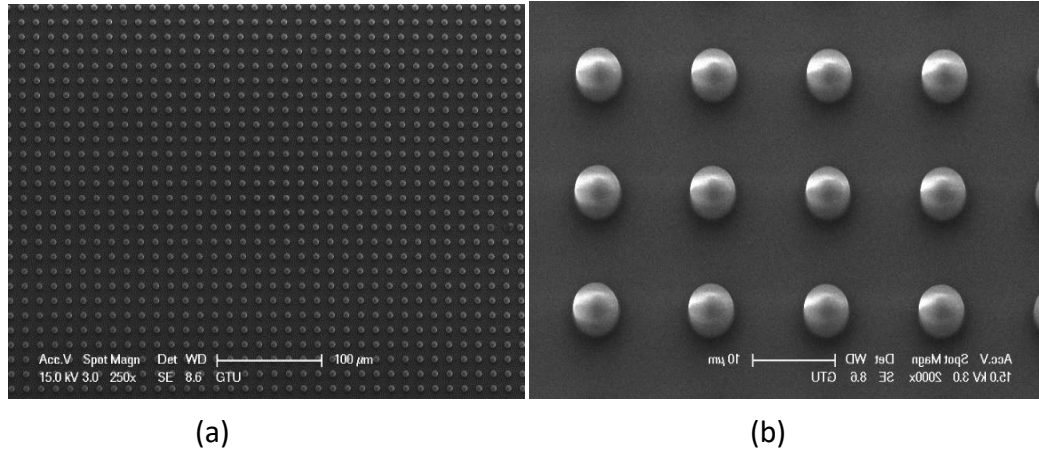


Figure 9.7: After the thermal reflow process, SEM images of spherical structure is taken from surface a) for 100 um, b) for 10 um.

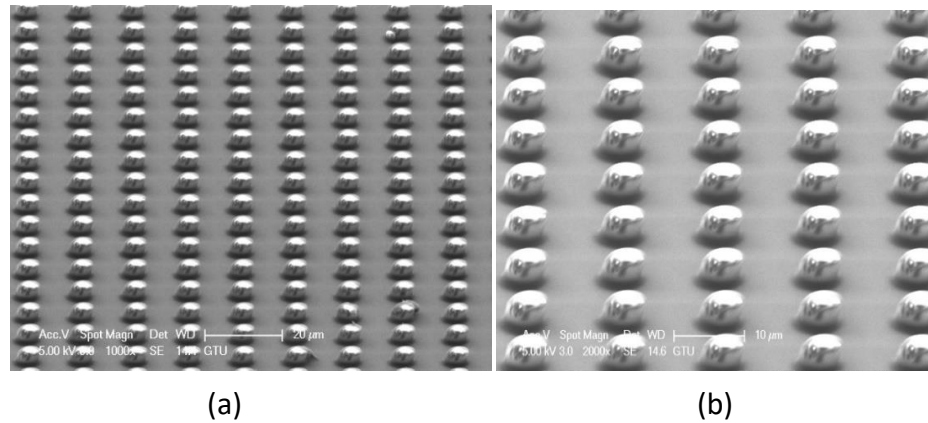


Figure 9.8: After the thermal reflow process, SEM images of spherical structure is taken from side a) for 20 um, b) for 10 um.

9.2. Thin-Film Growth Process

In this study magneto sputtering device was used for growth. Base pressure of the chamber is at 2×10^{-9} mbar. As the target material, $\text{Ni}_{80}\text{Fe}_{20}$ and $\text{Ni}_{55}\text{Fe}_{45}$ (permalloy) element was placed in the cathode region. Silicone is used as the substrate and placed in the anode. In this study, the film was grown on three different

surface of naturally oxidized silicon substrate. The first of those was grown directly on cleaned substrate, while the other two were grown on the patterned surfaces, which is obtained after lithography processes. Thermal annealing was not applied not to effect the shape of the patterns (Su-8 and AZ1505) by high temperature. Chemical cleaning was only carried out in a clean room before the lithography. Chemical cleaning process is described in detail in the lithography section. When preparing the substrate, it was attached to the holder with a punto and placed on the sputter.

Then, when the system was shut down, the appropriate vacuum was supplied, and then the plasma was formed, growth process was started. RF power supply is used. This system works with RF and DC power sources. We have used RF power supply in this. Growth processes were performed at 20 W and 2.10^{-7} Mbar.

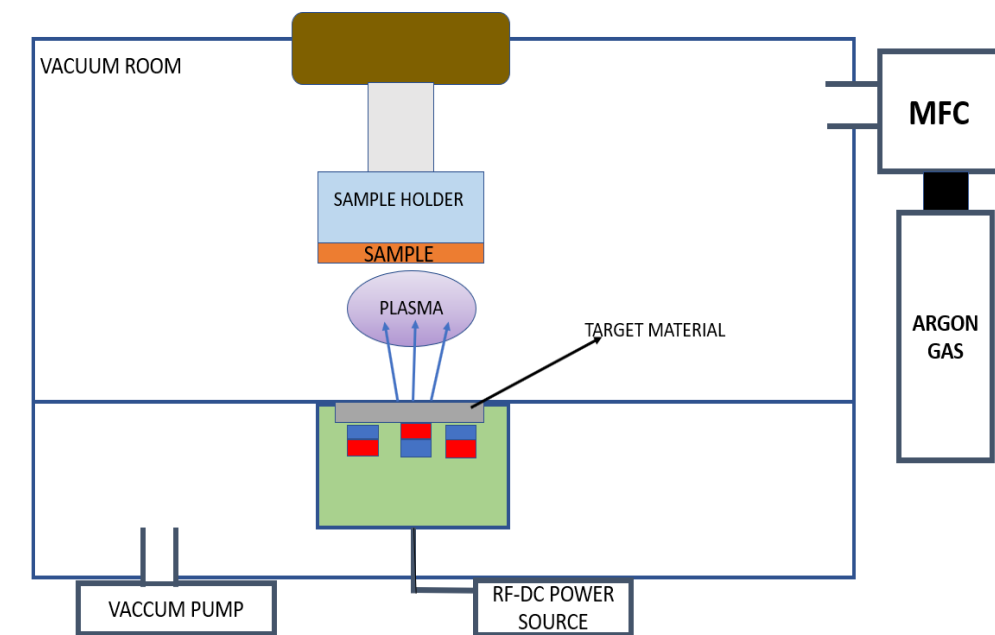


Figure 9.9: Magneto-Sputtering experimental schema.

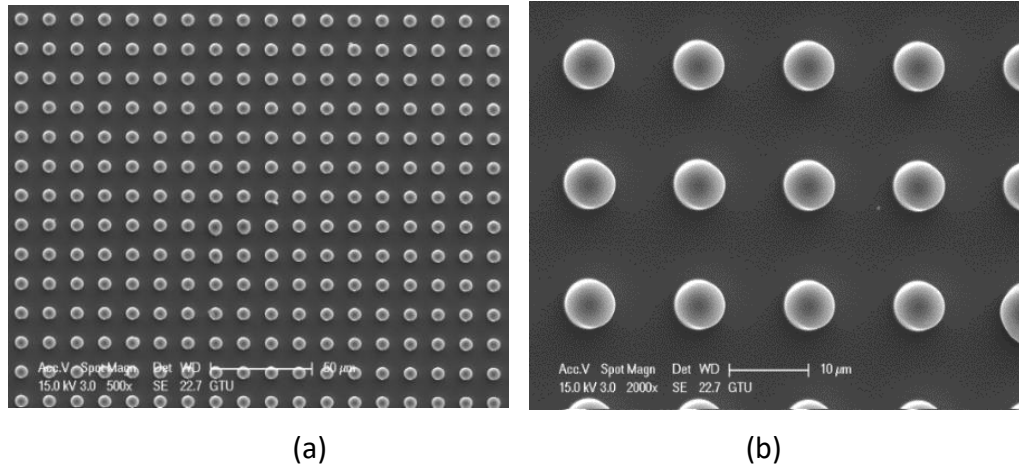


Figure 9.10: After the thin film growth process, SEM images of spherical structure is taken from surface a) for 50 μm , b) for 10 μm .

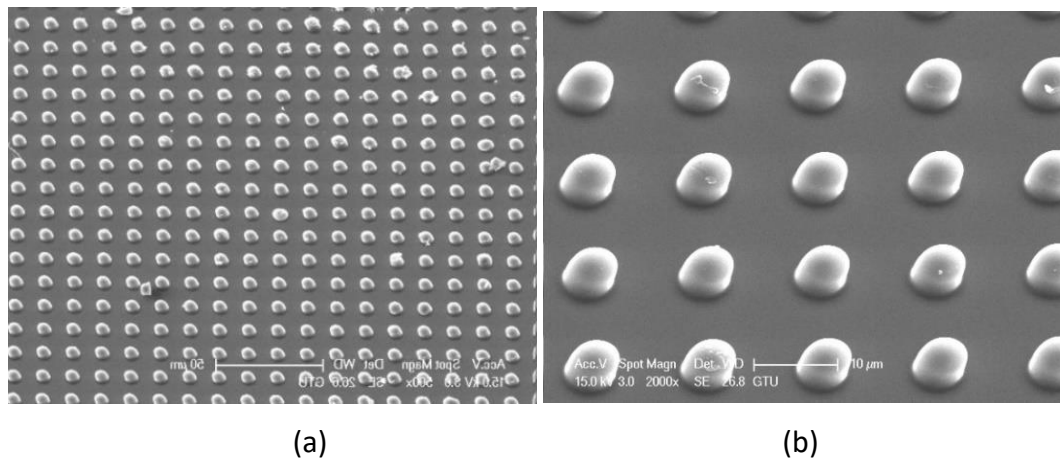


Figure 9.11: After the thin film growth process, SEM images of spherical structure is taken from side a) for 50 μm , b) for 10 μm .

9.3. Lift-Off Process

Lift-off operation is the process of removing the positive resist from the sample using acetone. With this process, positive resist was coated and then the positive resist in the unwanted parts were removed from the lithographed sample. Thus, our designs have been finalized. To summarize the stage of obtaining patterns:

- Substrate was coated with SU-8 3005, which has negative resistance and cylindrical patterns were obtained by lithography.
- Spherical shapes were obtained from cylinders by making thermal reflow.

- Substrate was coated with AZ1505 positive resist and lithography was performed.
- Thin film was grown on substrate.
- Lift-off was done.

10. RESULTS and DISCUSS

In this section, experimental studies will be given in this thesis and the results of these studies will be explained. In this study we have two different purposes. The first is to examine how the magnetic properties of a ferromagnetic material vary depending on the shape of the material. Our second aim is to examine the magnetic properties of the ferromagnetic thin film, which is grown only on spherical surfaces, depending on the thickness of the grown material.

10.1. Results of $\text{Ni}_{80}\text{Fe}_{20}$

In order to achieve the first purpose of this study, $\text{Ni}_{80}\text{Fe}_{20}$ ferromagnetic thin film was grown for three different surfaces. The first of these surfaces is a flat silicon substrate, the second is a spherical shape obtained by lithography on silicon substrate and the third is spherical surfaces obtained by lithography on silicon substrate.

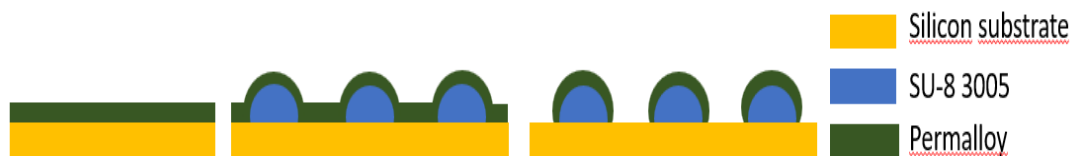


Figure 10.1: Schematic representation of cross - sections of film-grown surfaces.

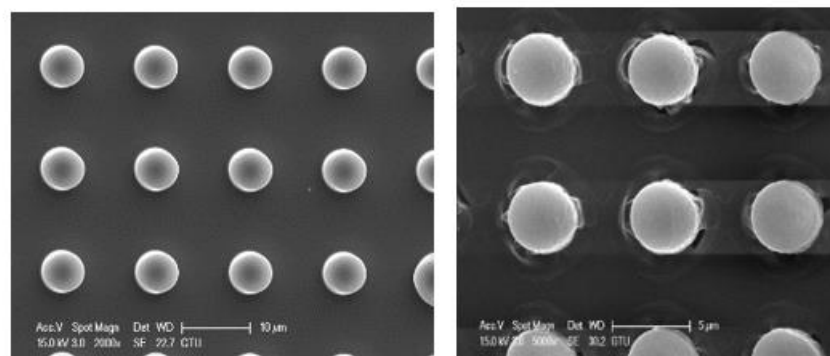


Figure 10.2: SEM images before and after lift-off operation of the film-grown surface, respectively. (Substrate + SU-8 photoresist + thin film ($\text{Ni}_{80}\text{Fe}_{20}$) and substrate + SU-8 photoresist + thin film ($\text{Ni}_{80}\text{Fe}_{20}$) + lift-off.

Figure 10.1 shows the cross-sections of 3 different surfaces on which $\text{Ni}_{80}\text{Fe}_{20}$ (permalloy) thin films were grown. The reason for choosing three different surfaces is to determine the difference of the films grown on the hemisphere from the films grown to a flat surface. SEM images of the films obtained are given in Figure 10.2. Figure 10.2 shows the SEM images before and after the lift-off operation after deposition the permalloy thin film. The fabricated spheres have a diameter of 3.5 μm and the distances between them are 5 μm . As can be seen from the SEM images, the desired spherical surfaces were obtained by a successful fabrication process.

XRD measurements were performed to perform structural analysis of thin films. The results of XRD measurements are given in Figure 10.3. As can be seen in these results, permalloy peaks were observed at 44.8 degrees. The peaks observed for this value of 2-theta indicate that the permalloy (111) has a crystalline sequence.

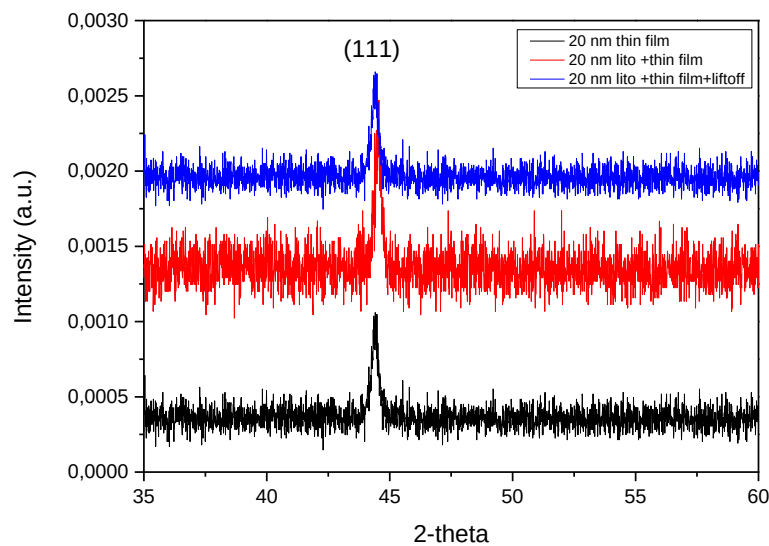


Figure 10.3: XRD measurement of permalloy coated surfaces.

For three different deposition, the MOKE was measured to determine the coercive areas and in which case they were easier to magnetize. The results of MOKE measurement are given in Figure 10.4 below. According to the MOKE measurement results, it was found that the magnetic thin film, which was only grown on the spherical surfaces, had the lowest coercive area and was the easiest to magnetize when exposed to the same intensity magnetic field. Although it has been observed that the magnetization of the magnetic thin film grown on a flat substrate is better

than magnetization of the film grown on the spherical surfaces, the coercive area of this film is only slightly higher than the coercive field of the film grown to the spherical surface.

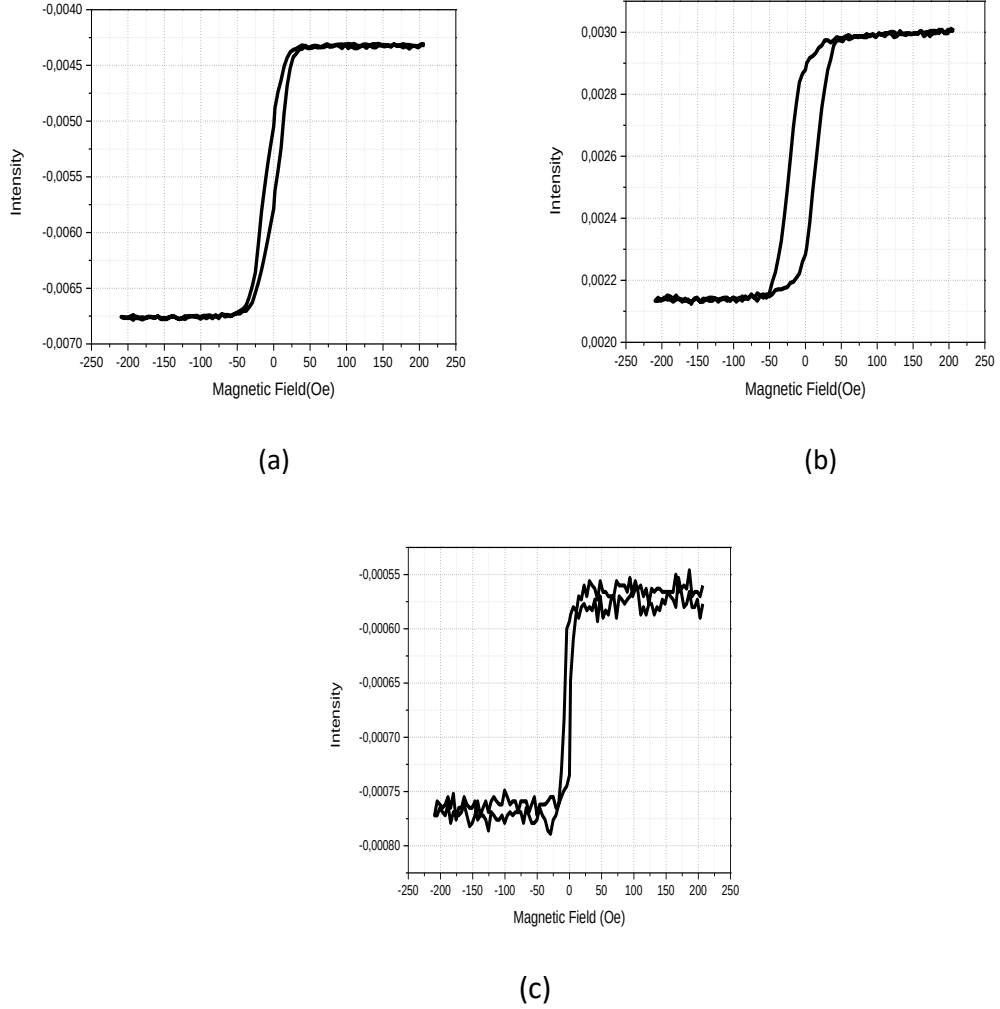


Figure 10.4: MOKE measurement results for $\text{Ni}_{80}\text{Fe}_{20}$ a) Thin film enlarged to the flat surface, b) thin film grown to lithographed surface, c) After the thin film surface, the lift-off was applied to the thin-film surface.

The FMR measurement results of the films which are grown for three different surfaces are given below. To examine the magnetic anisotropy, the external magnetic field was applied at different angles from the sample film plane to the film normal and the FMR Spectra ($d\chi/dH - H$) were measured for each angle value (Figure 10.5, Figure 10.6 and Figure 10.7. A magnetic field of 0 to 1000 Oe was applied for each angle value. Measurements were performed under room temperature conditions.

FMR spectra are given in Figure 10.6 for thin film, which is grown directly on the underside of a pattern. In the case where the magnetic field is parallel to the sample, the FMR peak was seen at 150 Oe. The resulting peaks first shifted towards the high magnetic field by varying the angle of the applied magnetic field, which varies depending on the rotation of the sample. When the applied magnetic field is exactly in the same direction as the film normal, the FMR peak is 820 Oe. In addition, the half-curve width of the FMR peaks decreased and the peak intensity increased. Figure 10.7 shows the magnetic spectrum curves of the films grown on a substrate furnished with spherical surfaces. As in the case of flat film, when the applied magnetic field was brought to an upright position, the FMR peak shifted to the areas where the magnetic field was high. And in this graph, it was observed that the peaks were expanded and shifted to the area where the magnetic field was high. The reason for the expansion of the peaks is that both the flat film portions on the surface and the parts of the film are grown spherically, even though the entire surface is covered with film. The fact that there were different absorptions in different parts of the face caused the absorptions to start and end in a larger area. Figure 10.8 shows only the magnetic spectra of thin films composed of spherical surfaces. In this graph, it was observed that the absorptions took place in a much narrower area. The reason for this is that the entire surface is not covered with films, and only certain regions are covered with films. In this graph, the FMR peaks oscillated between 200 Oe and 600 Oe. Again, due to the magnetic field being perpendicular to the plane surface, the FMR peaks occurred in the regions where the magnetic field was high. And the peaks of the peaks have shrunk more than the other two measurements. This indicates less power absorption. According to these results, although the power absorption in the flat films is more severe, it has been seen that the material needs a higher magnetic field to resonate. Depending on the direction of the magnetic field, we can show the effect of the shape anisotropy as the reason for the resonance condition to occur in higher magnetic fields [47]. The cause of the splint that occurs occasionally on the peaks may be due to the effect of the sphere surface and the angle and / or spin wave modes of the external magnetic forehead.

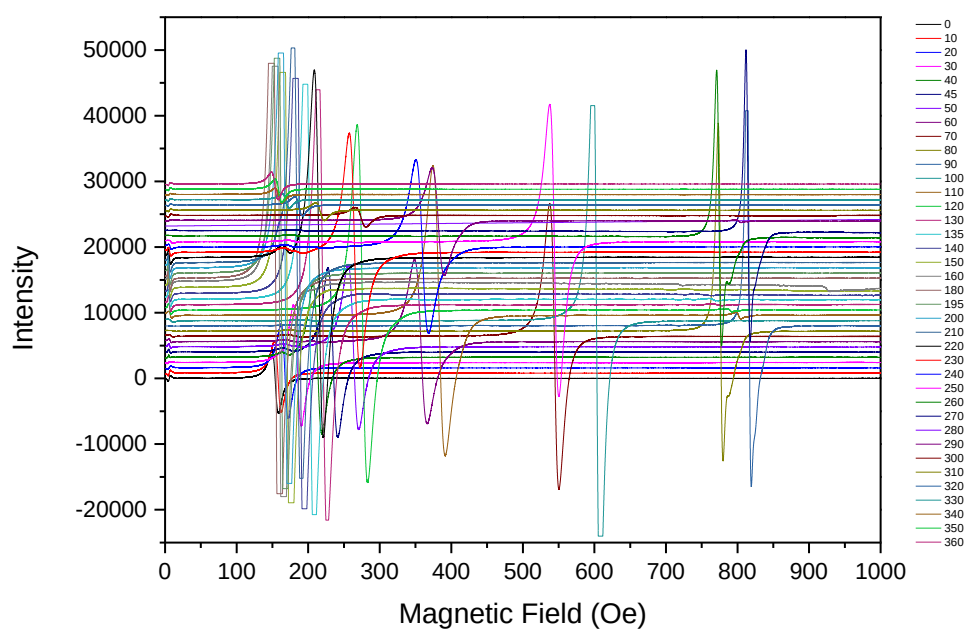


Figure 10.5: Stack graph of magnetic spectrum curves for $\text{Ni}_{80}\text{Fe}_{20}$ grown on silicon substrate.

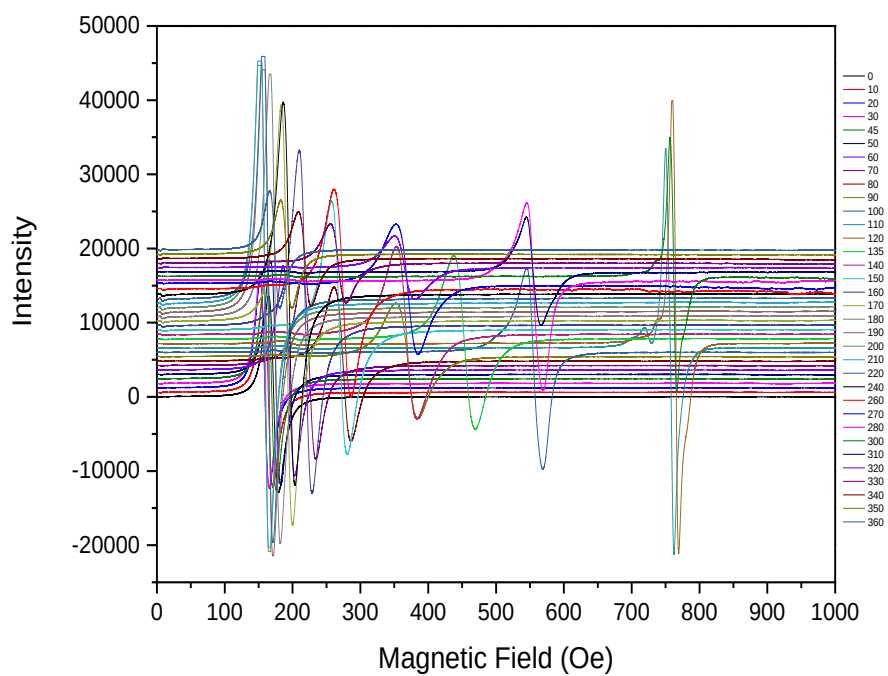


Figure 10.6: Magnetic spectrum curves stack graph for $\text{Ni}_{80}\text{Fe}_{20}$ coated surface after lithography process.

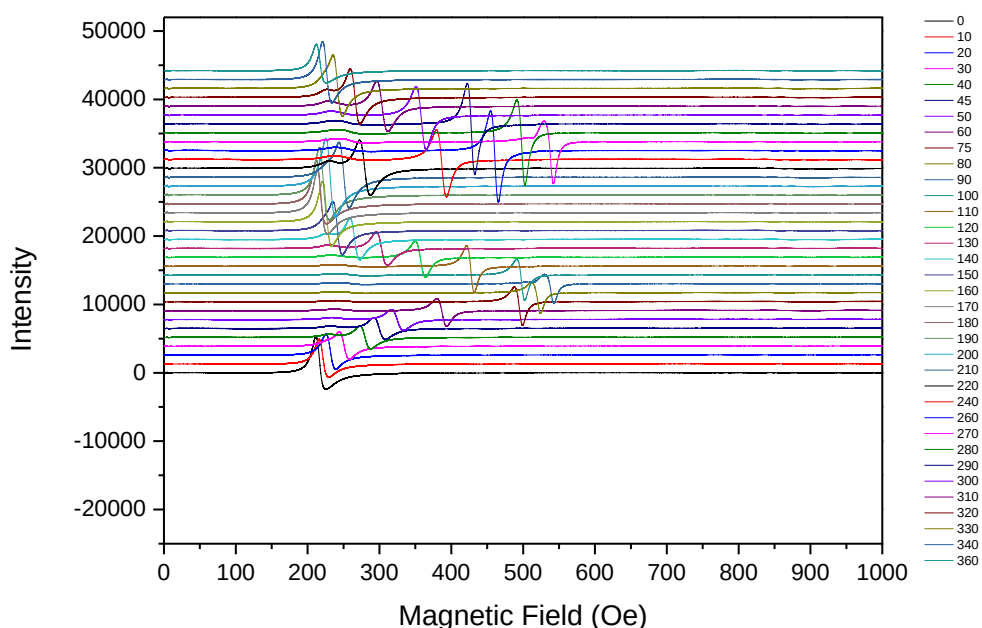


Figure 10.7: Magnetic spectrum curves stack graph for $\text{Ni}_{80}\text{Fe}_{20}$ grown surface after lift-off.

The angular change graphs of the FMR peaks are shown in Figure 10.8, Figure 10.9 and Figure 10.10. Here again, respectively, the resonance area graph for the flat film, resonance area graph for the grown film on the surface obtained from the spherical surfaces on the surface and the resonance area graph for the grown film only on spherical surfaces are included. Here, the magnetic field is first parallel to the sample plane (0 degree). Then, by rotating the sample, the magnetic field was brought to the vertical position (90 degree). And as the sample continues to be rotated, the magnetic field is first brought back to the parallel (180 degree) and again to the vertical (270 degree) position. In this way, the sample is rotated between 0 degrees and 360 degree so that the magnetic field is applied to the sample plane at different angles. According to these graphs, sample magnetization was found to be perpendicular to the sample plane in all three cases. Because sample magnetization increases to 90 degree and 270 degree when the sample is rotated to higher values. Depending on the shape of the film, different magnetization peaks were seen in the graphics. The maximum number of peaks was seen when the material was enlarged as flat film. This change in the number of peaks is due to the different types of

magnetization dynamics in different regions depending on the direction of the applied magnetic field. That is, the material has multiple magnetization dynamics. And this magnetization dynamics emerge when the direction of the magnetic field changes. Although the material has more magnetization dynamics in the form of a flat film, the magnetization dynamics are reduced when the shape of the material is changed. Since the materials have different filling rates, the magnetization dynamics of the material are different in their intensity [48]. As the material is fully crushed, a more severe magnetization is observed, while the material decreases as the magnetization intensity decreases.

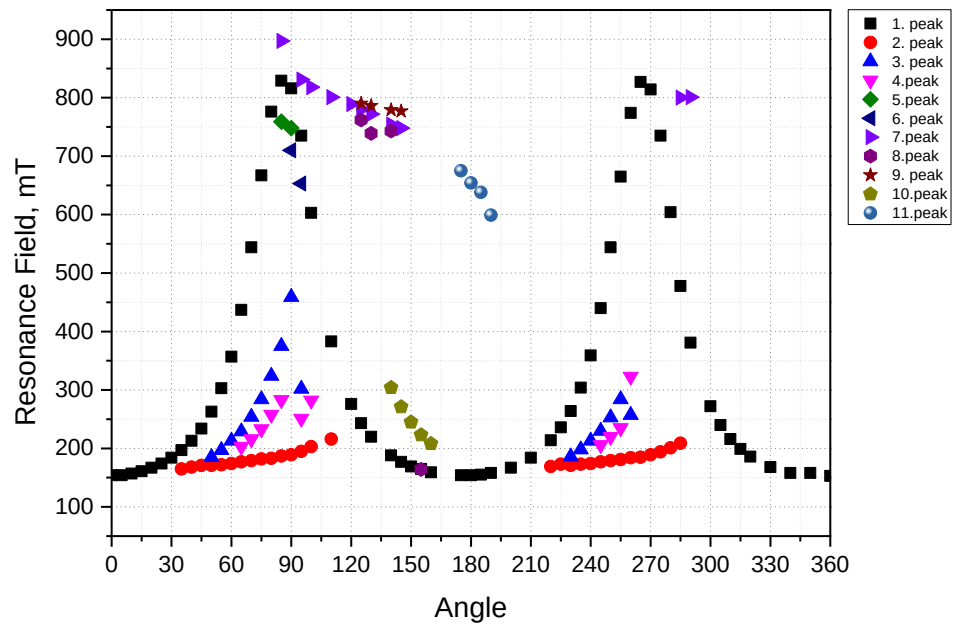


Figure 10.8: Resonance field graph for $\text{Ni}_{80}\text{Fe}_{20}$ grown on silicon substrate.

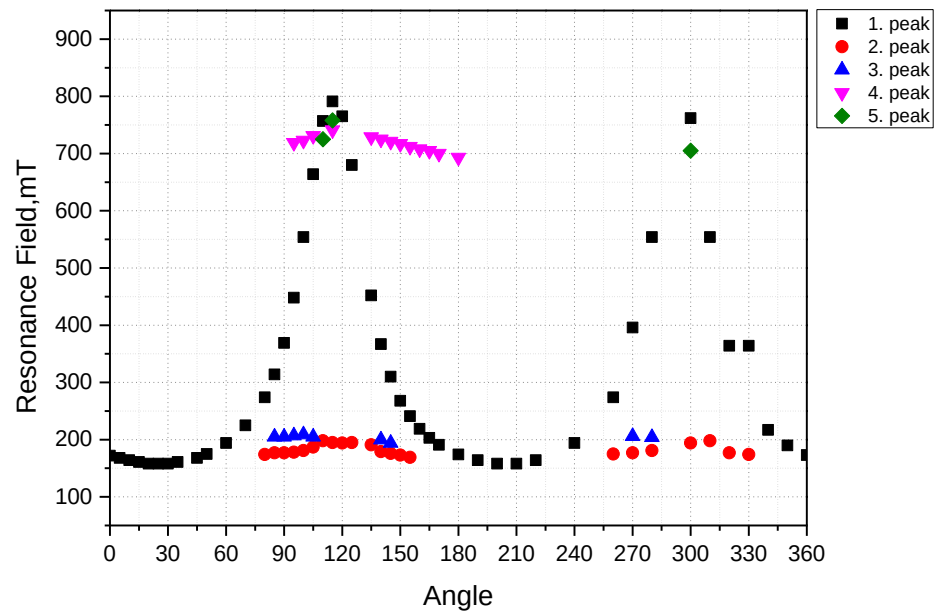


Figure 10.9: Resonance field graph of $\text{Ni}_{80}\text{Fe}_{20}$ grown surface after lithography.

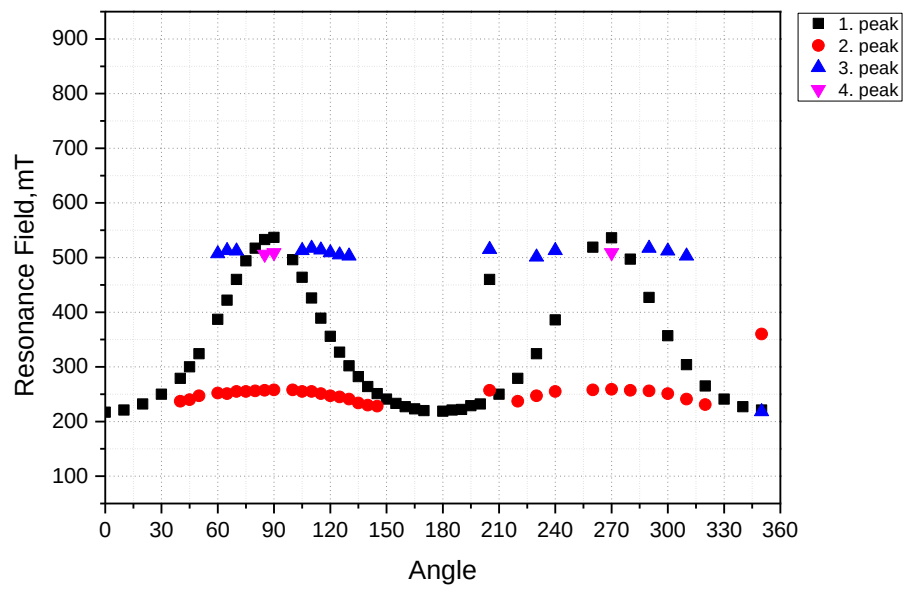


Figure 10.10: Resonance field graph of $\text{Ni}_{80}\text{Fe}_{20}$ grown surface after lift-off.

10.2. Results of $\text{Ni}_{55}\text{Fe}_{45}$

At this stage of the study, three different thickness films were grown on the same shape. $\text{Ni}_{55}\text{Fe}_{45}$ was used to change the film. The thickness of the grown films is 5 nm, 10 nm and 20 nm. Films with three different thickness were grown and the magnetic properties of the spherical surfaces changed depending on the film thickness. Figure 10.11 shows the cross section of the $\text{Ni}_{55}\text{Fe}_{45}$ (permalloy) thin-film coated surface. In Figure 10.12, Figure 10.13 and Figure 10.14, SEM images of the permalloy thin film-grown surfaces are included. According to the SEM images, a successful fabrication process was performed to obtain the desired spherical surfaces. The spherical surfaces used for this study have diameters of 4 μm , and the distances between the spheres are 4 μm .



Figure 10.11: Schematic representation cross- section of film grown surface.

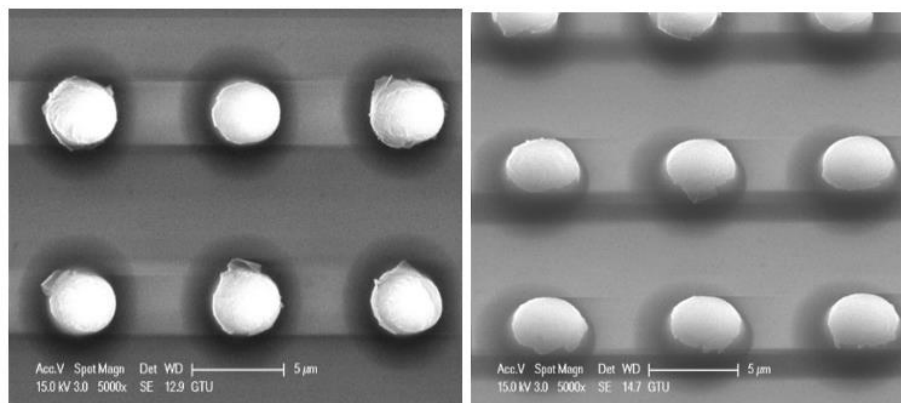


Figure 10.12: SEM images obtained from the surface and side for 5 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$, for 5 μm resolution from the surface, for angle 10 μm resolution.

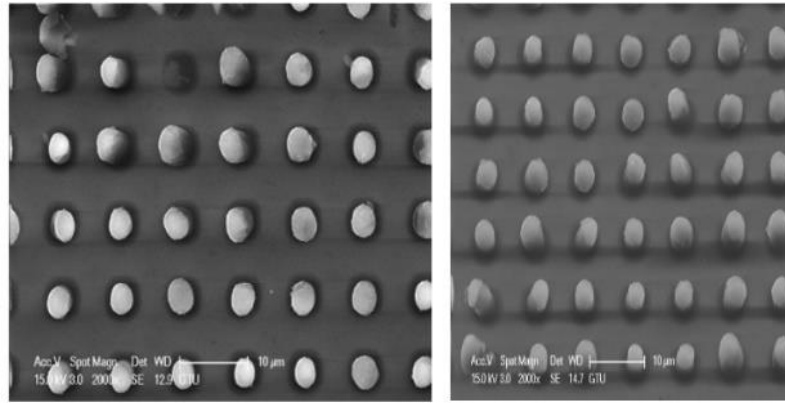


Figure 10.13: SEM images obtained from the surface and side for 10 nm-thickness $\text{Ni}_{55}\text{Fe}_{45}$, for 10um resolution, for 10um resolution from the surface.

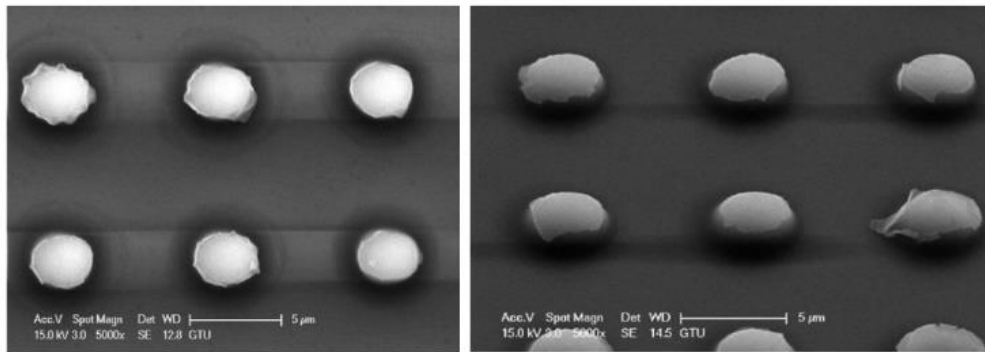


Figure 10.14: SEM images obtained from the surface for 20 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$ and angled from, for a resolution of 5 um from the surface, for a resolution of 5 um from the side.

XRD measurements were performed for structural analysis of thin films. The results of XRD measurements are given in Figure 10.15. As can be seen in these results, permalloy peaks were observed at 44.8. The peaks observed for this angle indicate that the permalloy (111) has a crystalline sequence.

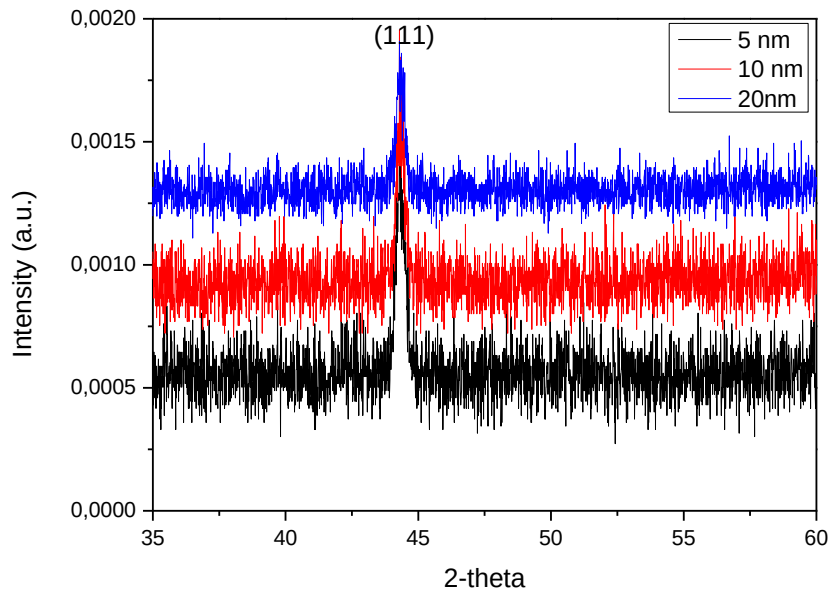


Figure 10.15: XRD measurements made for three different thickness studies a) (black) for 20 nm thickness thin film, b) (red) for 10 nm thickness thin film, c) (blue) for 5 nm thickness thin film.

In this part of the study, FMR measurements were taken to examine the magnetic properties of magnetic thin films. FMR measurements were taken for three different thicknesses. Measurements were performed under room conditions. First, the magnetic field is applied parallel to the surface and then the sample is rotated and the magnetic field is sent to the sample with different angles. The magnetic FMR spectrum graphs for the films grown at 5 nm, 10 nm and 20 nm thickness are given below in Figure 10.16, Figure 10.17 and Figure 10.18, respectively. According to these graphs, we observe that power absorptions for films with a thickness of 5 nm and films with a thickness of 10 nm take place between 100 Oe and 200 Oe. For measurements of 20 nm, power absorption was observed between 100 Oe and 500 Oe. In the case of thin films, the surface of the film cannot be permanently covered due to the brittleness on the surface, whereby discontinuities may occur between the surface pits and hills. With the increase in thickness, it can be said that the surface of the film is completely covered and thus provides continuity. This has led to an increase in the demagnetization area of the material. And accordingly, as the thickness of the magnetic material increases, the magnetic field that has to be applied

for the observation of the resonance peak is greater. Again, due to the increase in thickness, the splits on the spectra can be said to be due to the fact that the angle between the applied magnetic field and the surface is different due to the semi-spherical surface and due to the spin wave modes. Because for increasing thickness begins to behave like materials on a continuous surface, it appears similar behavior to the behavior observed in the continuous film. When the sample is rotated and the magnetic field is perpendicular to the sample plane, the intensity of the peaks is reduced due to the fact that the absorption is on a different surface depending on the structure of the shape. So the absorption in that area of the shape has been less. And accordingly, the intensity of the resonance peak has been low. However, the power absorption increases again depending on the thickness of the material.

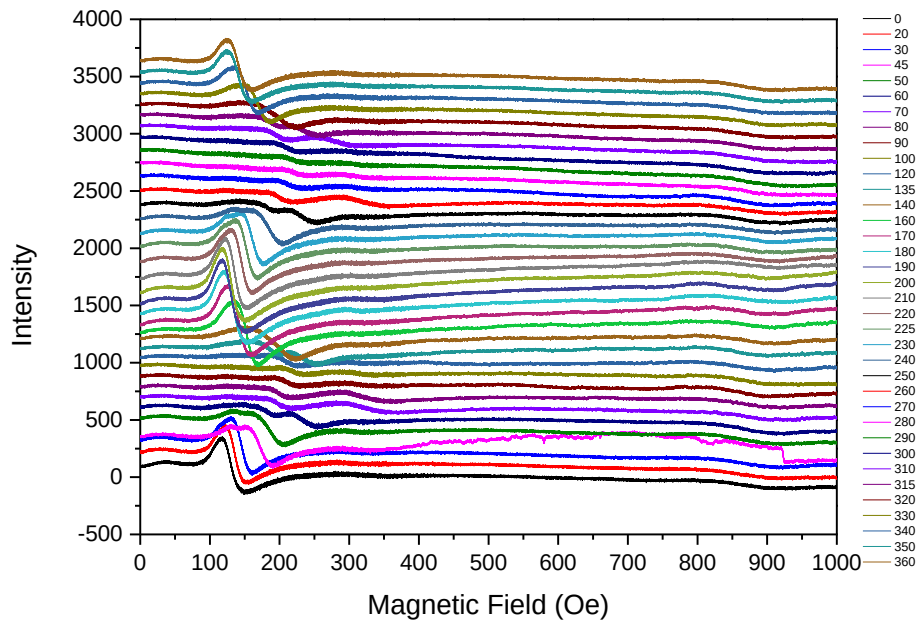


Figure 10.16: Magnetic spectrum stack graph for 5 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.

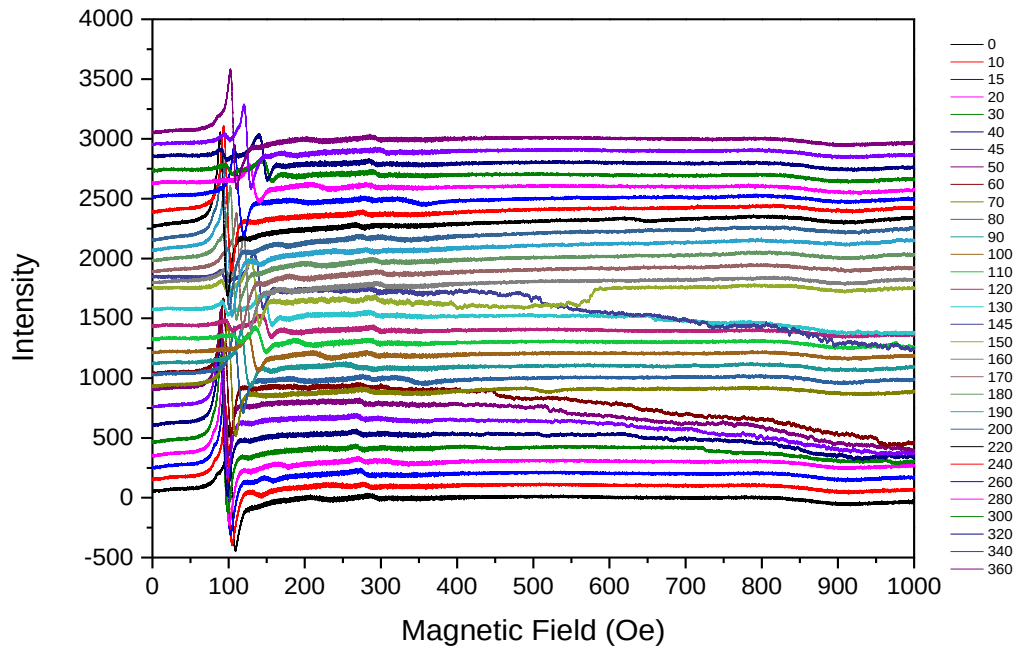


Figure 10.17: Magnetic spectrum stack graph for 10 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.

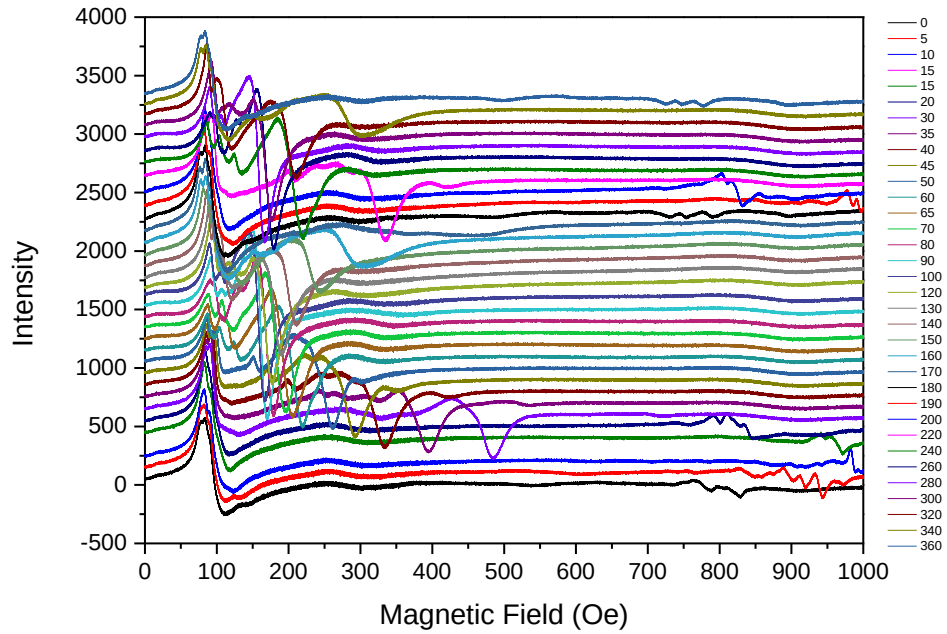


Figure 10.18: Magnetic spectrum stack graph for 20 nm thick $\text{Ni}_{55}\text{Fe}_{45}$.

Figure 10.19, Figure 10.20 and Figure 10.21 show angular-dependent resonance field graphs obtained from FMR measurements made for grown films at 5

nm, 10 nm and 20 nm thickness on spherical surfaces, respectively. During the measurements, the sample was rotated between 0 degree and 360 degree. In this way, the magnetic field is made from the state parallel to the sample plane and the measurements are made. According to these graphs, the magnetic magnetization of the sample was found to be greater when the magnetic field was applied perpendicularly. Because the resonance field value has reached 90 degree and 270 degree maximum values and then decreased as the sample continues to be rotated. The graphs show multiple magnetization curves. The reason for this magnetization curves to be seen more than one is due to the shape of the film. Because our film has a global shape, different magnetizations occur on the sample because the different surfaces of the sample absorb the magnetic field from different positions and different angles by rotating the sample. We can call it the effect of shape anisotropy. The change in magnetization magnitudes can be explained by the thickness of the sample. Because, as increases the thickness of the film grown on the sample, the roughness on the sample decreases and the sample has a smoother structure. Thus, the sample exhibits a continuous structure behavior [48]. Furthermore, due to the increase in occupancy rate on the sample, since the amount of absorption will increase, it causes the sample to form more severe peaks when reaching resonance.

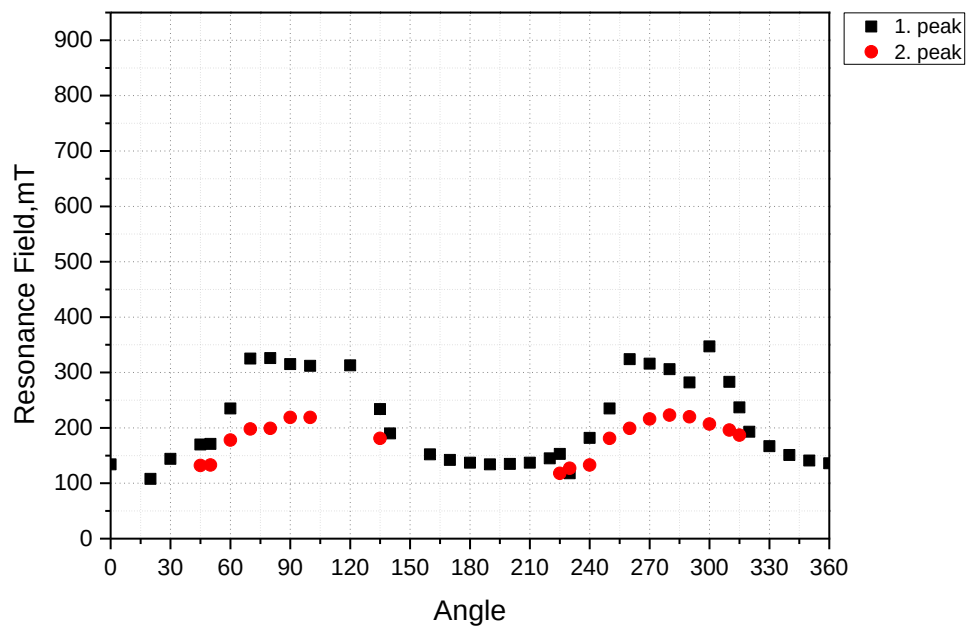


Figure 10.19: Resonance field graph for 5 nm thickness Ni₅₅Fe₄₅.

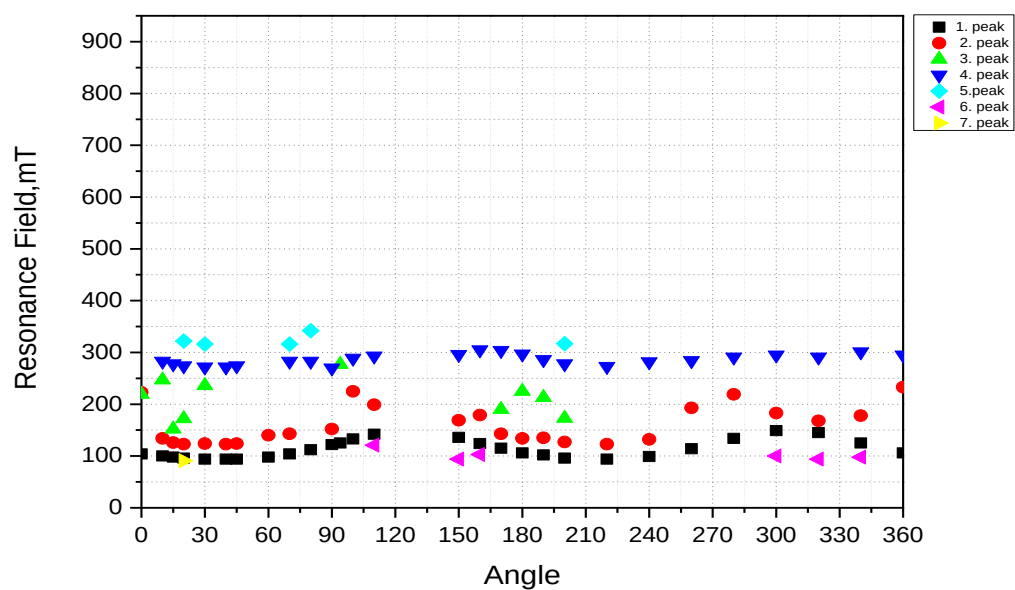


Figure 10.20: Resonance field graph for 10 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.

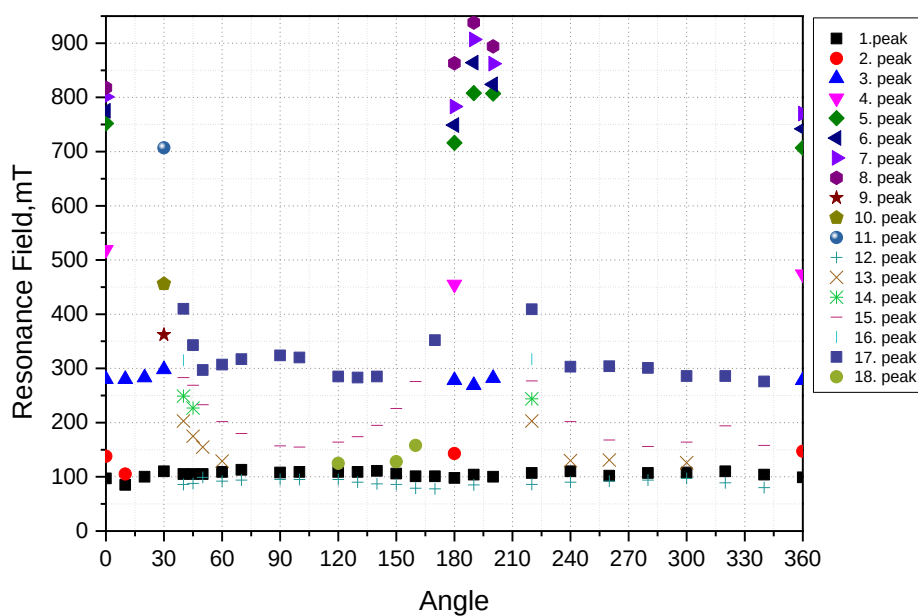


Figure 10.21: Resonance field graph for 20 nm thickness $\text{Ni}_{55}\text{Fe}_{45}$.

11. CONCLUSION

This thesis study, it consists of two parts. The first part is the fabrication part, whereby hemispherical surfaces were obtained using the photolithography method. After the hemispherical surfaces were obtained, ferromagnetic thin films were deposited by using the magnetto sputter method on the surfaces to be measured. Then, the characterization part of the thesis study started.

In the section of the thesis, $\text{Ni}_{80}\text{Fe}_{20}$ ferromagnetic thin film was grown for three different surfaces. The first of these surfaces is a flat silicon substrate, the second is a spherical shape obtained by lithography on silicon substrate and the third is spherical surfaces obtained by lithography on silicon substrate. Thus, depending on the shape of the film-coated surface, the change in the magnetic properties of the ferromagnetic material has been investigated.

In the second part of the characterization, the magnetic properties of the magnetic thin films were investigated, directly depending on the thickness of the films enlarged on the hemispherical surfaces. Three different thickness films were grown for this purpose.

FMR analysis showed that the spectra and angular dependence of magnetic anisotropies are quite different compared to the film grown on flat surface due to the induced shape anisotropy of the hemispheres. We will continue to work on this subject to develop magnetic sensors by using these results. Also, the study will provide a different perspective for researchers in their future studies. When designing devices with hemispherical array structures, one can get benefit from this thesis.

REFERENCES

- [1] Bose J. C., (1898), "On the Rotation of Plane of Polarisation of Electric Waves by a Twisted Structure", Proc. Roy. Soc., 63, 146-152.
- [2] Lindell I. V., Sihvola A. H., Kurkijarvi J. and Lindman K. F., (1992), "The Last Hertzian, and a Harbinger of Electromagnetic Chirality", IEEE Antennas and Propagation Magazine, 34 (3), 24-30.
- [3] Kock W. E., (1948), "Metallic Delay Lenses", Bell Labs Technical Journal, 27 (1), 58-82.
- [4] Veselago V. G., (1968), "The Electrodynamics of Substances With Simultaneously Negative Values of ϵ and μ ", Soviet Physics Uspekhi, 10 (4), 509-514.
- [5] Pendry J. B., Holden A. J., Robbins D. J., and Stewart W. J., (1999), "Magnetism From Conductors and Enhanced Nonlinear Phenomena", IEEE Trans. on Microwave Theory and Tech., 47, 2075-2084.
- [6] Smith D. R., Padilla W. J., Vier D. C., Nemat-Nasser S. C., and Schultz S., (2000), "Composite Medium With Simultaneously Negative Permeability and Permittivity", Phys. Rev. Lett., 84, 4184.
- [7] Shelby R. A., Smith D. R., Nemat-Nasser S. C., and Schultz S., (2001), "Microwave Transmission Through a Two-Dimensional, Isotropic, Lefthanded Metamaterial", Appl. Phys. Lett., 78, 489.
- [8] Harey T. J., (2007), "Material Substruction in Complex Bodies", Elsevier Science.
- [9] Ames J. S., (1900), "The Effect of A Magnetic Field on Radiation", Universty of California, USA.
- [10] Qiu Z. Q., Badera S. D., (1999), "Surface Magneto-Optic Kerr Effect", 2000 American Institute of Physics, 71 (3), 1243-1255.
- [11] Weinberger P., (2008), "John Kerr and His Effects Found in 1877 and 1878", Philosophical Magazine Letters, 88, 897-907.
- [12] MMPA Standard No: 0100-00, (1964), "Standart Specifications for Permanent Magnet Materials", Magnetic Materials Producers Association, Chicago.
- [13] Ohring M., (1995), "Engineering Material Science", 1th Edition, Academic Press.
- [14] Soshin C., (2009), "Physics of Ferromagnetism", 2th Edition, Oxford Science Publication.
- [15] Brian F.P, (1999) " An Inclusive Model of Ferromagnetic Hysteresis", PhD Thesis, Queen's University Kigston, Ontario, Canada.

- [16] XIA X., (2015), "Magnetic Properties of Nano-Composite Partical", PhD Thesis Tuscaloosa, Alabama.
- [17] Atulasimha J., Bandyopadhyay S., (2011), "Nanomanyetik and Spintronic Devices for Memory and Computing", 1th Edition, Wiley.
- [18] Tacer E., (2004), "Ders Notları", İ.T.Ü Elektrik Elektronik Fakültesi, İstanbul.
- [19] Serway R. A., Beicher R. J., (1996), "Fen ve Mühendislik için Fizik", 5. Baskı, Palme Yayıncılık.
- [20] Çöktüren E., (2008), "Ferromanyetik Filmlerde Manyetik Yüzey Anizotropi Oluşumunun Nümerik Çözümlemesi", Yüksek Lisans Tezi, Trakya Üniversitesi, Fen Bilimleri Enstitüsü, Fizik Anabilim Dalı.
- [21] Cullity B. D. (1972), "Introduction to Magnetic Materials", Addison Wesley, 544, Canada.
- [22] Slichter C.P., (1963), "Principles of Magnetic Resonance", 3th Edition, Harper & Row.
- [23] Thomson T., (2014), "Metallic Film for Electronic, Optical Magnetic Applications", Woodhead.
- [24] Poole C. P., (1983), "Electron Spin Resonance: A Comprehensive Treatise on Experimental Technique", 2th Edition, Dover Publications.
- [25] J. Gomez, Weston J. L., Butera A., (2007), "Ferromagnetic Coupled Modes in Continuous/Granular Multilayers: Model and Experiments", Physical Review B, 76 (18), 184416.
- [26] Smith G. M., Lesurf J. C. G., Mitchell R. H., Riedi P. C., (1998), "Quasi-Optical cw mm-Wave Electron Spin Resonance Spectrometer", Review of Scientific Instruments, 69, 3924–3937.
- [27] Kalarickal S. S., Krivoski P., Patton C. E., (2006), "Ferromagnetic Resonance Linewidth in Metallic Thin Films: Comparison of Measurement Methods", Journal of Applied Physics, 99, 093909.
- [28] Barry W., (1986), "A Broad-Band, Automated, Stripline Technique for the Simultaneous Measurement of Complex Permittivity and Permeability", IEEE Transactions on Microwave Theory and Techniques, 34, 80–84.
- [29] Kennewell K. J., Kostylev M., Ross N., Magaraggia R., Stamps R. L., Ali M., Staskevich A. A., Greig D., Hickey B. J., (2010), "Magnetization Pinning at a Py/Co Interface Measured Using Broadband Inductive Magnetometry", Journal of Applied Physics, 108, 073917.
- [30] Kittel C., (2005), "Introduction to Solid State Physics", 8th Edition, Wiley.
- [31] Prozorov R., Kogan V. G., (2018) "Effective Demagnetizing Factors of Diamagnetic Samples of Various Shapes", Physical Review Applied, 10, 014030.
- [32] Akdoğan N., (2004), "İnce Filmlerde Manyeto-Optik Ölçümler", Yüksek Lisans Tezi, Y.T.Ü, İstanbul.

- [33] Xiao H., (2001), "Introduction to Semiconductor Manufacturing Technology", 2th Edition, Spie Press .
- [34] Web 1, (2018), <http://www.temizodamalzeme.com/location.html>, (Eriřim Tarihi:02/11/2018).
- [35] Web 2, (2018), <http://www.temizodamalzeme.com/location.html>, (Eriřim Tarihi:02/11/2018).
- [36] MacFadyen D.N., (1983), "On the Preferential Etching of GaAs by H₂SO₄-H₂O₂H₂O", J. Electrochem. Soc., 130 (9), 1934-1941.
- [37] Hornyak G.L., Dutta J., Tibbals H. F., Roa A. K., (2008), "Introduction on Nanoscience", 1th Edition, CRS Press.
- [38] Arpapay B., (2010), "Device Production And Characterization From GaAs / AlGaAs Based Semiconductor Structures", Master Thesis, Anadolu Universty, Department of Physics.
- [39] Shaw D. W., (1981), "Localized GaAs Etching With Acidic Hydrogen Peroxide Solutions", J. Electrochem. Soc., 128, 874-880.
- [40] Aksu P., (2017), "Dik ve Paralel Anizotropilli Filmlerin Büyütölmesi, Manyetik ve Yapısal Özelliklerinin İncelenmesi", Doktora Tezi, Gebze Teknik Üniversitesi, Kocaeli.
- [41] Jilani A., Abdel-wahab M. S., Hammad A. H., (2017), "Material Science-Modern Technologies for Creating the Film System and Coating, Advance Deposition Techniques for Thin Film and Coating", Print ISBN 978-953-51-3003-1.
- [42] Web 3, (2018), <https://bilimfili.com/hiperfizik/hbase/quantum/bragg.html>, (Eriřim tarihi: 27/10/2018).
- [43] Web 4, (2018), <https://muhendishane.org/kutuphane/temel-malzeme-bilgisi/kristal-yapilarda-yon-ve-duzlemler/>, (Eriřim Tarihi:27/10/2018).
- [44] Inkson B. J., (2016), "Material Chaacterization Using Nondestructive Evaluation (NED) Methods", 1th Editon, Woodhead Publishing.
- [45] Demirci E., (2011), "CoO/Co Manyetik İnce Filmlerde Kaydırma (Exchange Bias) Etkisi", Yüksek Lisans Tezi, Gebze Yüksek Teknoloji Enstitüsü.
- [46] Prat-Camps J., Navau C., Sanchez A., Chen D., (2016), "Demagnetizing Factor of a Hollow Sphere", IEEE Magnetic Letter, 7.
- [47] Okay C., Aksu P., Deęer C., Yıldız F., (2018), "Tailoring the Magnetic Anisotropy of Cobalt-Gold Thin Films", Turk J Phys., 42, 335-341.
- [48] Yıldız F., Lee H. J., Jeong Y. H., Kazan S., Aktaş B., Song J. H., (2008), "Magnetic Properties of Cobalt-Ion-Implanted SiO₂ Thin Films", Journal of the Korean Physical Society, 53 (6), 3699-3703.

BIOGRAPHY

Özlem AKIN was born on 24.04.1991 in Erzurum. She completed his primary and high school education in Erzurum. Between the years 2011-2016, she completed her undergraduate education in Electrical and Electronics Engineering at Karadeniz Technical University. In 2017, she started to work as a Research Assistant at Erzurum Technical University Electrical and Electronics Engineering Department. She started her Master of Science education in 2017 at Gebze Technical University, Nanotechnology Institute and she is still continuing.